UNIVERSITAS
FRIBURGENSIS

Categorical Effects in Visual Selective Attention: Evidence from Investigating Foundations, Disturbances and Development

Dissertation for obtaining the degree of doctor at the philosophical faculty of the University of Fribourg (Switzerland)

07. December 2009

Submitted by Sandra Utz (born in Donauwörth, DE)

Approved by the philosophical faculty on request of the professors
Joseph Krummenacher (1st assessor) and **Hermann Müller** (2nd assessor)

Fribourg, 29th March 2010 Prof. Dr. Thomas Austenfeld (dean)

Nihil tam difficile est, quin quaerendo investigari possit! (Terentius)

Nichts ist so schwierig, dass es nicht erforscht werden könnte! (Terenz)

Structure

1. Summary

Since in almost every theory of visual selective attention, categories (e.g., colour, letter, or size) play a crucial role, I investigated these categorical processes in more detail. More precisely, the studies focused on the foundations, certain disturbances and the development of these processes.

One recent and very influential theory of visual selective attention is the “theory of visual attention” (TVA) developed by Claus Bundesen (1990). Bundesen assumed that the categorisation of objects is an automatic process. If someone looks at an object he or she will automatically categorise and therefore recognise it. Other theoretical examples are the guided search model by Wolfe (e.g., Wolfe, 1994) or the dimension weighting account by Müller, Heller and Ziegler (1995). According to these models, objects are selected predominantly if they stand in big contrast to other surrounding objects. If objects stand in contrast to the other objects, the so-called saliency activation for these objects will be very high. The saliency signals are computed based on the category (or dimension) of the object according to the contrast to the surrounding objects - the higher the contrasts, the higher the saliency activation. The assumption of dimension-based saliency signals could be proven by Müller, Heller and Ziegler (1995) and Müller and Found (1996).

As mentioned before, TVA predicts that all categorisation processes are executed automatically without any possibility of influencing these processes. In the first project I wanted to challenge this assumption by investigating potential influences on categorising objects or the experimental stimuli, respectively. With two simple experimental paradigms (partial and whole report procedures) the four different attentional components (capacity of visual short-term memory, processing speed, spatial distribution of attentional weights and the selection effectiveness) proposed by the TVA (Bundesen, 1990) can be measured. If the performance reflected in the four components can be influenced, this would argue strongly against an automatically working categorisation process. Found and Müller (1996) found influences of changes or repetitions of target-defining dimensions in consecutive trials on the reaction times of their participants in visual search experiments[1]. Faster reaction times

---

[1] In visual search experiments participants have to indicate as quickly and as accurately as possible if a pre-defined target surrounded from a certain number of distractors is present or absent.

could be observed if the target-defining dimension was repeated on consecutive trials and slower reaction times if the target-defining dimension changed. Therefore, in a series of experiments it was investigated if bottom-up (i.e., stimulus-driven) changes, repetitions in target-defining features (e.g., red, small), or dimensions (e.g., colour, size) influence not only reaction times in visual search but also the performance, reflected in the four components of the TVA (Bundesen, 1990). According to Found and Müller (1996) the performance was expected to deteriorate if the feature or dimension was changing in consecutive trials and to ameliorate if the feature or dimension was repeated. In proximate experiments the effects of top-down (knowledge-based) influences were tested as well. Since both the bottom-up and top-down manipulations influenced the components of the TVA (Bundesen, 1990) and therefore the categorisation process, the assumption of automatic categorisation processes needs to be updated. Furthermore, an interesting finding was the repeatedly found changes in the visual short-term memory capacity - normally assumed to be a very stable component of the system. The results argue for a variable capacity, depending on different aspects.

In a series of experiments, I wanted to investigate specific questions with regard to the characteristics of the TVA (Bundesen, 1990). The question was if different spatial arrangements of the experimental stimuli, repetitions of exactly the same stimuli in consecutive trials, or repetitions of the same stimulus within the same trial affect the categorisation process and therefore the four attentional components of the TVA (Bundesen, 1990). Actually, all different manipulations affected the components. (Detailed descriptions of the experiments and results can be found in chapter 5.1.)

The focus of the second project was on people having disturbances in visual processing. A group of people with Asperger's syndrome (a mild form of autism) were investigated because of their enhanced categorical abilities. In the literature, the superior abilities in visual perceptual tasks in people within the autistic spectrum are repeatedly mentioned. So, for example, in visual search tasks in which subjects have to indicate as quickly and as accurately as possible if a pre-defined target-stimulus within a certain number of distracting stimuli is present or absent, subjects with autism showed significantly better performance and differing results pattern compared to healthy control groups (e.g., Plaisted, O'Riordan and Baron-Cohen, 1998b). Since it is not clear if people with Asperger's syndrome show similar results pattern as people with autism or as healthy control groups, this was

investigated in a series of visual search tasks. Results revealed very similar performance patterns of the Asperger's group compared to healthy controls. However, the Asperger's group searched significantly faster and more effectively for the presence or absence of a target than the healthy controls. In the following experiments, the processing difference in visual search and the possible location of the difference (early and pre-selective or late and post-selective) in the visual processing stream was investigated. Results point at a late processing benefit associated with object recognition or object identification of the people with Asperger's syndrome. The last experiments tested the influences of the stimulus material (letters) on the processing difference. The differences in search performance detected in the visual search experiments are probably, at least partially, due to the fact that highly overlearned letter stimuli were used. (Detailed descriptions of the experiments and results can be found in chapter 5.2.)

Since categorising objects is a very basic and important process, the developmental aspect is of great importance. In the last project three different age groups of children (first, second, and third graders) were investigated with TVA (Bundesen, 1990) - based testing procedures. Results showed that the capacity of visual short-term memory increased considerably from the first to the third grade. Additionally, with increasing age, children were significantly faster (higher processing speed) and selected relevant information noticeably better. All mentioned components were therefore developing mainly in concert. Altogether, the results are in accordance with an extended version of the global trend hypothesis (Hale, 1990; Kail, 1986) assuming that all information processing components develop simultaneously. (Detailed descriptions of the experiments and results can be found in chapter 5.3.)

All three projects demonstrated very well the importance of the categorisation process for selection performance. Results showed that the categorisation process can be influenced by certain easy manipulations, that some people show specific advantages in this ability and finally that children's ability to categorise objects is not fully developed in early childhood; rather the ability develops over the course of childhood.

2. Summary in German

Da in beinahe jeder Theorie zur selektiven visuellen Aufmerksamkeit die Kategorisierung von Objekten (Kategorien wie z.B. Farbe, Grösse, Buchstabe, etc.) eine zentrale Rolle spielt, wurden diese Kategorisierungsprozesse im Detail untersucht. Die durchgeführten Studien fokussierten die Grundlagen der Kategorisierung, spezifische Störungen im Kategorisierungsprozess und schlussendlich die Entwicklung dieser zentralen Fähigkeit. All diese verschiedenen Felder tragen zu einem besseren Verständnis der Selektionsmechanismen der visuellen Aufmerksamkeit und der Kategorisierung von Objekten bei.

Im Speziellen geht es im ersten Projekt um die Grundlagen und die Beeinflussbarkeit des Kategorisierungsprozesses. Im Zentrum der Studie steht eine aktuelle und sehr einflussreiche Theorie der selektiven visuellen Aufmerksamkeit, die “Theorie der visuellen Aufmerksamkeit” (TVA; Bundesen, 1990). Claus Bundesen geht davon aus, dass die Kategorisierung von Objekten ein automatischer und nicht beeinflussbarer Prozess ist. Wenn jemand ein Objekt sieht, wird das Objekt sofort zwangsläufig kategorisiert und damit erkannt. Andere wichtige Ansätze, in denen Kategorisierung eine zentrale Rolle für die Selektion spielt, ist zum einen das Modell der gesteuerten Suchen von Jeremy Wolfe (z.B. Wolfe, 1994) und der „Dimensionsgewichtungsansatz“ von Müller, Heller und Ziegler (1995) und Found und Müller (1996). Den Modellen zufolge werden Objekte dann selektiert, wenn sie in grossem Kontrast zu anderen, umliegenden Objekten stehen. Die sogenannte Salienzaktivierung für die Objekte, die sich deutlich von den anderen unterscheiden, ist dann besonders hoch. Salienzsignale werden basierend auf der jeweiligen Kategorie (oder Dimension) eines Objektes berechnet, was durch die Studien von Müller, Heller und Ziegler (1995) und Found und Müller (1996) bewiesen wurde. Je höher der Unterschied zu den umliegenden Objekten, desto höher das Salienzsignal des Objektes und desto höher die Wahrscheinlichkeit, dass dieses Objekt selektiert wird. Wie zuvor erwähnt, sieht die TVA die Kategorisierungsprozesse als automatische Prozesse an, die nicht beeinflusst werden können. Im ersten Projekt wurde diese Annahme untersucht, indem potentielle Einflüsse auf den Kategorisierungsprozess von Objekten bzw. experimentellen Stimuli getestet wurden.

Aus den Daten zweier einfacher experimenteller Verfahren (Ganzbericht und Teilbericht), können die von der TVA (Bundesen, 1990) angenommenen Aufmerksamkeitskomponenten (Kapazität des visuellen Kurzzeitgedächtnisses (KZG), Verarbeitungsgeschwindigkeit, attentionale Gewichtung und die Effektivität der Selektion von relevanten Informationen) geschätzt werden. Wenn die Leistung, widergespiegelt in den vier Aufmerksamkeitskomponenten der TVA (Bundesen, 1990), beeinflusst werden kann, spräche dies gegen einen automatisch ablaufenden Kategorisierungsprozess. Found & Müller (1996) konnten Einflüsse auf die Reaktionszeiten der Versuchspersonen in visuellen Suchexperimenten[2] durch Wechsel oder Wiederholung der zielreizdefinierenden Dimension in aufeinanderfolgenden Durchgängen finden. Sie konnten schnellere Reaktionszeiten finden, wenn die Dimension der Zielreize in aufeinanderfolgenden Durchgängen wiederholt wurde und langsamere Reaktionszeiten, wenn die Dimension sich änderte. In einer Reihe von Experimenten wurde im ersten Projekt untersucht, ob die bottom-up (d.h. stimulusbasierten) Wechsel oder Wiederholungen von zielreizdefinierenden Merkmalen (z.B.: rot, klein) oder Dimensionen (z.B.: Farbe, Grösse) auch die Leistung, widergespiegelt in den vier Komponenten der TVA, beeinflusst. Nach Found und Müller (1996) wäre demnach zu erwarten, dass sich die Komponenten der TVA (Bundesen, 1990) verschlechtern, wenn sich das Merkmal oder die Dimension in aufeinanderfolgenden Durchgängen verändert, sich jedoch verbessern, wenn das Merkmal oder die Dimension des Zielreizes wiederholt wird. Wenn die Komponenten durch bottom-up Informationen verändert werden können, stellt sich die Frage, ob das auch bei wissensbasierten (top-down) Informationen der Fall ist. Der Einfluss von top-down Informationen auf die Komponenten der TVA (Bundesen, 1990) wurde durch das Einsetzen von validen, invaliden oder neutralen Hinweisreizen getestet. Es konnten sowohl merkmals- als auch dimensions-basierte Effekte gefunden werden. Demzufolge wirkten sich bottom-up Wechsel oder Wiederholungen auf die Komponenten der TVA (vor allem auf das visuelle KZG und die Verarbeitungsgeschwindigkeit) und damit den Kategorisierungsprozess aus. Auch der Hinweisreiz (top-down information) beeinflusste die Komponenten der TVA (im Speziellen das visuelle KZG). Sowohl bottom-up Veränderungen bzw. Wiederholungen, als auch top-down Informationen konnten demnach die Leistung verändern, was gegen die in der TVA (Bundesen, 1990) angenommene

---

[2] Bei visuellen Suchexperimenten müssen die Teilnehmer so schnell und so genau wie möglich angeben, ob sich ein vorher definierter Zielreiz unter den präsentierten Reizen befindet oder nicht.

automatische Verarbeitung (bzw. Kategorisierung) spricht. Obwohl das visuelle KZG als relativ stabile Komponente angesehen wird, zeigten sich doch mehrfach Veränderungen in seiner Kapazität. Vermutlich ist das visuelle KZG eher als eine Komponente anzusehen, die durch unterschiedliche Anforderungen und Situationen verändert werden kann.

Des Weiteren wurden in diesem Projekt Fragestellungen hinsichtlich spezifischer Eigenschaften der TVA untersucht. Die Auswirkungen von Wiederholungen desselben Stimulus in einem Durchgang, der räumlichen Anordnung der Stimuli und von Wiederholungen exakt gleicher Durchgänge auf die Leistungen der Versuchspersonen (reflektiert in den Aufmerksamkeitskomponenten der TVA) wurden getestet. Tatsächlich wirkten sich auch diese Veränderungen auf die Komponenten der TVA aus. (Detaillierte Beschreibungen der Experimente finden sich in Kapitel 5.1.)

Im zweiten Projekt geht es um Personen mit Störungen in ihren Wahrnehmungsfunktionen. Personen mit dem Asperger Syndrom (milde Form von Autismus) wurden wegen ihrer überdurchschnittlichen Wahrnehmungsfähigkeiten untersucht. Einige Studien konnten überdurchschnittliche Leistungen von Personen mit frühkindlichem Autismus in visuellen Suchexperimenten feststellen (z.B.: Plaisted, O'Riordan und Baron-Cohen, 1998b). Das Ziel des Projektes war es zu untersuchen, ob Personen mit dem Asperger Syndrom ein ähnliches Ergebnismuster in der visuellen Suche zeigen wie die autistischen Teilnehmer oder, alternativ, wie die gesunde Kontrollgruppe. Die Aspergergruppe zeigte ein Ergebnismuster, das dem der Kontrollgruppe sehr ähnlich war, jedoch suchten sie deutlich schneller und effektiver. Die Ergebnisse führten zur Frage, ob der Verarbeitungsunterschied eher auf einer frühen (vor-selektiven) Stufe (Extraktion von Merkmalen, Berechnung der Salienzsignale) oder auf einer späten (post-selektiven) Stufe des visuellen Verarbeitungsprozesses (Objekterkennung oder Objektidentifikation) zu finden ist. Es zeigte sich, dass die besseren Leistungen der Asperger Gruppe nicht durch Unterschiede in den frühen Prozessen der Merkmalsextraktion, sondern eher auf späteren Stufen der Objekterkennung oder –identifikation entstehen. Die letzten Experimente testeten, ob bestimmte Eigenschaften der Stimuli (Buchstaben), die in den Experimenten verwendet wurden, verantwortlich für den Unterschied sein könnten. Die Ergebnisse lassen vermuten, dass die unterschiedlichen Leistungen in den visuellen Suchexperimenten in der Asperger Gruppe, verglichen mit der gesunden Kontrollgruppe, wahrscheinlich oder zumindest teilweise durch die verwendeten, hoch überlernten, Buchstaben verursacht wurden. (Detaillierte Beschreibungen der Experimente finden sich in Kapitel 5.2.)

Da die Kategorisierung von Objekten ein grundlegender und wichtiger Prozess ist, lag im dritten Projekt der Fokus auf der Entwicklungsperspektive des Kategorisierungsprozesses. Kinder dreier verschiedener Altersgruppen (1., 2. und 3. Klässler) wurden mit TVA- (Bundesen, 1990) basierten Testverfahren untersucht. Im Vergleich zur 1. Klasse stieg die Kapazität des visuellen KZG deutlich in der 3. Klasse an. Ausserdem wurden die Kinder mit zunehmendem Alter beträchtlich schneller und konnten die wichtigen Informationen bemerkenswert besser selektieren. Insgesamt stimmen die Ergebnisse mit einer erweiterten Form der globalen Trendhypothese (Hale, 1990; Kail, 1986) überein, die davon ausgeht, dass sich alle Informationsverarbeitungsprozesse gleichzeitig weiterentwickeln. (Detaillierte Beschreibungen der Experimente finden sich in Kapitel 5.3.)

Alle drei Projekte konnten insgesamt deutlich demonstrieren, wie wichtig der Kategorisierungsprozess für die Selektion ist. Die Ergebnisse zeigten, wie man den Kategorisierungsprozess beeinflussen kann, dass Kinder nicht von Anfang an volle Kategorisierungsfähigkeiten haben, sondern sie sich erst im Laufe der Kindheit entwickeln und welche spezifischen Vorteile Personen mit dem Asperger Syndrom haben.

3. Introduction

A recent paper by Kuhn and Land (2006) reported about how magicians fool our brain. The cognitive psychologist Kuhn threw a ball in the air a few times and caught the ball every time. The final throwing was only simulated but the psychologist moved his hands like the previous times and his head and eyes traced the imaginary trajectory. However, he had actually hidden the ball in his hand and not thrown it. Interestingly, almost all members of the audience could swear the ball was thrown into nothingness. With eye-tracking methods - recording the eye movements of the observers - researchers could show that the eyes were not looking at the location where the ball was disappearing. Crucial for fooling the observers are the head and eye movements of the psychologist - attracting the attention of all observers to the expected location of the ball. Magicians are thus fooling our higher cognitive systems, not our eyes. Attention is working like a spotlight, illuminating a small area of a visual scene. Only details in the area we are concentrating on are identifiable, the rest is completed by memory, predictions, expectations and suggestions. Coming back to the ball example mentioned before, observers focused their attention on the eye and head movements of the magician and their cognitive system completed the illusion by the expectation of the ball trajectory. Magicians are fooling us on locations where we are not attending at. It is very important for our normal life to select the relevant information and ignore all irrelevant information – in the case of magicians (or the psychologist's ball trick) we fail in doing so. We select the irrelevant information of the eye and head movements of the psychologist and ignore the relevant information of not throwing the ball again into the air.

However, attention plays a major role not only in tricks of magicians, but obviously also in our normal lives. If someone is driving a car there are the car sounds; people walking on the pavement; other cars are driving beside, in front of, or behind; the driver is talking with his passengers; the indicators of the speed and tank are moving; and many more stimuli are reaching the driver's sensory systems. However, if the siren of an ambulance is sounding, children are playing on the street, traffic lights turn red, or a car is stopping in front of the driver, he/she has to react immediately in the correct way to prevent something bad from happening. In such cases the driver has to select the relevant information for his current behaviour and to ignore the bunch of irrelevant information all around him. Due to the fact that our processing resources are limited to a certain amount of information and are not able to process all information around us, it is very important that only the relevant information is processed to control our thinking and behaviour. The basic cognitive ability underlying selection is referred to as ‘attention’. Selection can be determined by internal goals of the subject or external stimuli (e.g., siren of the ambulance). According to the example mentioned above, it becomes obvious that traffic is only functioning so well because most of us are able to select the relevant information. These intact attentional functions are thus essential for appropriate life and learning of people. Attention is involved in most cognitive processes such as perception, memory, planning, behaving, orienting and problem solving (Zimmermann & Fimm, 1993). Attention has many more functions than only that of selection, e.g., the orienting or the focusing function, however, my research focuses on the aspect of selection.

Research in the field of attention has a far-reaching tradition going back to the beginnings of the 19th century. The starting point of the modern attentional research lies in the 1950s. Mainly, during this time research focused on the selective function of attention. The intensive and long standing tradition of research in the field of attention has been resulting in numerous accounts, theories and research methods for investigating different aspects of attention.

Of particular interest in the search for a deeper understanding of the selective part of visual attention are, first of all, the *fundamentals* of attention operationalized in different ideas, how attention is exactly working in different settings. Moreover, the investigation of people with *enhanced* perceptual and attentional abilities is of great importance. The last aspect of interest is the investigation of the *developmental* perspective of visual attention. All these fields are contributing to a better understanding of the selection mechanisms.

Since categorisation of objects is a main issue in each theoretical account mentioned later, I have been investigating the above mentioned three main fields of interest in the research of attentional selection with a specific focus on categorical processes: more specifically the first project concerns the foundations of visual selective attention by combining two important theories of visual selective attention and answering the question of whether the categorisation process is influenceable by simple manipulations; the second project deals with people having enhanced perceptual abilities, namely people with Asperger’s syndrome; and the third project focuses on the developmental perspective of selective attention in children. Before I begin the discussion of my different research projects, I need to first introduce the theoretical and empirical development in selective visual attention research and then deduce the main theoretical accounts contributing to the issues under investigation.

4. Theoretical Background

There are many different theories concerning the field of selective attention and one historical starting point is the work and the ideas of Colin Cherry in 1953. He observed an interesting phenomenon at a party: although quite a few conversations are conducted simultaneously we are able to ignore other conversations and focus our attention on one specific conversation. Later on this is referred to as the 'cocktail party phenomenon'. Therefore, Cherry became interested in auditory selective attention and investigated this real-life phenomenon, namely the ignored speech, in more detail by simplifying it with his newly-developed paradigm of dichotic listening. The participants were confronted with a different message to each ear via a headset. Their selection task was to repeat the message of one ear aloud and to ignore the message in the other ear. Results showed that although participants had no memory of the message in the ignored ear concerning semantics (e.g., changes from meaningless to meaningful information were ignored) they perceived a disturbing tone and a change of the speaker (e.g., from female to male voice). Cherry (1953) concluded that unattended speech is processed only on the physiological level, but not on a semantic level. It seems that the unattended information is blocked off very early before the semantic information is available. Further evidence for a filter or a 'bottleneck' in the processing system came from Welford's experiments in 1952, which revealed that reaction times (RTs) to the second of two presented stimuli are dependent upon the time between the two stimuli. If two stimuli are presented very close to each other on the time axis, RTs increased for the stimulus presented second (psychological refractory period). It seems that two stimuli cannot be processed simultaneously – arguing for a processing 'bottleneck'.

To further extend the findings of Cherry (1953) that unattended speech is processed not on a semantic level, Donald Broadbent (1958) posed the question of how it works if semantic information needs to be reported. In a variation of the dichotic listening method he presented pairs of digits simultaneously to both ears. Participants were asked to recall the digits by ear (condition 1) or in order of their appearance (condition 2). Results showed that 65% of the digits could be recalled correctly in condition 1 compared to 20% correctly reported digits in condition 2. Interestingly the subjects preferred to recall the digits grouped by the presentation location (ear) not by the presented pairs. Thus, the selection of information again seems to be based on physical stimulus properties (e.g., location). Furthermore Broadbent (1958) suggested that if listeners are required to extract meaning from the source information, they need to switch between them. Switching is slow and effortful and thus one tries to switch only as few times as possible arguing for the existence of a buffer in which information is stored before being reported.

Out of his results with the dichotic listening paradigm Broadbent (1958) developed his filter-model for attentional selection. According to this model two simultaneously presented information get access to a sensory buffer in a parallel, temporally simultaneous fashion. On the basis of physical properties (e.g., location) only one information may pass, i.e., is selected or filtered out. The other is blocked off, however, briefly available for potential later access. Since Broadbent assumes a single, central, serial, and capacity-limited processor the filter is necessary for protecting the capacity-limited processing system from overload. The information that passes the filter in an 'all-or-none' fashion can be analysed by higher-level units, become conscious, and control the response of a subject. Since –in Broadbent's view - selection takes place on the basis of physical properties the locus of selection, the bottleneck, is situated at an *early* processing stage. However, results of several studies argued against an early selection. Referring to the cocktail party phenomenon e.g., Moray (1959) noted that one's own name can be noticed although the speech is unattended. He argues for a break-through of unattended meaning through the filter. Furthermore, Anne Treisman (1960, 1964) found semantic processing of unattended information. These findings argue against an 'all-or-none' filter proposed by Broadbent (1958).

Since the results argue against the all-or-nothing filter theory of Broadbent (1958) Treisman (1960) developed her 'attenuation'-theory, in which she assumed that unattended information is transmitted and processed, but in an attenuated 'more-or-less' fashion. Again the filter is assumed to be relatively early in the course of processing, however, more flexible than Broadbent (1958) suggested.

Summing up, according to Broadbent (1958) and Treisman (1964) selection takes place at the early component of the information processing system, at which the information input strikes the system.

Contrary to the view of early selection, Deutsch and Deutsch (1963) assumed a selection of relevant information on *late* processing stages. All incoming information is analysed exhaustively. The perceptual encoding at the beginning of visual selective processing takes place in a parallel fashion and all input information is weighted according to their relevance for the current task or goal determinating whether a stimulus is processed by higher cognitive mechanisms (processing semantics e.g.) or not. Only the important information gets conscious and can elicit a reaction. According to Deutsch & Deutsch (1963) all sensory signals reach automatically the same and the highest processing level independently of the attentional focus on them or not. Thus, selection occurs not until complete processing of all information and according to their semantic content - not physical properties.

The question of early or late selection of relevant information is not yet clarified. Posner and Snyder (1975) tried to resolve the debate by supposing a flexible filter according to the particular purposes. Johnston and Heinz (1978) assumed that in order to minimize capacity demands selection is localised at the earliest possible processing stage determined by the respective task.

A more recent theory combines the assumptions of early selection theories that perception is a limited process with the assumption of late selection theories that perception is an automatic (not under complete voluntary control) process in which available capacity remains (e.g., Lavie, 1995). More specifically, perceptual processing is automatic until it runs out of capacity. The voluntary processing assesses priorities determining if attention is allocated to relevant or irrelevant information. Certainly relevant information should get higher priorities than irrelevant information. Any spare capacity not taken by high-priority information is automatically allocated to irrelevant information. Selection is then the logical consequence of allocating attention. Summing up, only processes with high load will be selective. Clear physical distinction (very early processing stage) between relevant or irrelevant information determines only if selection is appropriate or not.

4.1. Location-, Feature-, and Object-based Selection

Beside the historical development of the different theories and according to more recent research we can subdivide the theories into three principles underlying selective processing: location-, feature-, and object-based selection.

For location-based selection the most famous representative is Michael Posner (1980) with his newly developed cueing paradigm. After a central fixation cross a symbolic (central) cue - an arrow - points at a location left or right of the fixation cross where a target item is likely to appear. The cue should direct the spotlight of visual attention to this particular location. The time to detect the target item, presented in one of the two possible locations, is measured. Three different cue conditions exist: In the neutral condition the target equally likely appears at either of the two locations, i.e., the cue gives no information of the upcoming target item. If the cue is valid, the target item appears at the location indicated by the cue and if cueing is invalid, then the target appears at the location opposite to the one indicated by the cue. These different conditions result – compared to the neutral condition - in reaction time (RT) benefits (faster RTs) if the cue validly indicates the location of the target and in RT costs (slower RTs) if invalidly. Different kinds of cues can be presented. If a peripheral, direct 'stimulus' cue - like a flash at the possible target location - directing the attentional spotlight is presented, this shifting effect is referred to as an exogenous cueing effect, namely an outside generation of attentional shifts. All processes that are engaged are based on this external stimulation (e.g., a flash) and can be seen as low-level 'reflexes' drawing attention automatically. A central, symbolic cue (like an arrow) that directs attention generates the cueing effect inside the subject, referred to as the endogenous cueing effect. Processes engaged here are based on ones internal goals and controlled by voluntary high-level processes sending attention to the requested location. Findings concerning the two different cueing effects revealed that the exogenous cue draws attention automatically and overrides the endogenous cue effect (Müller & Rabbitt, 1989). Stronger costs (invalid cue condition) and benefits (valid cue condition) can be found in the RTs. Posner's (1980) findings of attention directed to a specific location argue for a location-based selection process.

As mentioned before not only location-based selection is proposed. The idea of feature-based selection first arose by Neisser in 1964. Attention seems not to be directed to a specific location but to specific features of the objects in a visual scene. Neisser's participants had to search for the presence or absence of a previously indicated target letter in lists consisting of lines with four to six letters. 25 to 40 letter rows were presented simultaneously. Results showed that it is easier to find a present target letter than to indicate the absence of the letter. Searching for the presence of a target letter does not involve the identification of the surrounding letters (distractor letters). Therefore several rows can be searched simultaneously in a parallel manner. If the letter is absent, each list must be searched in turn in a serial fashion. In a slightly different task Neisser (1964; Neisser & Beller, 1965) presented target and distractor letters categorised by features (lines [straight vs. bent], alignment of the lines [vertical, horizontal, diagnonal], intersections). The relations between the features of the targets and distractors affected the search RTs. If targets and distractors shared several features, RTs became slower relative to when no or less features were shared. They interpreted that several letters are processed simultaneously - otherwise no interference of features should be observed - and secondly, since features affected search RTs, that letter processing is based on different features and cannot be seen as processing of unified wholes.

Another theory claiming that selection is feature-based is Allport's (1971, 1980) 'analyser' theory. Allport briefly presented coloured digits inside of coloured shapes. Participants had to recall one or more features. Results revealed that reporting a form feature is not affected by whether a colour feature was also reported. However, the report of a form feature was negatively affected by the report of another form feature (Xu, 2002). A follow-up study by Wing and Allport (1972) could show that the report of spatial frequency and orientation did not affect either report; however, the report of two orientation features did interfere with each report. The authors interpreted their results with a system of analysers for the perceptual analysis. Each analyser is dealing with a specific dimension (e.g., colour, orientation, size). Therefore two features from the same dimension have to share the same analyser and can only be encoded with interference. Whereas two features from different dimensions can be analysed without interference since they are processed by different analysers (Xu, 2002; see also Treisman, 1969). According to this theory selection is based on features and their belonging to the same or to a different dimension. The idea of selection dependent on different dimensions will be further discussed in the dimension-based selection idea of the account of Müller, Heller and Ziegler (1995) and Found and Müller (1996). However, first I have to mention further feature-based accounts emerging out of one main experimental paradigm.

The paradigm used as basis for the following theories of feature-based selective attention is referred to as 'visual search'. In visual search experiments, participants have to indicate as fast as possible if a predefined target stimulus surrounded by a certain number of distractor stimuli is present or absent. The number of stimuli in a search display is termed display size. Apart from the accuracy analysis, the reaction times (RTs) of the observers are analysed as the main variable of interest. RTs reveal the elapsed time between the presentation of a stimulus and the subsequent behavioural response of the observer, thus indicating how quickly somebody can respond to a particular stimulus. The overall RT includes several cognitive and motor components like perception, analysis of the display, memory retrieval, planning of a response and response execution. RTs are displayed as a function of display size (search RT function), namely $RT = a + b\ n$, with a being the y-axis intercept of the search function indicating the time necessary for the completion of component processes not directly related to target-search (e.g., analysis of the display, decision about response, connection with a response and response execution), b being the slope of the function and thus the search rate measured in time per display item indicating how efficient the search is done and n the number of display items.

There are two different main search types: ‘feature search’ and ‘conjunction search’. In a feature search task, the target is unique with regard to one feature. The time it takes to detect the target in this type of search is independent of the number of distractors present in the display. All display items can be processed in an efficient way and in parallel (search rates [b] below 10 milliseconds [ms] per display item). In a conjunction search task, the target is unique in terms of a unique combination of features. With increasing display size the time it takes to detect the target in this search type increases linearly. If the target is absent, all display items (n) have to be searched exhaustively to assure that there is definitely no target. In case a target is present on average half of the objects ($n/2$) have to be scanned to find the target. Finding the target self-terminates the search process. Search rates (b) above 10 ms per item and the resulting 2:1 target-absent to target-present search rate ratio (target-absent RT function increases twice as steep as the target-present function with increasing display size) indicate a serial and self-terminating search of all display items (Treisman & Gelade, 1980; Davis & Driver, 1998).

Treisman and Gelade (1980), Treisman (1988) and Treisman and Sato (1990) again consider selection to be based on features of objects. With feature and conjunction search experiments Treisman and Gelade (1980), Treisman (1988), and Treisman and Sato (1990) tried to solve the specific problem of how separately coded object features are integrated to form coherent perceptual objects and developed as explanation the ‘Feature Integration Theory’ (FIT). According to FIT, in a first step several primary visual features in the search display are processed and represented in separate feature maps (e.g., red, green, vertical, horizontal). These feature maps are spatio-topic maps of dimension specific feature representations, namely dimension-based feature maps. Specific locations in the maps correspond to specific display locations of the stimuli. Resultant, corresponding locations in different maps can be related. Object features are registered in the feature maps pre-attentive (no attention necessary) and therefore the presence of a certain target-feature in the feature search can be checked in parallel and simultaneously for all objects. In a next step the activations in the separate feature maps are integrated in an overall map of locations. Now the binding problem occurs: how can the separately coded object features be combined to a coherent object? At this point, attention comes into play. The allocation of the focus of attention to one location of the overall map of locations binds together the features represented at the respective locations on the feature maps. “Thus focal attention provides the ‘glue’ which integrates the initially separable features into unitary objects.” (Treisman & Gelade, 1980, p 98) Since the focus of attention is allocated to the location of the master map of locations the allocation to one object is conceived location-based.

According to the FIT the bottleneck (capacity limitation) in processing lies in the serial working, attention demanding binding stage. Binding occurs only for one object at a given time. Therefore conjunction search is carried out in a serial fashion because for the conjunction of features each stimulus has to be taken into account separately. To sum up, concerning the two kinds of search reported above, feature search can be performed in a parallel fashion, pre-attentively, and therefore fast. The presence of a target can already be detected by means of activation in one feature map. Whereas conjunction search can be performed in a serial fashion, attentive (allocation of focal attention) and therefore slower than the feature search. The presence of a target can only be detected by combining several features and therefore attention is needed (Treisman & Gelade, 1980).

Empirical support for this theory comes from the phenomenon of illusory conjunctions (Treisman & Schmidt, 1982). Treisman and Schmidt presented displays consisting of multiple shapes with different colours flanked by two black digits. Participants were asked to first report the identity of the black digits and afterwards the coloured shapes. Results showed that the different colours and shapes were often bound together erroneously (e.g., presented was a blue circle and a red square and the participants reported a blue square and a red circle). The finding of wrong binding of features of briefly presented un-attended objects is consistent with the idea of the FIT that focused attention is necessary to correctly bind the different features of the preattentive stage together to whole objects. Note that the failure to remember the correct combinations of shape and colour does not necessarily imply that a right combination is not possible without attention. Indeed, recent research revealed different explanations to the phenomen of illusory conjunctions (Egeth & Lamy, 2003).

Numerous results of visual search experiments after the original formulation of the FIT showed that the simple dichotomy of parallel, pre-attentive and serial, attentive search is not sufficient for explaining. The slopes of the search functions varied from absolutely flat to very steep arguing more likely for a continuum. For this effect the similarity between targets and distractors as well as the similarity between the distractors is relevant. In the original version of the FIT (Treisman & Gelade, 1980) processing takes place exclusively bottom-up (stimulus-driven). Results of other search experiments argue for additional top-down (knowledge-based) influences on search performance. A number zero (‘0’) surrounded by letters pops out of the display, whereas a letter ‘O’ among other letters does not. A series of alternative accounts were proposed to explain these findings. The ‘Guided Search’ model of Jeremy Wolfe (e.g., Wolfe, Cave & Franzel, 1989; Cave & Wolfe, 1990; Wolfe, 1994) is one of the most important approaches to mention here.

Based on the results of feature and conjunction search tasks and inspired by the Feature Integration Theory (e.g., Treisman & Gelade, 1980), Wolfe and his colleagues developed the ‘Guided Search’ (GS) model (e.g., Wolfe, Cave & Franzel, 1989; Cave & Wolfe, 1990; Wolfe, 1994) as an alternative explanation for selection behaviour. Wolfe assumes that targets in visual search are detected by a multi-stage mechanism. These different processing stages have to succeed for selecting a target out of a number of distractors. In a first stage, all features of all display objects are extracted (e.g., red, green) and categorised in the different dimensions (e.g., colour, orientation). Each dimension is represented in one topographic map. The spatial arrangement of the display is sustained and the specific activation for each feature is coded. Wolfe (e.g., Wolfe, Cave & Franzel, 1989; Cave & Wolfe, 1990; Wolfe, 1994) introduced the idea of saliency (Crick, 1984) signals into visual selection; saliency representations are all generated in parallel for all features. Saliency signals are computed by contrasting values of visual features. Saliency activation includes areas that differ significantly from the surround, i.e. the higher the difference, the higher the saliency activation. In a further step the dimension-based saliency signals are summed up into overall saliency representations, controlling or *guiding* the deployment of the focus of attention. Areas with high saliency activation are locations with high informational content and should be sampled by selective attention with priority to make this info available for the higher order cognitive processes of object identification and recognition. Thus, Wolfe explains feature-based selection with the guidance of attention to the location with the highest activation (based on saliency signals). In Figure 1 and Figure 2 the functional architecture of the model for a feature search and a conjunction search task are depicted. Since in the feature search task the saliency activation is considerably higher at the target location compared to all other locations, the focus of attention is guided very fast to the highest activation in the overall map of activations. In the conjunction search task, there are many dimension-based saliency activations resulting in much activation on the overall map of activations with only small differences. Therefore, the attentional focus needs more time to find the target location explaining the slower RTs in conjunction search.

His model includes - contrary to Treisman’s FIT (Treisman & Gelade, 1980) - bottom-up mechanisms of attentional control as well as top-down mechanisms of attentional guidance (knowledge-based activation of pre-specified target features). Note, that top-down influences were neglected in the original version of the FIT (Treisman & Gelade, 1980). The model can account for illusory conjunctions by explaining the phenomenon with activations on the map without spatial assignment. However, the guided search model neglects for example the basic weightings within dimensions.

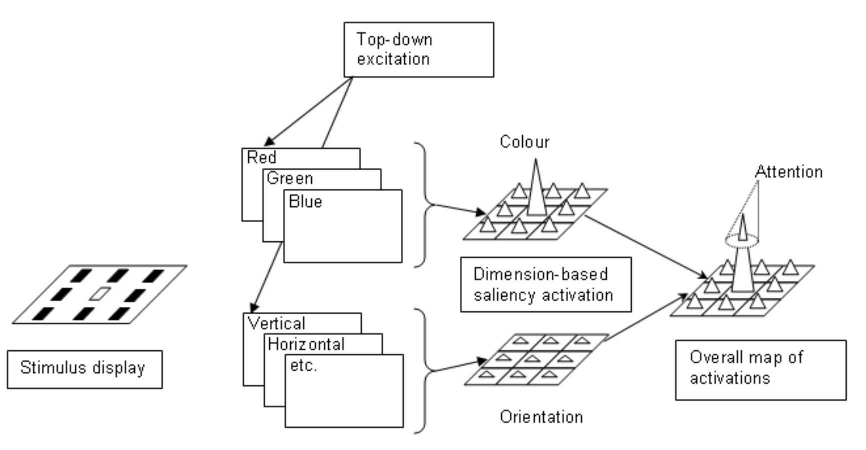


Figure 1. Functional architecture of the GS model for a feature search task.

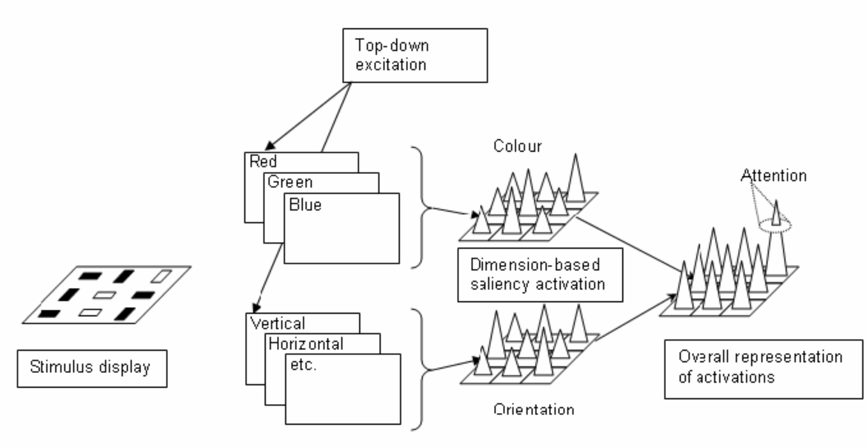


Figure 2. Functional architecture of the GS model for a conjunction search task.

Maljkovic and Nakayama's (1994) 'priming of pop-out' account again argues for feature-based effects. The participant's task was to indicate as fast as possible if the odd-coloured diamond was cut off on the right or on the left. They could find a great improvement in performance when the same stimulus was repeated compared to when the stimuli in successive trials changed. Maljkovic and Nakayama (1994) concluded that the repetition of the attention-driving feature (e.g., colour) could prime the pop-out arguing for a feature-based selection process.

Another saliency based model on the basis of the 'Guided Search' model and the results of Maljkovic and Nakayama (1994) and again trying to explain attentional selection, is the 'Dimension Weighting' account (DW) of Müller, Heller and Ziegler (1995; Found & Müller, 1996; Müller & O'Grady, 2000). In further developing the feature-based selection view they assume a dimension-based selection mechanism for visual search based on dimension-specific saliency signals. Dimensions are, for example, ‘colour’ with the features red, green and so on or ‘orientation’ with the features tilted to the left or to the right. In GS the idea of basic weightings within dimensions was neglected. The analysis of RT data in successive search trials revealed RT costs when the target defining dimension changed and RT benefits when the target defining dimension stayed the same across consecutive trials. Treisman (1988) found that if targets are variably defined either across or within a dimension there was an intercept cost for cross-dimension conditions compared to within-dimension conditions. Müller, Heller and Ziegler (1995) and Found and Müller (1996) concluded that a limited processing resource has to be shared between different dimensions. This requires shifting the limited processing resources between dimension-based processing modules. In the actual search trial the first processing step is to extract the features and translate them into feature maps. Saliency signals are computed in parallel for all dimensions and summed up onto dimension maps. The higher the difference on one location the higher the saliency signals. On the basis of the different dimensions, saliency signals are weighted and then going onto the master saliency map where activations for the different dimensions can be compared. The target-defining dimension should be weighted highest compared to all other dimensions (see Figure 3). Amplifying one dimension consequently reduces the weight of the other dimensions. This implies for successive trials that if the weights are increased for the previous relevant dimension, the activity in the master-map accumulates faster for that dimension arising in inter-trial facilitation which can be seen in faster RTs in the second trial of consecutive trials. Shifts of the limited processing resource from one dimension to another, when changes in the target defining dimension arise, result in inter-trial RT costs (slower RTs in the second trial of consecutive trials). Dimensional effects are assumed to be very early effects arising at the beginning of the visual processing progress and can be influenced by top-down information. The result of dimensional modulations is important because now processes that are assumed to be automatic seem to be dependent on limited resources and can be manipulated cognitively.

Intertrial transition effects were first investigated by Müller, Heller and Ziegler (1995) and Found and Müller (1996). The Feature Integration Theory (Treisman & Gelade, 1980) or the Guided Search model (Wolfe, 1994) assumed that the reaction on an actual trial is not influenced by its history, i.e. in which dimension or feature the target was defined in the trial before the actual trial. However, according to the results of Müller and his colleagues, performance in the actual trial is always dependent on the inter-trial history.

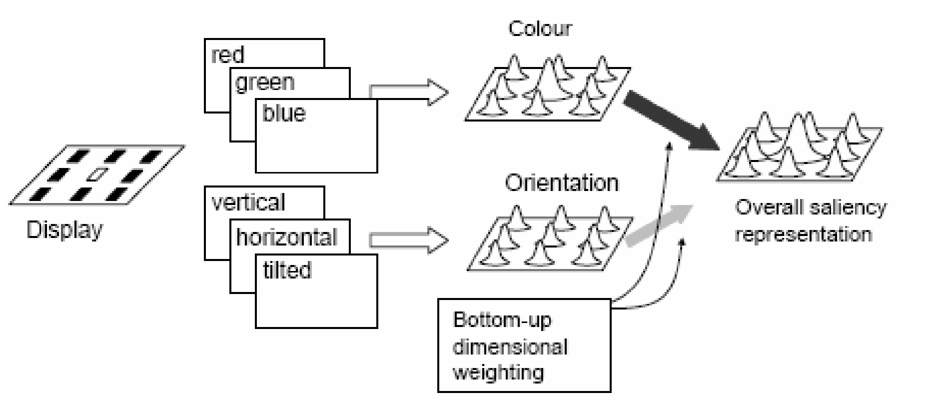


Figure 3. Functional architecture of the DW account for a feature search task.

One further alternative to the FIT (Treisman & Gelade, 1980) is the 'Attentional Engagement Theory' (AET) of Duncan and Humphreys (1989). Since this feature-based theory had direct influences to one very important theory for my dissertation, namely the Theory of Visual Attention (TVA; Bundesen, 1990) the theory will be discussed in the section 4.2 and 4.3.

Whereas Neisser (1964, 1965), Allport (1971, 1980), Treisman and colleagues (e.g., 1980, 1988, 1990), Wolfe and his colleagues (e.g., 1989, 1990, 1994), Maljkovic and Nakayama (1994) and Müller and his colleagues (1995, 1996, 2000) propose that selection is carried out feature- alternatively dimension-based, the position of John Duncan (1984) is indicative of an object-based selection process. Thus, attention is not directed to a specific location or to specific features or dimensions of objects but to the object itself. Separating between location- and object-based accounts is difficult because each object is on a certain location. One way is to present relevant and irrelevant objects on the same location. The items under investigation were superimposed objects. The objects consisted of a rectangle with a hole on the right or left side, combined with a dashed or dotted line tilted to the left or to the right. Participants had to judge the characteristics of either one of the objects (e.g., the structure of the line [dotted or dashed]) or both objects (e.g., location of hole in the rectangle and structure of line). Duncan measured the judgement accuracy depending on whether the judgment refers to one and the same object or to the two different objects, and found that accuracy was better when the judgments referred to one object compared to when they referred to both objects - although both objects were located on the same place. Attention seems to be focussed on certain objects not on certain locations. Therefore problems arise if attention has to be dispersed to two objects.

In a recent study, Müller and O'Grady (2000) adapted Duncan's (1984) object judgement task. Observers were required to make cross-dimensional dual colour-form judgements and within-dimension dual-colour or dual-form judgements to one or two overlapping, briefly-presented objects. They could demonstrate that judgment accuracy was reduced in a condition in which the features to be judged were defined across dimensions (hue, size) causing cross-domain costs, rather than within dimensions (hue, saturation). This dimension-based effect on judgment accuracy appeared additionally to an object-based effect.

These results were in accordance with the above-mentioned Dimension Weighting account (e.g., Müller, Heller & Ziegler, 1995) and Duncan's view of object-based attention (1984).

Further evidence concerning object-based selection comes from Steven P. Tipper (1985). Two objects, one drawn with a solid line and one with a dotted line, were presented one upon the other. The participants had to name the object drawn in solid line and to ignore the object in dotted line. If the ignored object and a new object were presented – again one upon the other – participants had more problems to name the previously ignored object than the new object. This effect is termed negative priming. Negative priming refers to a slowed response identification time to a target stimulus that has been previously ignored. Since objects were presented on the same location, this negative priming effect argues for object-based selection.

4.2. Development of Bundesen's (1990) Theory of Visual Attention (TVA)

One of the most influential recent object-based theories at a mathematical level is Claus Bundesen's (1990) 'Theory of Visual Attention' (TVA). The theory has become one important theory of choice in neuropsychology, whereas the FIT (Treisman & Gelade, 1980) or GS (e.g., Wolfe, Cave & Franzel, 1989; Cave & Wolfe, 1990; Wolfe, 1994) are very important theories in research of the fundamentals of attentional selection. Since one main focus of the present thesis lies on this theory, I want to extensively discuss the development of the theory and the influences of previous theories and ideas.

George Sperling's (1960, 1963, 1967) investigations and interpretations concerning the visual short-term memory (vSTM) influenced the development of Bundesen's 'Theory of Visual Attention' (TVA; 1990). Sperling investigated how selection from displays with several elements takes place. Sperling briefly presented displays with a three by four matrix of letters or digits. The observers' task was to report as many letters of the entire array as they could remember (the task is later referred to as 'whole report'). The results showed that the number of correctly reported items was close to the number of items in a display with four or less than four items and averaged between four or five in displays with five or more items. If they presented a mask (terminating the after-image of the presented stimuli on retina, later called iconic memory) after the presentation of the stimuli, they observed that if presentation times were increased from zero up to 50/100ms, the number of correctly reported items increased from zero to about four. If there was a further increase in presentation times, the rate of increase in correctly reported items was much smaller. Sperling concluded that the immediate memory span was, on average, 4.5 correctly reported items (regardless of display size or presentation times). This result led to the assumption of a capacity-limited visual short-term store. Besides, the 'whole report' performance seems to be stable and limited.

In a slightly different task – similar to the whole report procedure - Sperling again briefly presented displays with a three by four matrix of letters and digits. The presentation was followed by one of three cue-tones (randomly), differing in frequency and each representing one line of the matrix to be recalled. The observers could report 75-90% of items from any given, randomly-cued line (the task is later referred to as 'partial report'). This result was not expected as the number of letters reported corresponds to much more information than indicated by the whole report results. Consequently, Sperling concluded that much more information is available than it was supposed by the whole report results. This result is known as 'partial report superiority' (75% immediately available in contrast to 33% indicated by whole report).

In a further experiment, he varied the interval between stimulus offset and the auditory cue. The partial report superiority diminished with increasing cue interval and at one second the partial report performance equals the whole report performance. The same effect could be observed with a visual cue. The results provide evidence for a rapidly decaying sensory trace (or iconic memory) lasting less than one second. Furthermore, strategy shifts with increasing intervals could take place (e.g. anticipation of where the cue could appear).

Overall, out of his results of the partial and whole report tasks, Sperling assumed that because the sensation of a physical stimulus outlasts its physical duration, there exists a sensory store, also referred to, in the visual domain, as the iconic memory. Observers are able to recall a stimulus which is not physically displayed anymore. The iconic memory is very sensitive to interference by subsequent non informational stimuli, e.g. a mask, and therefore can be easily disturbed. The information stored in iconic memory is of pre-categorical nature (units of visual image are equivalent to physical stimulus). Most important for the following ideas is the concept of a limited capacity visual short-term memory store. Independently of the presentation times and the number of items, on average only 4.5 items can be reported.

The findings of Sperling (1960, 1963, 1967) and of the previous reported authors inspired the development of Bundesen's Theory of Visual Attention (TVA, 1990). Bundesen's aim was to develop a theory concerning a *general mechanism* for attentional selection (Bundesen & Habekost, 2008). Bundesen proposed that attentional selection is influenced by an intelligent agent combined with a powerful selection mechanism (Bundesen & Habekost, 2008). Since a global theory of visual attention does not come in one go I want to extensively describe the different steps of the development.

At the beginning, Bundesen and his colleagues (Bundesen, Pedersen & Larsen, 1984; Bundesen, Shibuya & Larsen, 1985) discussed a choice model for describing the partial report behaviour. Choice models are non-processing models and thus are not making statements about the temporal course of information processing. Since non-process models are not enough for describing visual selective behaviour, race models defining the temporal course of processing have to be discussed afterwards. Race models can be mathematically derived from choice models. The theory of visual attention (TVA) can be seen as a combination of choice models for recognition with the race model framework. TVA is not only a processing model but also a computational model, in which computations are specified by which selection is supposed to be done (Bundesen & Habekost, 2008).

The choice model for the first forerunner of TVA incorporates the concept of a limited-capacity short-term store (Sperling, 1960, 1963, 1967) and the choice axiom of Luce (1959).

Luce's choice axiom - also referred to as the ratio rule - claims that the probability of selecting one item out of many items is not affected by the presence or absence of other items. Therefore selection is independent of all other irrelevant alternatives. Mathematically, the probability (*P*) of selecting the next item *i* (not yet selected) from a finite choice set (*S*) of *j* items is defined by the weight assigned to item *i* (w_i) divided by the sum of all weights of the irrelevant - not yet selected - alternatives (w_j) in the choice set (*S*).

$$P_S(i) = \frac{w_i}{\sum_{j \in S} w_j} \tag{1}$$

Weights (*w)* correspond to measures of typically salient properties of a particular item.

In a specialisation of the choice axiom each weight value (*w*) is a product of two new factors. One, the parameter $\eta(x,i)$, is a measure of similarity between stimulus *x* and all stimuli belonging to category *i*. The other factor is the bias of choosing the target category *i* (β_i). The model is not a pure choice model anymore but a *biased* choice model (Luce, 1963).

$$w_x(i) = \eta(x,i)\beta_i \tag{2}$$

Inserting equation 2 into equation 1, the probability (*P*) of selecting the target category *i* for stimulus *x* increases with the product of the measure for similarity ($\eta(x,i)$) between *x* and stimuli belonging to category *i* and the bias for choosing the target category (β_i) (equation 3). The probability decreases with increasing degree of match between *x* and any alternative category *j* and with increasing bias for an alternative category (Bundesen & Habekost, 2008).

$$P(i) = \frac{\eta(x,i)\beta_i}{\sum_{j \in R} \eta(x,j)\beta_j} \tag{3}$$

The choice models by Bundesen, Pedersen & Larsen (1984) and Bundesen, Shibuya & Larsen (1985) are based on the biased choice model by Luce (1963) and try to account for performance in multi-element displays with targets accompanied by several distractors in which observers have to report as many targets as possible while ignoring all distractors (Bundesen & Habekost, 2008). In both whole and partial report all correct answers reflect the items that entered, with probability *Θ* (at approximately 100%), the limited capacity vSTM. As previously mentioned, the capacity is limited to on average 4.5 items (Sperling, 1960). Entering the vSTM is conducted by sampling without replacement and stops in case the vSTM is filled up with approximately 4 to 5 items. Once an item is selected it stops affecting the selection process of other items. The selection of 4 or 5 particular items also referred to as the total number of items entering the vSTM (*K*), is performed according to Luce's choice axiom (see equation 1).

Bundesen, Pedersen & Larsen (1984) developed a model with three parameters, on the basis of Luce's ratio rule. First they took the total number of items entering the vSTM (*K*) mentioned before. They assumed that the probability *Θ* that a target enters the vSTM and is reported is a constant at a value of 1, meaning that all targets that entered the short-term store are perfectly sustained and reported. The mean number of targets reported correctly is closely proportional to the product of *K* and *Θ* (also referred to as *K')*.

Since all targets are assigned equal weights (*w*) and all distractors are assigned equal *w*s among themselves, the weight of a target is assumed to be at 1 and the weight of distractors at *α.* The parameter *α* indicates the efficiency of selecting pre-dominantly targets and ignoring distractors - also referred to as *selection efficiency*. If *α* is close to zero, selection is approximately perfect, if *α* is close to one, equal numbers of targets and distractors are selected and thus sampling is non-selective and if *α* is bigger than one, more distractors than targets are selected. Parameter *α* is assumed to be independent of display size, i.e. independent of how many targets or distractors are present in a display. In a display, there are not only targets and distractors but also extraneous noise elements present. Therefore the model has to account for the small probability that one of those noise elements is selected by adding parameter *ε*, which is the total weight of all not yet selected extraneous noise elements and becomes a constant with increasing elements that get encoded into vSTM (Bundesen, Pedersen & Larsen, 1984). In sum, the three-parameter version consists of parameter *K'* (product of *K* and *Θ*, with *Θ* = 1, given *α* and *ε* are kept constant), the selection efficiency *α* and the total weight of extraneous noise elements *ε*.

Bundesen, Pedersen and Larsen (1984) tested their three parameter model with several kinds of partial reports (based on colour, shape etc.) and – averaging across conditions - the model accounted for 99% of variance with the number of targets and distractors. They obtained good fits to the mean number of correctly reported items as a function of targets (*T*) and distracters (*D*). Some notes according to the three parameters have to be made: Estimates for *K* showed little variations with the chosen selection criterion and thus argued for a general storage capacity limit, estimates for *ε* were rather small arguing for only very little effects of extraneous noise elements on performance and estimates for *α* varied widely across conditions accounting for changes in performance with changes in selection criteria (Bundesen, Pedersen & Larsen, 1984; Bundesen & Habekost, 2008).

In 1985, Bundesen, Shibuya and Larsen extended the three-parameter choice model for partial report to a model with four distinct parameters: the total number of items entering vSTM (also referred to as the capacity of vSTM (*K*)), the probability that a target entered the vSTM and is reported (*Θ*)*,* the weight of a distractor (*α*)*,* and the total weight of extraneous noise elements (*ε*). All of the assumptions made for *K*, *α,* and *ε* in the three-parameter model have remained unchanged. Therefore again *α* is assumed to be the same regardless of the number of targets or distractors present in the display. The only remarkable difference lies in the assumptions concerning the probability *Θ* that a target enters the vSTM and gets reported. The probability is not supposed to be a constant with the value of 1 but rather a free parameter. The reduction to parameter *K'* as the product of *K* and *Θ* is not kept any longer in the four parameter choice model of Bundesen, Shibuya and Larsen (1985). If *Θ* is a free parameter, no reliable separate estimates for *K* and *Θ* can be derived from patterns of mean scores like in Bundesen, Pedersen & Larsen (1984).

The mode of functioning of the four parameter model is the following: A subject tries to select from short presented displays as many targets (*T*) as possible while ignoring distractors (*D*). Regardless of *T* or *D,* four items are transferred to short-term memory store. The following example shows the probability (*P*) of the first selected item being a distractor, second item a target, third extraneous noise and the fourth again a target equals

$$P = \frac{\alpha D}{(T + \alpha D + \varepsilon)} \cdot \frac{T}{[T + \alpha(D - 1) + \varepsilon]} \cdot \frac{\varepsilon}{[(T - 1) + \alpha(D - 1) + \varepsilon]} \cdot \frac{(T - 1)}{[(T - 1) + \alpha(D - 1) + \varepsilon]} \tag{4}$$

If two targets enter the store, the conditional probability distribution for the number of correctly reported targets is equivalent to the binomial distribution for two Bernoulli trials with probability Θ for success.[3]

The four parameter version revealed excellent fits by fitting the model to data. Parameter ε was kept constant near zero and the estimates for the remaining parameters ($K \approx 3.5$, α varied from .05 up to .40, and $\Theta = .92$) were plausible (Bundesen, Shibuya & Larsen, 1985).

Since all choice models are non-processing models and provide only information according to the selection outcome, it is necessary to introduce processing models, namely the prominent type of the race models, which can account for the temporal course of visual selection (Bundesen, 1987). According to these models, the selection is achieved by a race between all objects present in the visual field for getting processed since the first elements reaching the state of being processed are the ones that become conscious and can control behaviour. All elements start the race at the same moment in time ($t = 0$) (Bundesen, 1987). Some main characteristics of race models have to be discussed: First the assumption that processing times for all individual elements present in the visual field are independent. This assumption implies parallel processing of all elements without interference. Central for a selection race is additionally that different amounts of processing capacity allocated to an element influence the processing rate of this element, not the type of processing. Processing capacity is often assumed to be limited or even fixed - summing up to a constant. Theoretically possible is also an unlimited processing capacity. In this case each individual element is not affected by adding other elements (Bundesen, 1987; Bundesen & Habekost, 2008). The distribution of processing capacity across all elements can be best explained by attentional weights (Rumelhart, 1970). For each element i and j in the display attentional weights w_i and w_j are assigned. The ratio between the amount of capacity allocated to element i and j equals the ratio between the weights w_i and w_j of both elements. Attentional weights are assumed to be constant across choice sets. Since the race is assumed to be a stochastic process controlled by statistical probabilities the last important characteristic of race models is their probability distribution. The race for attentional selection seems to follow a memory-less exponential distribution. Under the condition that the element is not

---

[3] There are two possible results of a Bernoulli trial: success or failure to reported items correctly.

yet selected, the probability of this element to be selected at any given time is independent of the time the element has undergone in processing (Bundesen & Habekost, 2008). Thus the previous selection process is not remembered and at any given time there is the same probability of being selected. Same predictions can be derived by a race model with the above mentioned characteristics as in the choice model (Bundesen & Habekost, 2008).

Both the three-parameter version proposed by Bundesen, Pedersen and Larsen (1984) and the four-parameter version proposed by Bundesen, Shibuya and Larsen (1985) fitted very well to observed data and supported the idea of independence of parameter α from display size. Bundesen (1987) tested again the assumption of independence and modified the model by incorporating a new parameter reflecting any dependency of α upon number of items in display: $\alpha = a^{\left(N^b\right)}$ with N as the total number of not yet selected items and $a \geq 0$. He specified different cases: for N equal to 1, α is equal to a, regardless of b, for b equal to 0 this model is equivalent to the old four-parameter model with α constant at a regardless of N. For $a < 1$ and $b < 0$ the parameter α is an increasing function of N with tendency to 1, i.e. no selectivity takes place, and N tends to infinity. For the last case if $a < 1$ and $b > 0$, the function of α is a decreasing function of N with tendency to 0 which implicates perfect selection and N tends to infinity (Bundesen, 1987).

These findings support the four-parameter choice model for partial report with an α seeming independent of T and D: the goodness of fit was only very slightly improved by introducing b as a free parameter and estimates for b were very small (median near 0) (Bundesen, 1987).

The described race model (Bundesen, 1987) cannot decide between an unlimited processing capacity and a limited processing capacity with constant attentional weights. Processing with limited capacity is characterised by a slowing down in processing if more elements are added to the display, whereas processing with unlimited capacity would not be affected. An independent race model with unlimited processing capacity has the same distribution function for any element, regardless of the choice set. The selection probabilities (P_s) are:

$$P_s\left(W\right) = \sum_{i \varepsilon \varepsilon} \int_0^\infty \mathit{\Pi}_{h \varepsilon \varepsilon \; -[i]} F_h\left(t\right) \mathit{\Pi}_{j \varepsilon \varepsilon - W} \left[1 - F_j\left(t\right)\right] dF_i\left(t\right) \tag{5}$$

with *W* as a subset of the choice set *S* and consisting of *K* items. By the independence assumption, the probability (P_S) that the *K* members of *W* are the first *K* items reaching the state of being processed when selection is from choice set *S* is given by equation 5 (Bundesen, 1987). In an independent race model with limited processing capacity, we have to discuss the quantitative variations in the amount of processing capacity. As mentioned before, variations in the amount of processing capacity allocated to an item concern the rate at which an item is processed (not the type of processing). The effect of processing an item from time 0 to time *t* with a constant capacity of *C(x)* units at time *x* equals the effect of processing an item from time 0 to time $\int_0^1 C(x)dx$ with a constant capacity of one unit.

Thus, $F_i(t) = G_i\left(\int_0^t C_i(x)dx\right)$ is the conditional distribution of processing time for an item with the capacity allocated to item *i* at time *x* equal to $C_i(x)$ units and $G_i(t)$ as the conditional distribution function (capacity allocated to item *i* is constant at one unit).

The quantitative notion of capacity is a simple generalization of Rumelhart (1970) mentioned above.

In an independent race model with limited processing capacity and constant attentional weights are the distribution functions $F_i(t)$ working like conditional distribution functions for processing times of element *i* (with attentional weight w_i) and a variation in capacity *V(t)*. The capacity allocated to element *i* at time *t* is equivalent to $w_iV(t)$:

$$F_i(t) = G_i\left(\int_0^1 w_i V(x)dx\right) = H_i\left(\int_0^1 V(x)dx\right) \tag{6}$$

To exclude one of the possibilities (limited vs. unlimited processing capacity) Shibuya and Bundesen (1988) investigated partial report performance by introducing pattern masks terminating display presentations. They presented a circular array of digits or letters at nine different exposure durations (10 to 200ms) and subjects had to report as many target digits as possible while ignoring the distractor letters. Individual frequency distributions (hundreds of data points per subject) of the partial report performance (number correctly reported targets) as a function of the number of targets (2, 4, or 6) and the number of distractors (0, 2, 4, 6, or 8) at the nine different exposure durations were analysed and led to the conclusion that this distribution can be best predicted by a four-parameter fixed-capacity independent race model (FIRM; Shibuya & Bundesen, 1988). FIRM makes certain assumptions: Processing times are exponentially distributed, processing capacity and storage capacity are limited and the selectivity is time-invariant (Shibuya & Bundesen, 1988). Threfore, Shibuya and Bundesen (1988) argue in favour of a limited processing capacity.

Processing starts with collecting sensory evidence for each element that the actual element is a target (a digit in Shibuya & Bundesen, 1988) by comparing the actual element with representations in visual long-term memory (vLTM). The described sampling process takes place t_1 ms after display onset. The sensory evidence should be approximately the same for all targets (w_1) and for all distractors (w_0). During the sampling process, the time it takes to sample an element is exponentially distributed. In the next step all elements start a race to become encoded into vSTM with limited processing capacity. The total capacity is fixed at C elements per second, distributed over all elements directly proportional to the strength of sensory evidence or more precisely to their attentional weights (w_0, w_1) that the element is a target. Since the evidence should be stronger for targets, targets should get more processing capacity than distractors and thus be processed faster in the race for becoming encoded into vSTM before the capacity limit is reached. If the capacity limit is reached, or if t_2 ms after mask onset have passed, sampling stops. The difference between the two delays t_1 (sampling time after display onset) and t_2 (time after mask onset) is also referred to as parameter t_0 - indicating the maximum ineffective exposure duration (in TVA (1990) called minimum effective exposure duration) or a measure of the threshold of conscious perception. In the last step, the targets that entered vSTM are reported. The number of correctly reported items is the same as the number of sampled items in the display.

To summarize, FIRM is able to predict the probability distribution of the correct performance of one observer as a function of the number of elements (targets and distractors) and exposure duration for any observer's values of just four simple characteristics of the observer's attentional capabilities: Processing capacity (C), selection efficiency (α) calculated by dividing attentional weights of distractors (w_0) by the attentional weights of targets (w_1), capacity of vSTM (K) and the maximum ineffective exposure duration

(t_0). The maximum likelihood fits of FIRM to data of Shibuya & Bundesen (1988) were remarkable good.

The parameters of the total weight of extraneous noise elements (ε) and the probability that a target entering vSTM gets reported (Θ) were not included in FIRM. Possibly parameter ε was excluded because of the negligible effects of extraneous noise elements on performance found in Bundesen, Pedersen and Larsen's study (1984). Parameter Θ was set to 1 in FIRM and thus is not necessary to be considered.

The different parameters proposed by Bundesen, Pedersen and Larsen (1984), Bundesen, Shibuya and Larsen (1985), Bundesen (1987), and by Shibuya and Bundesen (1988) are summed up in Table 1.

Table 1. The different parameters proposed in the course of development of the TVA (Bundesen, 1990).

	Parameter
Bundesen, Pedersen & Larsen (1984)	K', α, ε
Bundesen, Shibuya & Larsen (1985)	K, Θ, α, ε
Bundesen (1987)	K, α, b, Θ
Shibuya & Bundesen (1988)	C, α, K, $t0$

Before explaining the version of the 'Theory of Visual Attention' (TVA) by Claus Bundesen in 1990, I have to briefly discuss a theory influencing some ideas of the TVA. The 'Attentional Engagement Theory' (AET) by Duncan and Humphreys (1989), again trying to explain the processes in visual selection, explains the performance in different search tasks without any kind of saliency signal like the GS (e.g. Wolfe, Cave & Franzel, 1989; Cave & Wolfe, 1990; Wolfe, 1994) or DW account (e.g. Müller, Heller, Ziegler, 1995) but as a result of different types of similarities; in detail, dissimilarities between the targets and distractors and distractors themselves. However, again – like the FIT (e.g., Treisman & Gelade, 1980; GS (e.g., Wolfe, Cave & Franzel, 1989; Cave & Wolfe, 1990; Wolfe, 1994) or DW account (e.g., Müller, Heller, Ziegler, 1995) – Duncan and Humphreys (1989) propose a multi-stage model for attentional selection containing three stages. In the first stage, they assume a parallel perceptual segmentation and analysis of the visual scene. The elements of the scene are grouped into structural units according to their similarity or dissimilarity in a pre-attentive process, i.e. it does not affect behaviour. Therefore no limited resources are accessed. In the next stage, in which the selection takes place, all elements in the visual field compete for entrance in the capacity limited visual short-term memory (vSTM). Selection is based on template matching (matching of the actual element with templates or representations stored in visual long-term memory (vLTM)) and weight-linkage (the weightings of similar objects are linked into a group that can be selected or deselected as a whole). Only those elements which get access to the vSTM can then influence higher cognitive processes in the encoding stage. The competition for entrance in vSTM, template matching of the actual object with representations in vLTM and weight-linkage are very important ideas for the TVA (Bundesen, 1990).

4.3. Bundesen’s (1990) Theory of Visual Attention (TVA)

The theories and ideas explained at the beginning and the forerunners described in the last sections result in Claus Bundesen´s (1990) formulation of the ‘Theory of Visual Attention’ (TVA).

Beside the discussed ideas and theories, two important observations related to visual selection were important for the TVA (Bundesen, 1990). Sperling (1960) observed that if the number of targets increases, the probability of identifying an object is reduced, arguing for limited capacity and for processing resources (i.e., attention) once allocated to one object not being available for other objects. Secondly, targets are reported more accurately than non-targets. Therefore a top-down mechanism seems to assign the limited processing capacity to the targets not to the non-targets. If resources can be assigned to targets, non-targets can be ignored.

Since the theory tries to explain how visual selection is conducted, we should have a closer look to the characteristics of visual processing in TVA (illustrated in Figure 4 and Figure 5). Again, selection takes place in a multi-stage process - this time with two different processing steps. Very similar to the AET (Duncan & Humphreys, 1989), processing starts with an analysis of the visual scene where the most interesting parts of the display are localised (visual input). The visual input in the iconic memory (Sperling, 1960) represents a visual representation of what is on the retina. The actual elements in the display are compared in parallel with the stored representations in vLTM. If they are matching, they get activated. This process is the same as the AET idea of template matching. Again, this process is assumed to be capacity-unlimited and thus automatic. The result of this process is degree-of-match values shown in sensory evidence values $\eta(x, j)$ with x as the actual element and j as the vLTM representation (the category) - the higher the sensory evidence values, the higher the match of the actual element with the stored representation. After the described first, unselective stage, the activated representations (categorisations) in vLTM start a selection race for representation in vSTM in the second, selective processing stage. The capacity of vSTM is limited to K elements and thus only the first K winners of the stochastic race process, i.e. the first K elements that finish processing before the capacity is reached or the stimulus presentation is finished, get encoded into vSTM. Entrance into vSTM implies becoming conscious and being able to control selection behaviour. In TVA, the vSTM is constructed out of the vLTM: the activated representations in vLTM build the vSTM. Summing up, for recognising an object we have to select what we need for the matching with vLTM and than compare it with vLTM representations.

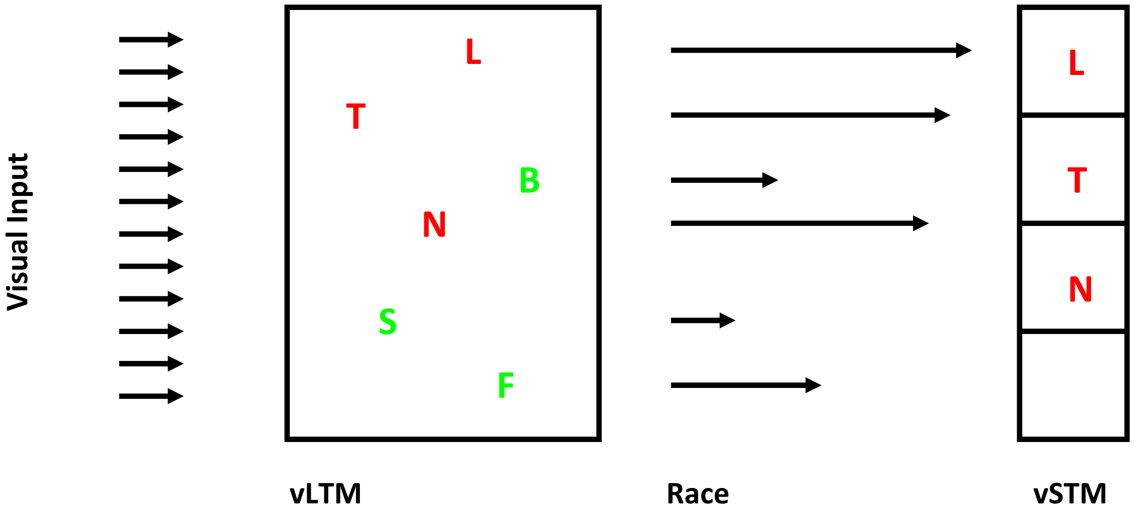


Figure 4. Schematic illustration of the visual processing assumed by the TVA (Bundesen, 1990; Bundesen & Habekost, 2008). Visual input activates representations in the vLTM which afterwards start a processing race for getting encoded into vSTM.

Selection in the second, selective processing stage takes place by means of two different selection mechanisms. First, elements are selected by filtering out or selecting the relevant target objects rather than irrelevant distractor objects. This process was first introduced by Broadbent (1982) assuming that filtering is selection on the basis of features and does not block everything; rather some unattended features could break through and influence later processes.

Filtering in TVA (Bundesen, 1990) is done by first computing attentional weights (w_x) for each element in the visual field and afterwards elements with high attentional weights are selected with higher probability. Weights are computed by

$$w_x = \sum_{j \in R} \eta(x, j) \pi_j \tag{7}$$

The attentional weight for element x is computed by the weighted sum of pertinence values. Pertinence (also referred to as priority or relevance) values (π) for a certain category are a new and top-down controlled (knowledge-based) component in the filtering process representing the current importance of attending to elements belonging to category *j*. Pertinence values should be high for the target category and low for the distractor category. Each pertinence value (π) of category *j* is weighted by the degree of evidence that *x* is actually a member of category *j*. *R* equals the set of all perceptual categories, η the strength of sensory evidence that element *x* belongs to category *j*. If the pertinence value of the target category (*j*) and the sensory evidence (η) that the actual element *x* is of the target category are high, the attentional weight for this element *x* increases proportional to the sensory evidence $\eta(x,j)$. The aim is to increase attentional weights of the elements belonging to the target category rather than the weights of all other elements and speeding up the processing of such elements. Therefore, the probability of getting selected increases. Summing up, filtering works as attentional selection and raises the probability that elements of the target category are selected.

However, filtering does not bias recognition. The conditional probability that the first categorisation finishing processing is the categorisation that *x* belongs to *j* given that the first categorisation is a categorisation of element *x* equals:

$$\frac{v(x, j)}{\sum_{i \in R} v(x, i)} \tag{8}$$

The probability is then not affected by filtering. In order to bias recognition the second mechanism is necessary.

This mechanism classifies the selected input – selected by the filtering mechanism. This process is called *pigeonholing* and reflects a categorisation bias categorising elements with respect to particular categories that are actually relevant for action: ‘Element *x* belongs to category *j*'. Bundesen (1990) refers to Broadbent's (1971) concept of pigeonholing as containing the process which relates evidence from the filter to a category state. Therefore pigeonholing is selection on the basis of categories by biasing the threshold of a category.

Pigeonholing in TVA (Bundesen, 1990) is based on the perceptual categorisation bias (β) determining how elements are categorised. Similar to the pertinence values, bias values are top-down controlled and based on the knowledge of the subject. The bias (β) should be higher for the target category than for the distractor category. If the bias associated with the target category j is high (in relation to other categories), i.e. that β_j is increased, which results for every element x of category j in an increasing processing rate (v) (whereas other v values are not affected) this results in a speeding up of the target categorisation.

Overall, pigeonholing raises the probability that a particular category – the target category - is selected. Visual recognition, which is the match with the stored categories (or representations) in vLTM is done by pigeonholing.

Both mechanisms are integrated in the combined theory of attentional selection (filtering) and visual recognition (pigeonholing) - the 'Theory of Visual Attention' (Bundesen, 1990), meaning that every element that is recognised is also selected and vice versa. The combined effect of filtering and pigeonholing, of adjusting the pertinence values and bias parameter, lies in increasing the processing rate v for every categorisation of a target element relative to processing rates for any other categorisation (Bundesen, 1990). If we have black target letters and white distractor letters, we have to ignore the distractors, filter out the targets and categorise the targets with respect to the letter category. According to TVA, we have to set the pertinence values for black as high and for white as low. Additionally, the bias should be high for the letter category and low for all other categories.

The probability that a certain element enters the vSTM – in other words the time it takes to complete categorisation - is displayed by the rate (of processing) equation:

$$v(x, j) = \eta(x, j)\beta_j \frac{w_x}{\sum_{z \in S} w_z} \tag{9}$$

The rate of processing for element x is computed by the strength of sensory evidence that element x is of category j weighted by the bias towards making categorisations of type j and the relative weight of objects x, given by the ratio of w_x over the sum of the weights w_z

of all elements. The processing rate increases if the sensory evidence is high, the target category is known (therefore the bias for this category is high), and the attentional weight is high for the actual element. If the match with the vLTM representation is optimal, the bias for a certain category is perfect and the attentional weight for this element is high, we get an optimal rate of processing resulting in very fast processing. Competition between the elements in the visual field is modulated by the processing rate. The rate of processing $v(x,j)$ is a function of η, β and π. After determining these values, the processing times for individual perceptual categorisations are mutually independent random variables. Strength of sensory evidence (η) values are computed in parallel across the set of elements and categories. There are no observable effects of η-values for any categorisations for which pertinence π and bias β are both 0 existing. If η, β and, π are supposed to be constant during stimulus exposure, then the processing rates are constant and the processing times for categorisations are exponentially distributed with $v(x,j)$ as exponential rate parameter. One example for the combination of the filtering and pigeonholing mechanisms is the one mentioned in Bundesen (1990):

Observers had to report every red digit in a mixed array of red and black digits. The first strategy is filtering, that means setting the pertinence value of the perceptual category 'red' high compared to the other categories. This results in selecting red rather than black and increases the rate of processing for every categorisation of red elements. The second strategy is to set the perceptual bias parameter for each type of digit high compared to the others. This results in recognising the identity of red digits rather than other attributes of the elements. The processing rate for every categorisation with respect to the type of digit relative to all other attributes is increased. The combined effect of adjustments of pertinence and bias is then an increase in the processing rate for every categorisation of a red element with respect to the type of digit - relative to other categorisations.

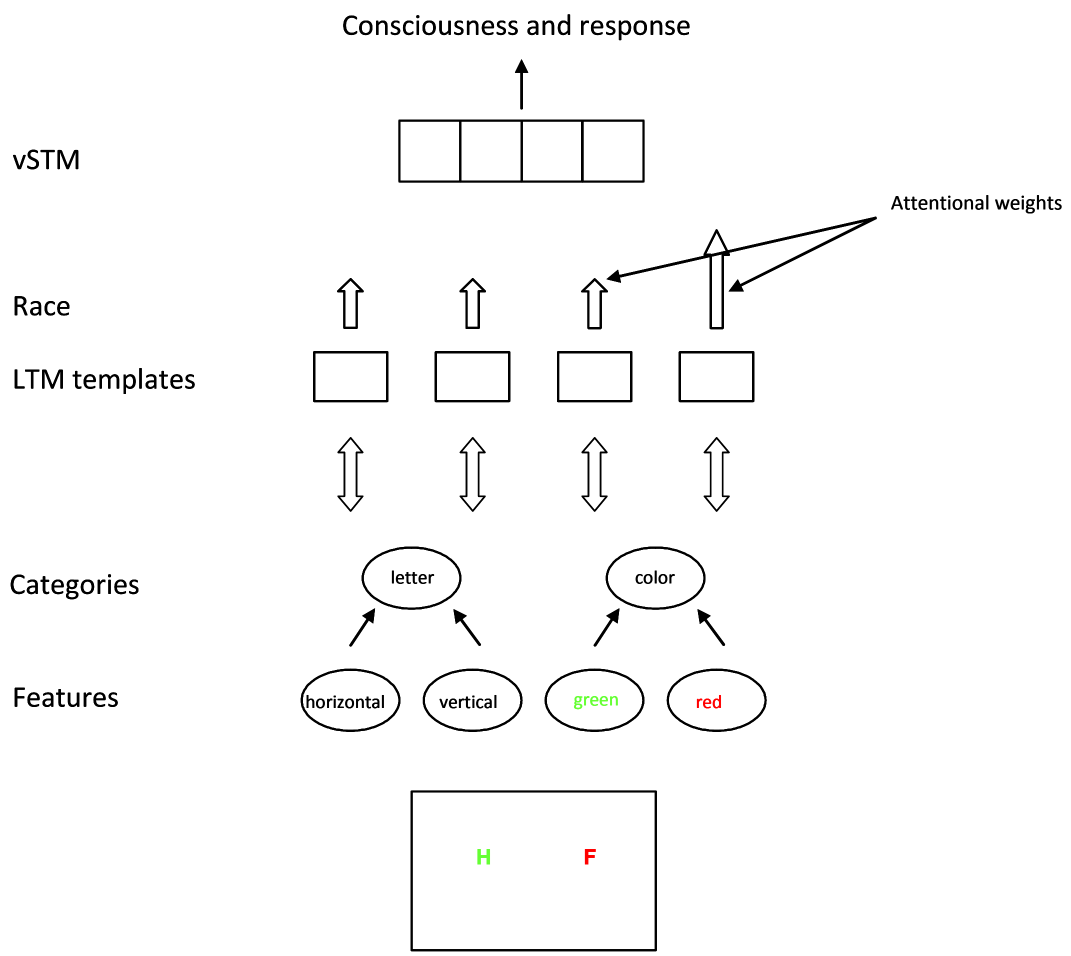


Figure 5. Processing architecture of the TVA (Bundesen, 1990).

According to TVA, visual selection performance can be reflected by a psychophysical function which is individually different for each observer. The function can be fitted to the data of two simple experimental paradigms (originally proposed by Sperling, 1960, 1963, 1967), namely the ‘whole report’ (subjects have to report as many briefly presented letters as possible) and ‘partial report’ (subjects have to report only some pre-defined (by a cue) briefly presented targets and ignore the distractors) as mentioned before in section 4.2. The mean score (number of correctly reported letters) is plotted as a function of exposure duration for different display sizes. The resulting exponential function can be best determined by four independent components. Therefore selection performance is influenced by four independent component processes, such as the vSTM *capacity (*reflected by parameter *K)*, *processing speed (*reflected by parameter *C)*, *top-down control (*reflected by parameter *α)*, and the *spatial distribution* of attention (reflected by parameter w_λ). The vSTM capacity is operationalized by the number of elements processed simultaneously in the vSTM. *K* indicates the maximum number of items reported on any single trial at any exposure duration. On average *K* is approximately at 3.5 correctly reported items on any experimental trial - independent of exposure duration or display size. The asymptote of the psychophysical function indicates the capacity of vSTM. How many elements per second are processible is indicated by the processing speed (*C*). This measure of identification rate is measured in elements per second and on average is around 30-40 elements per second. The total processing speed is shared out among the different elements in a visual scene according to their attentional weights and is constant across variations in number of elements and their attentional weights. The slope of the psychophysical function reflects the processing speed. If the slope is flat, it needs more time to reach the asymptote (*K*) arguing for a slower processing speed. The steeper the function is, the faster the processing. Processing speed *C* is computed as sum of *v* values across all perceptual categorisations of all elements:

$$C = \sum_{x \in S} \sum_{j \in R} v(x, j) \tag{10}$$

C can often be treated as a constant. If discriminability is perfect ($\eta_0 = 0$), then $C = \eta_1 \beta_1$. The capacity of vSTM and the processing speed are indicators for the general information processing efficiency of the system and can be estimated out of the data of whole report (originally proposed by Sperling, 1960, 1963, 1967). The whole report method was adapted by Duncan et al. (1999). Following a central fixation point, on the right or the left side vertical columns of five red or green letters were presented very briefly for three different exposure durations, followed by masks on each letter position or no masks resulting in six data points (short exposure duration, unmasked; short exposure duration, masked; middle exposure duration, unmasked; middle exposure duration, masked; long exposure duration, unmasked; long exposure duration, masked). An equal and sufficient number of trials are presented for all conditions and averaged for the different conditions (Duncan et al., 1999). The (psychophysical) whole report function of correct performance can be fitted into these six data points. The resulting six exposure durations reveal a broad performance spectrum reflecting the early and the late section of the subject’s whole report function (Finke et al., 2005). The observers’s task is to report as many targets as possible regardless of the order.

The next component, the attentional weight (w), attributed to particular items in a display, is a probability, ranging from 0 to 1. Targets should get higher weights than distractors, higher processing speed and thus a higher probability to win the race for becoming encoded into vSTM. They are computed according to equation 7. Interestingly, the spatial distribution of the attentional weights (w_{λ}) can be computed out of the attentional weights to the left and to the right hemi-field and can reveal tendencies for preferring the one or the other hemi-field. The spatial distribution of the attentional weights is an interesting indicator for the diagnosis of e.g. visual hemi-neglect, where people neglect one visual hemi-field. Values of 0.5 indicate equal weighting of both hemi-fields, values bigger than 0.5 indicate a spatial bias to the left hemi-field and values smaller than 0.5 indicate a spatial bias to the right hemi-field.

The last component, the selection effectiveness, that is, if the relevant (target) information can be selected and irrelevant (distracting) information be ignored, an ability of great importance because of the capacity limitation of our system, can be displayed by the top-down control (α). The top-down control is computed as the ratio between the weights attributed to the target category relative to the weights attributed to non-target categories. Values at zero indicate perfect selection; values at one indicate no selection (equal selection of targets and non-targets) and values bigger than one indicate the selection of distractors and ignoring of targets. The top-down control is on average around 0.4. The attentional weights and the top-down control are indicators of the spatial distribution of attention and can be estimated out of the data of partial report (originally proposed by Sperling, 1960, 1963). The partial report method was adapted by Duncan et al. (1999) for their specific purposes. One or two letters are presented briefly for one exposure duration in the corners of a virtual square around the central fixation point followed by masks. Targets are pre-defined by a colour cue (e.g., all red letters) - contrary to Sperling (1960, 1963) where the cue was a tone - and have to be reported; non-targets (e.g., all green letters) have to be ignored. One target could be presented alone, accompanied by a non-target or by a second target.

4.4. Summary and Evaluation

Summing up, by integrating the biased choice model and the race model according to the TVA, attentional selection is carried out in parallel and follows an exponential probability distribution. Attentional selection (filtering) and visual recognition (pigeonholing) is done by making perceptual categorisations of all elements present in the visual field. Categorisations are made if they can win the stochastic race process and enter the limited-capacity vSTM. Therefore elements are selected and recognised at the same time (not early or late selection) as members of particular categories. TVA can be seen as a unified theory of selection and recognition. If a sensory system supplies measures of the strength of sensory evidence and is given adequate top-down settings of pertinence and bias values, the system is able to do filtering and pigeonholing by using elementary algebraic operations, namely the weight equation (7) and the rate equation (9), determining the processing rate of each element participating at the race for getting encoded into vSTM. Therefore – contrary to the historically older theories described above - TVA is a computational account of selective attention (Bundesen & Habekost, 2008).

Since Bundesen's aim (according to Bundesen and Habekost (2008)) was to develop a theory concerning a *general mechanism* for attentional selection, he proposed that attentional selection is influenced by an intelligent agent combined with a powerful selection mechanism. If sensory input meets the visual system, this powerful mechanism in detail can be seen as a computational system able to conduct filtering (selects input by criteria) and pigeonholing (classifies selected input with respect to pre-specified categories) controlled by parameters from a high-level executive system. Various empirical findings (e.g., object integrality in selective report, effects of number and spatial position of targets in divided attention studies, effects of selection criterion and number of distractors in focused attention studies, effects of delay of selection cue, effects of practice in visual search) in different attention tasks can be explained by the TVA (Bundesen, 1990).

The TVA furthermore tries to find a solution to the old discussion about early selection, i.e. selection before recognition based on simple physical features; or late selection, i.e. selection after recognition and based on complex properties. Both are claiming selection and recognition as two distinct processes (Bundesen, 1990; Bundesen & Habekost, 2008). In early selection theories, selection precedes recognition and thus full recognition only takes place for all selected elements, selected by simple physical features. If only selected elements have to be recognised, the requirements on perceptual decision making are reduced. However, since selection is based on basic physical features, selection is rather primitive (Bundesen & Habekost, 2008). In late selection theories recognition precedes selection. Every element in the display has first to be recognised and then the target elements can be selected according to their belonging to the target category. Therefore selection is intelligent because it is based on any categorisation at the recognition stage. However, each element in the visual scene has to be recognised and causes a high demand on perceptual decision making. On account of these negative characteristics of both early and late selection theories the TVA tries to solve the conflict by assuming that selection and recognition are two aspects of one and the same process and occurring simultaneously. Therefore the TVA is “a unified theory of visual recognition and attentional selection” (Bundesen & Habekost, 2008; p. 43). The mechanism managing this (already described above) selects among possible categorisations (*x* belongs to *j*). The probability of selecting a specific category depends on the strength of sensory evidence (η values) that ‘*x* belongs to category *j*’ and that *x* belongs to the target category. The η values are computed before selection takes place and the selection is based on categorisation not on basic physical features – in agreement with late selection theories. The categorisation only takes place for those elements that are selected and therefore get encoded into limited capacity vSTM – in agreement with early selection theories (Bundesen & Habekost, 2008).

The theory allows for the formal description of separate attentional components estimated out of the data obtained with the simple ‘whole report’ and ‘partial report’. Attentional functions and dysfunctions (e.g. Duncan et al., 1999; 2003; Finke et al., 2006, 2007; Peers et al., 2005; Habekost & Rostrup, 2007) can be assessed with a state of the art theoretical foundation. Since so many studies are conducted using the whole and partial report methods for assessing attentional dysfunctions, the methods have to be evaluated with respect to the four central strength of a test methods, namely specificity, sensitivity, reliability and validity. Because the methods are measuring relatively pure aspects without any disturbing complex motor component (the investigator types the reported letters), no reaction times are measured and the performance can directly be analysed into the different attentional components, the criteria of specificity is fulfilled. In several studies minor attentional deficits and subtle functional disturbances could be detected by using the methods of whole and partial report. Therefore, the methods seem to be very sensitive. The reliability (the consistency of the measurement) is very high for estimates of the capacity of vSTM (K), processing speed (C) and attentional weights (w), but not for the top-down control (α). The estimates of α are related to a substantial measurement error possibly caused by the fact that α is computed as the ratio of two different variables (attentional weights of targets and attentional weights of distractors) or the fact that the encoding of distractor elements in vSTM is not directly visible in the experimental data. Whatever might cause the low reliability of α, one has to be cautious in interpreting the results concerning this parameter. The last criterion, namely the validity, is satisfied since the parameters used for data modelling can account for a wide range of findings from other experimental tasks. The used stimuli (letters) are well suited for the investigation of simple visual objects and the recognition of letters is highly efficient due to the fact that they are highly over-learnt forms. Because we have a large set of approximately equally difficult identifiable letters available, the probability of guessing can be minimized. Furthermore letter perception is quite robust to brain damage. The relationship between the used stimuli to visual objects in general is thus satisfying. Important for the validity is also the relationship of the parameters to other clinical measures of visual attention. Significant correlations between all four parameters and their paired clinical tests and no or negligible correlations with their non-paired tests could be found by Finke et al. (2005). Thus, the whole and partial report methods measure what they intend to measure (construct validity is given). The last crucial point for the validity is the functional specificity of each parameter. Since all parameters are not correlated to each other except for a moderate correlation between the capacity of vSTM and the processing speed, Finke et al. (2005) assume that the parameters represent separate aspects of visual processing (discriminant validity).

Between 1990 and 2009 a lot of further developments have taken place. The TVA (Bundesen, 1990) was for example combined with the CODE theory explaining perceptual grouping by proximity (van Oeffelen & Vos 1982) and led to the extended ‘CODE theory of visual attention’ (CTVA; Logan, 1996). CTVA can account for a wide range of spatial effects in visual attention. More interesting concerning my issues and my future research is the development of the ‘neural theory of visual attention’ (NTVA) by Bundesen, Habekost and Kyllingsbæk (2005). They tried to bridge cognition and neurophysiology in their neural interpretation of Bundesen’s (1990) TVA.

4.5. The Neural Theory of Visual Attention (NTVA)

Bundesen, Habekost & Kyllingsbæk (2005) attempted to apply the computational principles of the TVA (Bundesen, 1990) to attentional effects at the single-cell (neuronal) level.

Typical neurons in the visual system can represent the properties of only one object at a time and therefore each neuron is specialized for signalling only one perceptual feature. The rate of activation of a neuron, which is dependent on the total activation of all neurons supporting the categorisation, represents the transmitted information. Total activation of the neuron is influenced by the sensory evidence that the actual object has the target feature, by the general bias for making this type of categorisation and by the relative attentional weight of the actual object.

In TVA (Bundesen, 1990) visual processing is characterised by two processing stages. All processing stages are displayed in Figure 6. At the beginning of the unselective stage the cortical system has to localise the most interesting parts in the new visual scene. In neural terms (NTVA; Bundesen, Habekost & Kyllingsbæk, 2005) the receptive fields of the neurons responsible for visual input contract randomly across different locations and thus process unselectively. Neurons transmit information about objects according to their feature selectivity and this information is used for computing the attentional weights. The information from different sensory neurons is summed up according to the weight equation (equation 7) in a priority map. The comparison of actual objects with representations in vLTM is carried out by higher pertinence values for the target category and higher degree of match between the actual object and the stored vLTM representation, producing different activations at different locations of the priority map. These activations are stored in the priority map and used in the second, selective stage characterised by the competition of different categorisations for becoming encoded into vSTM.

The second stage includes the filtering process (selection of relevant objects) and pigeonholing (categorising of selected elements). According to NTVA (Bundesen, Habekost & Kyllingsbæk, 2005) filtering changes the number of neurons in which the actual object is represented. The priority map is used for remapping the neurons’ receptive fields. As a result the neurons are more likely to respond to objects with higher attentional weights (seen in priority map) and therefore more neurons are allocated to process features of these objects. The attentional weights correspond to the number of neurons responding to one object. Pigeonholing changes the activity level of the neurons (coding for a particular feature) by scaling the firing rates. Perceptual bias for one category emerges from multiplying the activation of each neuron signalling the particular categorisation. Therefore neurons fire more vigorously if they have feature specializations corresponding to the actual perceptual bias of the whole visual system. As in TVA (Bundesen, 1990), attentional selection is the combined effect of filtering and pigeonholing and controls the total activity level in each population of neurons signalling particular categorisations of an object. In competition (TVA: the race) with other cell populations supporting other categorisations, each population's level of activity determines whether the categorisation becomes encoded into the vSTM and therefore can win the race. One of these cell populations, most probably one with a large number of highly activated cells, sends off a signal that can capture one of the few free 'slots' in the vSTM system. The vSTM system consists of the vSTM map and feedback interactions with sensory neurons. The topographically organized vSTM map establishes feedback circuits that keep visual presentations active. The map functions as a pointer to locations of the features of the selected objects. Neurons representing features of objects at these pointed to locations are kept active by reciprocal connections in the corresponding parts of the vSTM map. Encoding in vSTM implies a sustained activity of the cell population on a feedback loop between the sensory neurons and the vSTM map of locations, which makes it possible for visual presentations to outlast the original stimulation (after-image). Summing up, changes in activity at the cellular level add up to produce selection effects on the psychological level (Bundesen, Habekost & Kyllingsbæk, 2005; Bundesen & Habekost, 2008).

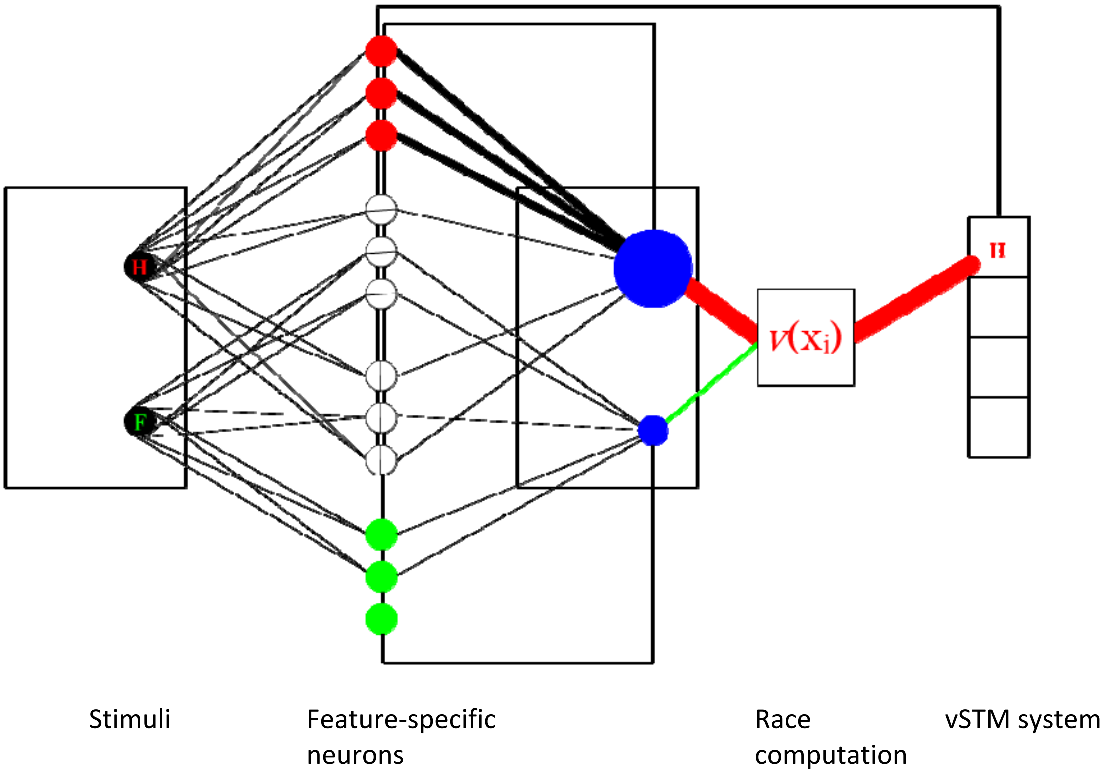


Figure 6. Displayed is the processing of two stimuli (red H and green F). The red target letter wins the race by accumulating more feature-specific neurons with higher firing rates than the green distractor letter and gets encoded into vSTM.

Another very interesting feature is the functional anatomy of the NTVA (Bundesen, Habekost & Kyllingsbæk, 2005) explaining where and how the computations and parameters of the NTVA are assumed to be distributed across the brain.

In the thalamic model of NTVA (Figure 7; Bundesen, Habekost & Kyllingsbaek, 2005) visual input arrives in the lateral geniculate nucleus (LGN) of the thalamus (1). Afterwards the information is transmitted to striate and extrastriate cortical areas in which the strength of sensory evidence (η) values are computed (2). The products of the η values and the pertinence values (π) are transmitted from the cortex to the priority map located in the pulvinar nucleus of the thalamus. These products are summed up as attentional weights of the objects (3).

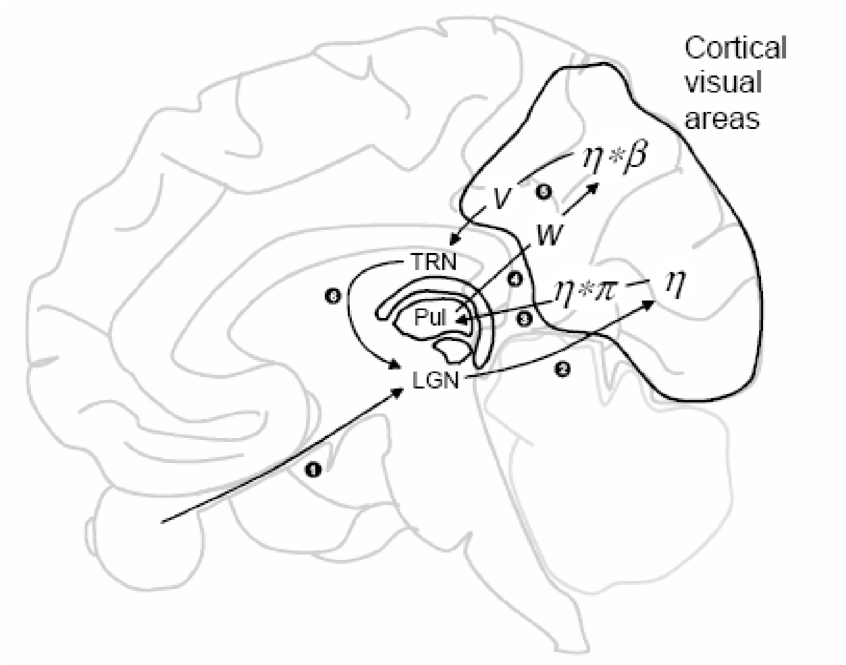


Figure 7. Thalamic model of NTVA. From: Bundesen, Habekost, and Kyllingsbæk (2005). A neural theory of visual attention: Bridging cognition and neurophysiology. Psychological Review, 112, 291-328. Copyright 2005 by the American Psychological Association.

After this unselective processing stage, the cortical processing capacity is redistributed from pulvinar into cortex according to the attentional weights. As a result, objects with higher weights are assigned more processing capacity and therefore are processed by more neurons during the selective processing stage (4). The product of the resulting *η* values and the bias (*β*) values are transmitted from the cortex to the vSTM map of locations presumably located in the thalamic reticular nucleus (5). By the time the vSTM map is initialised, all objects in the visual field start a race to become encoded into vSTM. In this race each object represented by all possible categorisations of this object participates with a firing rate proportional to the product of *η* values multiplied by the bias (*β*) values. For the winners of the race the thalamic reticular nucleus gates activation (represented by a categorisation) back to those cells in the lateral geniculate nucleus whose activation supported the categorisation (6). Therefore, activity in neurons representing winners of the race is sustained by positive feedback and makes it possible for visual presentations to outlast the original stimulation.

Summing up, the NTVA provides a close link between attentional functions at the behavioural and at the cellular level. Using the same basic equations mentioned in TVA (Bundesen, 1990), the theory can account for large proportion of attentional effects in the psychological literature and additionally attentional effects demonstrated in individual neurons.

4.6. Combination of the TVA and the DW Account

Since the object- and parameter-based TVA (Bundesen, 1990) and the later out of feature-based accounts like the GS model (e.g., Wolfe, Cave & Cave, 1989) developed dimension-based DW account (Müller, Heller & Ziegler, 1995; Found & Müller, 1996; Müller & O'Grady, 2000) are very influential theoretical accounts and can explain a wide range of findings in visual selective attention, it seems to be very interesting to have a closer look at their specific characteristics and a possible combination of the ideas of the TVA and the DW account.

If a visual stimulus encounters the eye, the visual information is transmitted through the lens onto the retina, where receptors transpose this information into an action potential. The action potential is travelling along the optic nerve to certain brain areas, more specifically, first to the primary visual cortex (V1 area) in the occipital cortex. At this point the cognitive processing models such as the TVA (Bundesen, 1990), the GS (e.g., Wolfe, Cave & Franzel, 1989) or the DW account (e.g., Müller, Heller & Ziegler, 1995; Found & Müller, 1996) come into play. In TVA as well as in the GS or DW model, the first processing step is extracting features out of the visual information. In TVA this takes place in the first processing step by localising the most interesting features in a visual scene. In the next step, TVA compares these features with stored LTM representations for recognising the present elements, whereas in the GS or DW models no LTM memory component is of relevance. However, very similar in principle are the ideas of feature extraction. In TVA the filtering mechanism selects the important features out of the scene by setting attentional weights for relevant elements high, and in DW or GS the extracted features are translated into feature maps. Afterwards, pigeonholing classifies the selected input with respect to their category (in TVA). In the DW or GS model the saliency signals for all dimensions are computed and summed up onto dimension maps. Therefore the information is categorised with respect to the dimension. The distribution of attentional weights on the objects according to their importance in TVA is comparable to the bottom-up weighting of the actual relevant dimension in DW taking place in the next step. However, despite the similarities, the models differ in their ideas of how selection finally takes place. The saliency activation (in DW bottom-up weighted according to the actual relevant dimension) decides in DW and GS if a certain element is selected or not. The attentional focus is guided to the location with the highest activation; elements at this location are selected and are able to control behaviour. On the other hand, in TVA those elements which won the selection race are selected and can catch one of the few slots in vSTM. Obviously, vSTM or LTM are not necessary for selection in GS. Comparison with LTM templates, i.e. object recognition and identification, does take place after the selection process is finished. However, in the DW account there is a memory component, namely an implicit memory trace. Therefore, the history of an actual trial influences the RTs on this trial.

Feature-based accounts assume a pre-attentive and automatic feature processing stage followed by an attentive stage of integrating features into coherent objects. This assumption has repeatedly been called into question. It could be observed that the processes of feature registration and saliency computation, that are assumed to be automatic, can be affected by limitations in processing resources. The TVA tries to explain and predict visual selective behaviour with the use of a limited set of just four different and independent components (reflected in parameters). The main shortcoming of the TVA is that it cannot account for phenomena of bottom-up control like the effects of the influence of specific characteristics of a stimulus of a previous trial on performance of the actual trial. The dimension-based DW account (Müller, Heller & Ziegler, 1995; Found & Müller, 1996; Müller & O'Grady, 2000) could show that the influence on RT's of the actual trial is dependent on the target-defining dimension in the previous trial in visual search experiments. At the time the TVA (Bundesen, 1990) was developed no-one ever investigated or detected dimensional effects in visual selective attention. As mentioned earlier, dimensional effects are assumed to be very early effects arising at the beginning of the visual processing progress and can be influenced by top-down information. Since performance can be influenced very early in the visual processing stream, the assumption of early, automatic and non-manipulable processing stated in FIT (Treisman & Gelade, 1980) or GS (Wolfe and his colleagues) cannot be maintained any longer.

The arising question is if certain characteristics of the TVA, namely the components describing attention, can be influenced by dimension-based modulations. According to the DW account (Müller, Heller & Ziegler, 1995; Found & Müller, 1996; Müller & O'Grady, 2000) these modulations should result in observable modifications of these components seen in increases of the components if the dimension stays the same, and decreases if the dimension is changing. Dimensional modulations in the components of the TVA would argue for processes in the TVA that are assumed to be automatic to be dependent on limited resources and to be cognitively manipulable. In this case, the parameter-based theoretical description of the processes involved in visual selective attention should be updated.

The experimental combination of these two theories and the testing of the above mentioned hypotheses are described in chapter 5.1.

In the next chapters the experimental studies based on the theoretical background of this chapter are described in detail. Since I have been investigating three main fields of interest in the research of the categorisation process, I will start in chapter 5.1 with my first project concerning the foundations of the categorisation process. In this project the experimental combination of the parameter-based TVA (Bundesen, 1990) and the dimension-based DW account (Müller, Heller & Ziegler, 1995; Found & Müller, 1996; Müller & O'Grady, 2000) was conducted. The influences of bottom-up feature changes and top-down influences on the categorisation process were investigated. Furthermore, specific questions concerning the characteristics of the TVA (Bundesen, 1990) were subjects of this chapter.

In chapter 5.2 my second project will be discussed, dealing with people having specific disturbances in their perceptual abilities, namely the enhanced performance of people with Asperger's syndrome. I investigated the processing differences between groups of people with Asperger's syndrome and healthy control groups. Furthermore, possible causes and the location of the difference in the visual processing stream are part of this project.

Chapter 5.3 - containing my third project - focuses on the developmental perspective of the categorisation process in children collected with a TVA based testing method. The development of the different TVA components (capacity of vSTM, processing speed, top-down control, and spatial distribution of attention) in three age groups is described.

5. Experimental Studies

5.1 Project I: Categorical Repetitions in Object Characteristics Affect Visual Short-Term Memory Capacity

5.1.1 Summary

The studies of Chapter 5.1 are dealing with the foundations of visual selective processing. Recent research has shown that performance in visual search is systematically affected by changes and repetitions of visual dimensions and features across consecutive experimental trials. In the first part of this chapter, Bundesen's (1990) formal psychophysical approach – the TVA – was used to examine the effects of a trial-based variation of visual dimensions (following the procedures of the Dimension Weighting (DW) account of Müller, Heller and Ziegler, 1995) and features (see Maljkovic and Nakayama's 1994, 1996 'priming of popout' approach) of to-be-reported objects on component functions of selective visual attention. Observers' task was to report the identities of as many briefly presented letters as possible either involving the entire set or a subset of letters indicated by a cue. Irrelevant features (colour, form) of the letters were repeated or changed across trials.

Results show significantly higher visual short-term memory (vSTM) capacity and more efficient top-down control if features of the search items remained unchanged in consecutive trials; further, an increase in the processing rate was observed when both the dimension and the feature stayed the same.

The findings argue for a modification of visual short-term memory capacity if a particular memory setting, established during a given experimental trial, can be employed in the following trial. Further evidence for the modifiability of short-term memory was provided in an experiment using trial by trial semantic pre-cueing.

Overall, the present findings argue for a modifiable short-term memory with a capacity determined by basic visual features and for a influencability of attentional components – proposed by the TVA – by bottom-up as well as top-down information.

In the second part of this chapter more specific questions concerning the characteristics of Bundesen's (1990) TVA are discussed. More specifically, the effects of using one stimulus letter twice in one and the same trial on the components of visual short-term memory and processing speed were tested. Furthermore different spatial locations of the letter

presentation as well as the effects of repeating exactly the same letters in consecutive trials were investigated.

5.1.2 Introduction

If someone drives a car it is highly important, in order to react appropriately in any given situation, to analyse very quickly the visual environment. The higher the capacity of the driver’s short-term memory, the better he or she can react. Furthermore, it is necessary to focus on currently important information like a child jumping in the street. Attentional weight should be higher for the observation of the child than, for example, for the level of the fuel indicator. In all situations the driver has to filter out the currently important and relevant information as quickly as possible and has to ignore irrelevant information in order to be able to react rapidly and appropriately. Without doing so, traffic would end up in chaos and many (more) accidents would happen. Another example for the importance of selectivity can be taken from free time activities. Imagine you are in an aerobics class where your instructor demonstrates different series of steps and your task is to copy the step sequence as good as possible. To be able to imitate the steps, you have to process what you see very rapidly. The higher your processing speed, the better you will be at this task. For adequate performance of the whole combination of steps it is necessary to keep all the steps in mind (or, at least, as many steps as possible). The higher the capacity of your visual short-term memory is, the better your performance. Because the capacity is limited you should set the attentional weight for your instructor to a very high, and for all other people and incidences in the room to a very low level. Doing so increases selection effectiveness and assists selecting the relevant information predominantly – the instructor – and ignoring irrelevant and distracting information such as the mistakes of your colleagues. The attentional components introduced above underlie the studies of the present chapter and they also constitute the theoretical core of one important current theory of visual selective attention, Bundesen’s (1990) ‘Theory of Visual Attention’ (TVA).

In order to understand the theoretical framework of the ‘Theory of Visual Attention’ (Bundesen, 1990), a discussion of the object recognition process is prerequisite. According to the TVA, the short-term representation of a currently presented object is compared to stored representations or templates in the visual long-term memory (vLTM). Recognition takes place if the representation of the current object matches a template stored in long-term memory. This is assumed to happen in the first processing step, the unselective stage of visual processing in TVA. First, the most interesting parts in the display are localised – i.e., the parts most interesting for further analysis. In a massively parallel comparison in which processing time is independent of the number of objects, currently seen visual information is matched with stored long-term memory representations or categories. Processing on the first stage is capacity unlimited and occurs automatically. The matching yields 'degree of match' values indicating how well the currently processed object matches the stored long-term memory representations or categories. The ensuing second stage of processing in TVA is characterised by a race for selection, or, respectively recognition of the different categorisations of objects (activated in vLTM) for representation in visual short-term memory (vSTM). Only the information represented in vSTM becomes conscious and can control behaviour. The capacity of vSTM is assumed to be limited to a certain number of objects (*n* objects); therefore all active categorisations of objects in visual long-term memory compete for entrance in vSTM. Only the categorisations of the first *n* winners that finish processing before the capacity limitation of vSTM is reached are represented in vSTM. Usually, in theories of memory (e.g., Baddeley & Hitch, 1974) vSTM is seen as a separate component of memory which is active as long as information is required; information no longer represented in vSTM is either lost or stored in long-term memory. Bundesen (1990) used an alternative concept of vSTM. In TVA he assumes that the vSTM is 'constructed' of the active representations (categorisations) of vLTM that compete for entrance in vSTM. Processing in the unselective stage is automatic and capacity-unlimited. The limitation comes into play within the selective stage in form of the vSTM capacity limitation.

The selection process, in the selective processing stage, can be biased by and described by a set of component processes: The capacity of vSTM indicates how many items can be processed simultaneously in vSTM. The capacity corresponds to the maximum number of elements that can be reported on any trial at any exposure duration (Duncan et al., 1999). If more than four objects need to be processed, capacity in most observers reaches an asymptotic value, i.e., a maximum of about three to four elements (objects) can be reported usually with exposure durations of about 100-200 ms (Sperling, 1967; Duncan et al., 1999).

A further component affecting selection is the speed of processing, measured as the identification rate in elements per unit time (i.e., items per second). The processing speed component shows how quickly presented elements can be processed. Processing speed and the capacity of vSTM are assumed to be relatively stable because they are indicators for the general information processing efficiency of an observer.

The third component is referred to as the attentional weight that is attributed to the elements in a display and attentional weights are used to indicate which display elements are strengthened and which ones are not. The laterality index of attentional weighting (computed from attentional weights of the left divided by the attentional weights of the left plus attentional weights of the right hemi-field) indicates a bias for a particular visual hemi-field or, in the case of healthy observers, equal weighting of both visual hemi-fields. Attentional weights are probabilities ranging from 0 to 1. Targets should get higher weights than non-targets and thus a higher probability to win the race for representation in visual short-term memory. Processing speed of all elements corresponds to their attentional weights. High attentional weight yields a faster processing speed and a higher probability to become represented in vSTM.

The fourth component of attentional selection in Bundesen's TVA is referred to as selection effectiveness or the top-down control. Top-down control indicates the ability to process relevant information predominantly and to ignore irrelevant information. Because of the capacity limitation of vSTM, the ability to top-down bias selection is highly important. Selection effectiveness is expressed as the weight attributed to the non-target category relative to the weight attributed to the target categories. Both parameters – attentional weight and top-down control – are indicators for the spatial distribution of attention. Comparable to and highly correlated with the processing speed is the basic sensory effectiveness (an additional TVA component). It reflects how well one object is processed when it is presented alone and depends on factors like discriminability or retinal position, for example.

TVA is an object-based account; selection operates on visual objects or perceptual groups of a visual scene. However, there are different theoretical approaches about how selective visual attention is presumably controlled. One account claims that selection is space-based (e.g., Posner, 1980); authors of the space-based camp propose that the location of a stimulus is selected. Object-based accounts claim that attention selects objects (e.g., Duncan, 1984; Bundesen, 1990); feature-based (or dimension-based) accounts (e.g., Allport, 1971, 1980; Treisman, 1980; Müller, Heller & Ziegler, 1995) assume that attention operates on visual features (e.g., red, small) or dimensions of features (e.g., colour, size). A very influential feature-based theory - based on results obtained with the visual search paradigm - is Treisman's 'Feature Integration Theory' (FIT; Treisman & Gelade, 1980; Treisman, 1988; Treisman & Sato, 1990). In a visual search task, the participant is instructed to search as quickly and accurately as possible for a (target) item that differs from all the other items in the display. The results of two different search types, feature search and conjunction search, are the foundation of Treisman's theoretical approach. In a feature search task the target is unique with regard to one feature. The time it takes to detect the target item in feature search conditions is independent of the number of distractor items present in the display and therefore leads to flat search functions (search reaction times [RTs] plotted as a function of numbers of items). All display items can be processed efficiently, in a parallel fashion. In a conjunction search task the target is unique in terms of a unique combination (conjunction) of features. In conjunction search, with increasing display sizes, the time it takes to detect the target increases linearly. This increase is indicative of inefficient, serial processing of display items.

According to Treisman and Gelade (1980) the function of attention is to integrate (bind) information of different features of an object which are processed by and represented in independent component modules, to form a global and coherent representation of an object. Treisman and Gelade (1980) assume that processing takes place in two consecutive processing stages: a pre-attentive stage where parallel encoding takes place and an attentive stage where the serial, limited-capacity processing takes place including feature binding through focal attention. The object recognition network used to identify the object currently under the focus of attention is similar in concept to the first processing step of Bundesen's (1990) TVA: temporarily stored object-describing features are matched with object descriptions stored in the long-term memory for objects. Contrary to TVA, there is no role, i.e. limitation, associated with memory in FIT.

An alternative feature-based account was developed to overcome problems of FIT. Wolfe and his colleagues proposed a saliency-based account, referred to as the 'Guided

Search' model (GS; Wolfe, Cave, & Franzel, 1989; Wolfe, 1994; Wolfe, 2007). As in FIT, findings with the visual search paradigm were at the foundation of the GS. According to GS, targets in visual search are detected by a multistage mechanism. In the first step, visual features are extracted and, in parallel, saliency signals are generated by a limited number of dimension-based modules. Saliency activation arises from objects that differ from objects in their neighbourhood. Saliency signals are computed by contrasting values of visual features – the higher the contrast, the higher the saliency signal. The second step involves the summative integration of dimension-based saliency signals into an overall saliency (priority) representation that controls, or *guides*, the allocation of the focus of attention. Areas with high saliency activation (with high informational content) are sampled with priority by selective attention to make the information contained in these areas available for the higher order cognitive processes of object identification or object recognition. That is, according to GS, attention is guided to the location with the highest activation first.

Memory limitations are again no issue in GS. Explicit knowledge of the target-defining feature expedites selection by a mechanism of top-down excitation of features at the level of feature representations.

In a series of studies, Treisman (1988) and Maljkovic and Nakayama (1994, 1996, 2000) found that, in feature (pop-out) search tasks early processes can be primed. Pop-out search is a very easy type of search, where the target seems to 'pop out' of the display, hence the term pop-out search. Targets and distractors are defined in the same dimension, and the target differs from distractors in one conspicuous feature (e.g., a red apple among green apples). A flat search function relating number of display objects to search RTs is found in pop-out search, because observers are able to search all the display items in a parallel efficient fashion. Put differently, the search reaction time is independent of the number of display items (the set size).

According to Maljkovic and Nakayama (1994, 1996, 2000) the repetition of attention-driving features (e.g., colour) is able to prime, i.e., to further speed resulting in faster RTs, pop-out search – hence the term 'priming of pop-out'. In general, priming refers to the concept that there is an improvement in performance without any associated costs. In the case of pop-out search, when target features are repeated, reaction times are expedited compared to when they alternate across trials. Further, Maljkovic and Nakayama (2000) found a beneficial effect of a short-term implicit memory system for fast reaction times. Maljkovic and Nakayama interpreted their findings as arising at the level of feature processing.

In an examination of the effects of dimension changes on search reaction times, Müller, Heller and Ziegler (1995) and Found and Müller (1996), in search for singleton feature targets, found reaction time benefits when the target-defining dimension (and feature) remained the same in consecutive trials (repetition of the target-defining dimension). Further, they observed reaction time costs when the target-defining dimension changed across trials. Priming of pop-out (Maljkovic & Nakayama; 1994, 1996, 2000) cannot fully explain these effects. Therefore, Müller, Heller, and Ziegler (1995) developed a new account, referred to as the 'Dimension Weighting' (DW) account. Dimension-based processing accesses a limited processing weight (similar to Duncan & Humphreys' [1989, 1992] Attentional Engagement Theory) that is shared between the different visual dimensions. The assumption of a limited processing resource argues against automatic, unlimited early processing as suggested by Treisman and Gelade (1980). According to the DW model, several processing steps are involved in the generation of reaction time benefits in conditions, in which the target-defining dimension remains the same across consecutive trials. First, dimension-specific saliency signals are computed and integrated to form the sum of individual dimension-specific signals on the level of the master-map of saliency. The process of saliency generation is identical to the one proposed by the 'Guided Search' model (Wolfe, Cave & Franzel, 1989; Wolfe, 1994; Wolfe, 2007). The sum of saliency signals is weighted by limited attentional weight. The weight for the relevant dimension increases and, importantly, the weight setting established in a given trial persists into the next trial. If, in the current trial, the target is defined in the same dimension as in the previous trial, the activity in the master-map accumulates faster, because attentional weight is set optimally for that dimension. Consequently, RTs are expedited. Put differently, inter-trial facilitation is observed, if the target-defining dimension remains the same across trials. Reaction time costs are incurred, however, if the target-defining dimension changes across consecutive trials. The limited processing resource has to be shifted to a different dimension in a time-consuming fashion, entailing reaction time costs in trials in which the target-defining dimension changes across trials. Müller, Heller and Ziegler (1995) suggested that dimension-specific RT costs and benefits are explained by an implicit memory of the dimension in which the target is defined. The implicit memory trace either expedited (dimension repetition) or impedes processing (dimension change).

Müller, Heller and Ziegler (1995) concluded that early visual processing involving the generation of dimension-based saliency signals is subject to limitations in processing resources (attentional weight).

The ‘Theory of Visual Attention’ (Bundesen, 1990) assumes that a memory component modulates selection. What is the nature of visual short-term memory or visual working memory?

In a recent study, Hollingworth, Richard and Luck (2009) demonstrated that visual short-term memory (vSTM) plays an important role in controlling saccadic eye movements. Meaningful behaviour is only possible if the eyes can be directed to relevant objects. Often, the eye movements fail the relevant objects, however. The function of vSTM is to remember the features of the object the current saccade was aimed to in order to be able to rapidly reacquire the target object after a failure to direct the saccade to the target object.

Visual short-term memory is assumed to be one major bottleneck of information processing. According to Marois and Ivanoff (2005), the capacity limitation of the vSTM store is primarily localised to the posterior parietal and occipital cortex. Miller (1956) proposed that the capacity of short-term memory corresponds to the magical number seven (plus or minus two). Quite some time later, Cowan (2001) called into question the ‘seven (±2) items’ limitation and argued that the capacity is fixed to about four items. Irrespective of whether it is limited to a capacity of seven or four items, short-term memory capacity is assumed to be a relatively stable component.

In contrast to the assumption of a stable short-term memory capacity, however, recent research demonstrates that vSTM is highly variable.

Alvarez and Cavanagh (2004) assumed, on the basis of their results of a substantial variation in visual short-term memory capacity across five different stimulus classes (Snodgrass line drawings, shaded cubes, random polygons, Chinese characters, letters, and coloured squares) that the capacity of vSTM is probably set both by visual information load and by the number of objects presented. The higher the information load of the stimuli was, the fewer items could be stored. The upper bound on capacity lay at approximately four to five items.

Makovski and Jiang (2007) found that the robustness of vSTM can be influenced by whether attention is focused or distributed in vSTM. Sligte, Scholte and Lamme (2008) proposed not one vSTM with varying capacity but multiple visual short-term memory stores. Sligte et al. suggested one high-capacity, but fragile vSTM, which is overwritten when new items are presented and a traditional vSTM store with a limit at about four objects. Further, attention appears to be able to influence items already stored in visual memory (Matsukura, Luck, & Vecera, 2007). Attention can serve to protect vSTM representations while they are being maintained.

Visual short-term memory in Bundesens' TVA (1990) is a type of memory that needs to maintain elaborated visual information. As mentioned before, vSTM, according to TVA, emerges from active representations in long-term memory that compete for (simultaneous) representation in capacity-limited vSTM. Visual short-term memory is assumed to be a stable measure of the general information processing efficiency.

The following experiments attempt to contribute to the discussion of stable versus varying capacity of the visual short-term memory by testing the vSTM concept of Bundesen (1990) regarding bottom-up and top-down modulation capability. This goal is achieved by integrating inter-trial modulations of visual features (see Müller, Heller & Ziegler; 1995) with a procedure that allows for the parameterisation and estimation of memory capacity – Bundesen's (1990) TVA. The estimation of the TVA component functions of selective attention is implemented with the use of the experimental paradigms of whole and partial report (as originally proposed by Sperling, 1960, and adapted by Duncan et al., 1999). In the present studies, the partial and whole report methods were extended by inserting single and multiple feature changes to test whether components of selection are modulated by bottom-up variations in stimulus characteristics. Müller, Reimann and Krummenacher (2003) found in visual search tasks that dimensional changes or repetitions can also be influenced by top-down information such as semantic cues presented previous to every search trial. In order to test whether components of visual selection are modulated by top-down processes, a valid, invalid or neutral semantic cue was presented previous to every trial in the partial and whole report tasks.

The whole and partial report methods (originally proposed by Sperling, 1960) used in the present experiments are based on the adaptation by Duncan et al. (1999) and Peers et al. (2005). The methods were adapted for the purposes of the present experiments.

In the whole report task, observers are required to report as many as possible of the five stimuli (letters) that are presented; in the partial report task, they are instructed to only report stimuli (letters) that are characterised by (a) pre-defined target feature(s), stimuli not corresponding to the description are to be ignored.

The whole and partial report procedures allow for the estimation of the attentional components of the TVA, capacity of vSTM (K), overall processing speed (C), sensory effectiveness (A), top-down control (α, a measure of selection effectiveness), and attentional weight (w) attributed to a particular object relative to the other objects in a display.

5.1.3 **Experiment 1 – 4: Bottom-up Changes**

Investigation of effects of stimulus feature changes or repetitions on measures of component attention functions

Experiments 1 – 4 were conducted to investigate effects of changes, across consecutive trials (N-1 → N) in stimulus features in a single dimension (colour; Experiments 1 and 2) and in multiple dimensions (colour and form; Experiments 3 and 4) on the component functions of attention proposed in Bundesen’s (1990) TVA.

5.1.3.1 Method

5.1.3.1.1 Experiment 1 – Partial Report

Experiment 1 (partial report) was designed to investigate the effects of a variation of the featural definition of the visual objects (letters) across experimental trials. The colour of target items was repeated or changed, in a pseudo-random fashion, in consecutive trials.

The partial report procedure was employed to obtain estimates of the top-down control function (α), the attentional weight (w) assigned to a particular object compared to the other display objects, and sensory effectiveness (A) for target items that were defined, on trial N, by the same (feature repetition) or by a different feature (feature change) on the preceding trial N-1.

The target items, letters, were either red or green and non-targets were always blue. The observers' task was to report the identities of red or green letters and to ignore blue letters (in trials in which target and non-target items were presented). Experiment 1 comprised of a total of 600 trials.

Participants. Fourteen observers (four male, ten female) participated in Experiment 1, all of them students of the University of Fribourg. Participants' age ranged between 20 and 30 (M = 23.80 years; SD = 2.80 years). They received course credits or were paid CHF 10. All observers had normal or corrected-to-normal vision, including normal colour vision. They had no previous experience with the partial report method.

Apparatus. Participants were seated in a darkened room at a distance of approximately 50 cm from a 19 inch cathode ray tube (CRT) computer monitor (Philipps Brilliance P202) controlled by a HP Compaq personal computer (3.2 GHz Pentium processor, 512 Mb RAM). The monitor resolution was set to 1280 x 1024 pixels and run at a refresh rate of 100 Hz. The experiment was programmed in MatLab using the Cogent 2000 library (Cogent 2000, Functional Imaging Laboratory, Wellcome Department of Imaging Neuroscience, UCL, London). The observers' responses were entered into the computer by the examiner and saved for offline analysis.

Stimuli and timing. The display of Experiment 1 was based on the experimental setup introduced by Peers et al. (2005). Search displays consisted of three letters presented to the left or right of a central fixation point or of six letters presented both to the right and left of fixation. The arms of the fixation cross subtended 0.7° of visual angle in length and 0.7° in height. The letters of the search display were arranged in semi-circles centered 4° from the fixation cross with the middle letter on the horizontal meridian and the other two letters at angles of 50° above and below. All letters subtended an area of 0.6 x 0.5 degrees of visual angle and were either red, green or blue (non-targets). Letter presentation was followed by a mask (subtending 0.8° x 0.8° degrees of visual angle) composed of the letter 'x' and the '+' sign superimposed upon each other. Letters for a given trial were picked randomly, at the beginning of each trial, from the set of {BCDFGHJKLNPQRSTVXYZ} without replacement, i.e., each of the letters would appear only once in a given trial. Letters and masks were presented on a black background.

A trial started with the presentation of the fixation cross, after 500 ms the fixation cross was replaced by the three letters in the left or right hemi-field or six letters, three of which were presented in the left and the other three in the right hemi-field. Targets were presented very briefly for an exposure duration that was determined individually in a pre-test[4]. Due to visual persistence of the stimuli in the iconic memory in unmasked conditions (Sperling, 1960) and the resulting longer effective exposure durations of up to several hundred milliseconds, the letter presentations in every trial were followed by masks, presented for 200 ms to avoid effects of the iconic memory.

The masks appeared at each stimulus location and were composed of a square (0.9°) with the corners connected by the two diagonals and horizontal and vertical contour lines connected by vertical and horizontal lines drawn through the center of gravity. After the disappearance of the masks, the screen remained blank while the participant reported the seen letters. The letters were entered in the computer by the experimenter using the keyboard and saved for offline analysis. The keyboard was hidden from the observer so as not provide any visual cues (by the key legends). The names of the identified letters were given in any order and without emphasis on response speed. If the observer was certain that all the letters were named, observers prepared for the next trial that was initiated by the examiner.

Procedure. To determine exposure durations for each individual observer, a pretest was conducted immediately before the experiment. For equating the baseline performance across the different observers the aim of the pretest was to find the presentation time that

---

[4] An adaptive pretest period with a starting exposure duration of approximately 100ms was used to test whether a subject was able to reach an accuracy of 70 to 80% correctly reported letters for the report of three targets to the left or two the right of the fixation cross. If subjects performed outside this range, exposure durations were adjusted accordingly during the pretest. Exposure durations were extended to 150ms if performance was below 60%, to 130ms if below 70%. If subjects performance was above 90% exposure durations were shortened to 40ms and if between 80 and 90%, to 60ms. The pretest stopped automatically if on average performance reached the criterion for 24 consecutive trials.

yielded a criterion accuracy of between 70% and 80% correctly reported letters in the conditions in which three letters presented either in the left or the right hemi-field was met.

Experiment 1 consisted of one session that took approximately one hour to complete.

There were five display types. Search displays consisted of three target letters in the left (3Tl) or in the right (3Tr) hemi-field, three targets in the left and three non-targets in the right hemi-field (3Tl-3N), three targets in the right and three non-targets in the left hemi-field (3N-3Tr), or six target letters (6Tlr), three of which were presented in the left and three in the right hemi-field (see Figure 2 for examples).

Target letters were always either red or green, non-target letters were always blue.

For each of the five conditions, 30 sequences of trials in which the target colour was repeated (repetition trials) or changed (change trials) across consecutive trials were presented (see Figure 1). In total, Experiment 1 comprised of 600 trials, split in 10 blocks of 60 trials each.[5]

With respect to the entire experiment (but not individual blocks) an equal number of trials per condition were presented. The letters were presented for one presentation time that was determined for each individual observer in a pretest immediately before the experiment. Search letters were masked in all experimental trials.

The participants were requested to report the identity (name) of the (red or green) target letters they were quite sure to have identified and to ignore the (blue) non-targets.

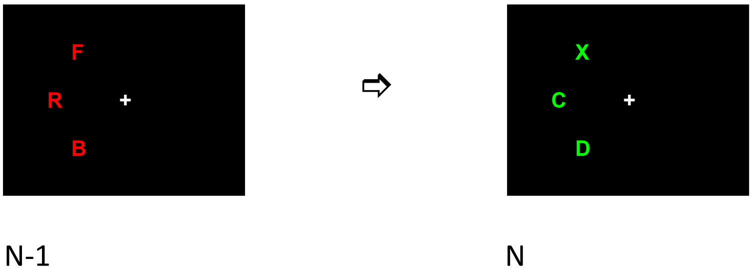


Figure 1. Example for the condition of colour change in pairs of consecutive trials (N-1→N).

---

[5] According to Finke et al. (2005), the minimum number of trials required for reliable parameter estimates is 18 trials (per condition).

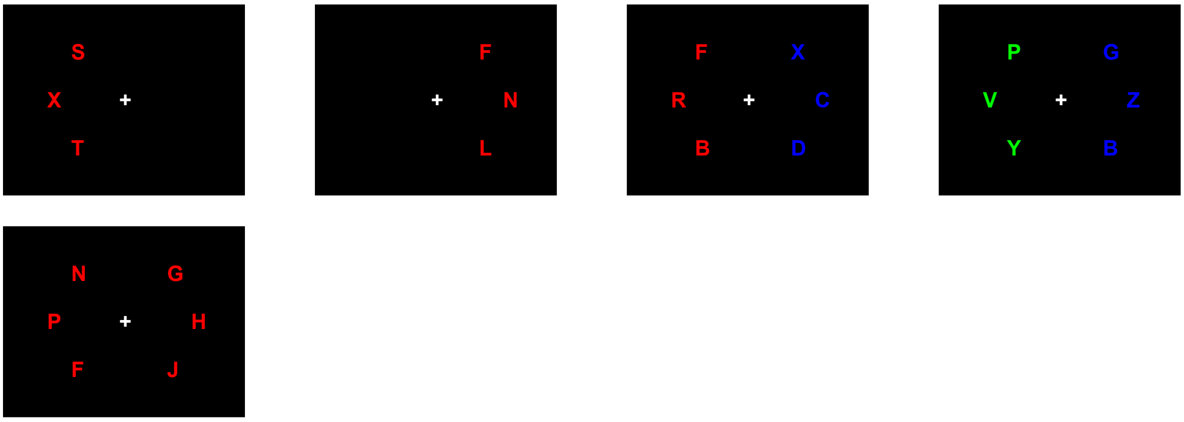


Figure 2. Different trial-types of the partial report experiment. Three targets in the left hemi-field or in the right hemi-field, three targets accompanied with three different coloured non-targets (in both hemi-fields) or six targets were presented.

5.1.3.1.2 Experiment 2 – Whole Report

The aim of Experiment 2 (whole report) was to examine effects of stimulus characteristics, namely feature changes versus repetitions across consecutive trials on visual short-term memory capacity (*K*) and processing speed (*C*). In Experiment 2 the colour of the search letters changed randomly across trials. The target letters were either red or green and the observers' task was to report the identity of all the red or green letters. The experiment consisted of 480 trials. The short-term memory (*K*) and processing speed (*C*) parameters were estimated based on subsets of the data set involving pairs of consecutive trials with colour repetition or colour change between the previous trial N-1 and the current trial N.

Participants. Twelve observers participated in Experiment 2 (four male, eight female), all of them students at Ludwig-Maximilian University of Munich. Their age ranged between 20 and 42 years (M = 25.5 years; SD = 5.9 years). They received course credits or were paid 8 €. All observers had normal or a corrected-to-normal vision, including normal colour vision. They had no previous experience with the whole report method.

Apparatus. Participants sat in a darkened room at a distance of approximately 50 cm from a Fuijitsu-Siemens Monitor VGA 15 inch Monitor controlled by a HP Compaq Business Ultra Slim Desktop Dc7600 personal computer (Pentium IV at 3.2 GHz, 512 Mb RAM). The monitor resolution was set at 1280 x 1024 Pixels and its refresh rate at 100 Hz. This experiment was programmed using the Cogent 2000 library (Cogent 2000, Functional Imaging Laboratory, Wellcome Department of Imaging Neuroscience, UCL, London).

The observers' responses were typed into the computer for later analysis by the experimenter.

Stimuli and timing. On the basis of the paradigm used by Peers et al. (2005) the display consisted of six letters with three letters on the left and three letters on the right side of the central fixation cross (0.7° x 0.7°). They were arranged in two semi-circles centered 4° from the fixation cross with the middle letter on the horizontal meridian and the other two letters at angles of 50° above and below. All letters had a size of 0.6 x 0.5 degree of visual angle and were either red or green. Half of the trials were followed by masks (0.8° x 0.8°), composed of an x and + one upon each other. The letters were picked randomly from the set of {BCDFGHJKLNPQRSTVXYZ} with the same letter appearing only once. All letters and masks were presented on a black background.

A trial started with the fixation cross for 500 ms which was replaced by the six target letters in the left and in the right hemi-field (see Figure 3).

Due to visual persistence of the stimuli in the iconic memory in unmasked conditions (Sperling, 1960) and this resulting in longer effective exposure durations of the letters for several hundred milliseconds, the letter presentations were in half of the trials followed by masks (for 200ms), and in the other half not. Masks should terminate the after-image of the letters and were composed of a square (0.9°) filled with an x and +, one upon each other. After the letters or masks disappeared, the screen was blanked and remained blank until all the responses of the participant were recorded. Letter names were reported verbally, in any order by the participant and entered into the computer by the examiner through the keyboard. The keyboard was hidden from the observer so as not provide any visual cues (by the key legends). After the participant was certain to have reported all the letter identities and was ready to carry on, the next trial was started by the examiner.

Procedure. Experiment 2 consisted of one session taking approximately one hour to complete. A total of 480 trials, split in ten blocks of 48 trials were presented. Estimation of the *K* and *C* parameters requires different exposure durations for the search display presentations, and further, performance measures of masked and unmasked conditions (see Kyllingsbæk, 2006, for details of the estimation procedure). That is, observers were presented with six different search displays: unmasked or masked and presented for short, medium and long exposure durations.

As parameters were analysed dependent upon the intertrial transition condition (colour repetition vs. colour change across consecutive experimental trials), for each display type 20 pairs of trials were defined to ensure reliable parameter estimates.[6] Pre-defined trial pairs were presented in random order across the entire experiment. That is, appearance of types of trials and feature (colour) repetition or change trials was equiprobable across the experiment, but not within blocks. (None of the observers was aware of the pre-defined trial sequences.)

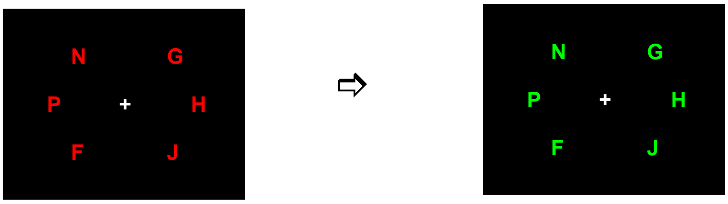
Individual exposure durations were determined in a pretest run immediately before the experiment. The pretest was aimed at determining the exposure duration for which criterion accuracy between 20 and 30% was met.[7] The resulting exposure time corresponds to the medium presentation time for masked search display; the short and long exposure durations correspond respectively to half and double the medium presentation time. In half of the trials, the search stimuli were masked, in the other half, they remained unmasked. The resulting six effective exposure durations are chosen as to reveal a broad spectrum reflecting both efficient and inefficient performances of a given participant in the whole report task (Finke et al., 2005). Exposure durations ranged between 22 and 316 (M = 108.05; SD = 76.93) (individual exposure times are given in Table 7). An equal number of trials for the six conditions (three exposure durations and unmasked vs. masked displays) was presented.

The participants were instructed to report the identity of those display letters they were certain to have identified. Letters could be reported in any sequence.

---

[6] According to Finke et al. (2005), the minimum number of trials required for reliable parameter estimates is 16 trials (per condition).

[7] An adaptive pretest period with starting exposure duration of approximately 100 ms was used to test whether a subject was able to reach an accuracy of 20 to 30% correctly reported letters for the report of six targets, three to the left and three to the right of the fixation cross. If subjects performed outside this range, exposure durations were adjusted accordingly during the pretest. Exposure durations were extended to 150ms if performance was below 10%, to 130 ms if below 20%. If subjects performance was above 40% exposure durations were shortened to 40 ms and if between 30 and 40%, to 60 ms. The pretest stopped automatically if on average performance reached the criterion for 24 consecutive trials.



N-1 N

Figure 3. Example of the whole report experiment for the condition in which the feature (colour) in pairs of consecutive trials (N-1 ⟶ N) changed. Presented were six target letters (three in the left and three in the right hemi-field).

5.1.3.1.3 Experiment 3 (a,b,c) – Partial Report

Experiments were designed to investigate whether repetitions and changes of visual dimensions and features across consecutive experimental trials (N-1 ⟶ N) affect parameters of the TVA (possible inter-trial transitions can be seen in Table 1). Search stimuli were letters defined on the dimensions colour (red or green) and form (uppercase or lowercase). Three types of intertrial transitions were examined in Experiments 3 and 4. In feature repetition trials, the features defining the search items remain identical across consecutive trials (e.g., N-1: red, uppercase, N: red, uppercase); in one-dimension change trials, the feature of one dimension changes whereas the feature of the other dimension remains the same (e.g., N-1; red, uppercase, N: green, uppercase [colour change] or red, lowercase [form change]); and in two-dimension change trials, the features of both dimensions change (e.g., N-1: red, uppercase; N: green, lowercase).

Table 1. Possible intertrial transition conditions of Experiment 3 and 4.

		Intertrial transition			
Feature Repetition		1-Dim Change		2-Dim Change	
N-1	N	N-1	N	N-1	N
red, low	red, low	red, low	green, low	red, low	green, up
green, low	green, low	red, up	green, up	red, up	green, low
red, up	red, up	green, low	red, low	green, low	red, up
green, up	green, up	green, up	red, up	green, up	red, low

Experiment 3a - Partial report with repetition of target positions

Experiment 3a (partial report) was designed to examine the effects of single and multiple feature repetitions versus changes on processes of top-down control (α, efficiency of resource allocation to targets versus non-targets), attentional weight (w) attributed to a given display object compared to the other objects, and sensory effectiveness (A).

The target letters were either red or green (colour) and either uppercase or lowercase (form), the non-targets always blue (either lowercase or uppercase). The observers were instructed to report the identity of the red or green letters and to ignore blue letters (if blue non-target letters appeared together with red or green target letters). In Experiment 3a, the presentation location (hemi-field) of target and non-target letters (in trials with non-targets) remained the same across consecutive trials in order to avoid potential confounds in the dependent measures by location changes. Experiment 3a comprised of a total of 720 trials.

Participants. Ten observers (two female, eight male) participated in Experiment 3a, all of them students at the University of Fribourg. Their age ranged between 20 and 26 years (M = 21.7 years; SD = 1.9 years). They received course credits or were paid 10 CHF. All observers had normal or a corrected-to-normal vision, including normal colour vision. They had no previous experience with the partial report method.

Apparatus. Participants sat in a darkened room at a distance of approximately 50 cm from a Philipps Brilliance P202 19 inch monitor controlled by a HP Compaq Business Ultra Slim Desktop Dc7600 personal computer (Pentium IV at 3.2 GHz, 512 Mb RAM). The monitor resolution was set at 1280 x 1024 Pixels and its refresh rate at 100 Hz. This experiment was programmed using the Cogent 2000 library (Cogent 2000, Functional Imaging Laboratory, Wellcome Department of Imaging Neuroscience, UCL, London).

The observers' responses were typed into the keyboard by the examiner.

Stimuli and timing. Stimuli and timing were exactly the same as in Experiment 1.

Procedure. Individual exposure durations were determined in a pretest run immediately before the experiment. As uppercase and lowercase letters were presented in the experiment, it was ensured that performance for both letter types was approximately on the same level. To adjust recognition performance for lowercase and uppercase letters, the following two-step pre-test procedure was employed individually for each participant. In the first step of the pre-test, isoluminantly coloured letters were presented; using a step procedure, the saturation of the colours of the lowercase letters was increased until recognition performance for lowercase letters was in the same range as for uppercase letters.[8] In the second step of the pre-test procedure, the exposure duration yielding the criterion accuracy of between 60 and 70 % in the condition with three letters (presented in the left or right hemi-field) was determined.

Experiment 3a consisted of one session taking about one and a half hours to complete. A total of 720 trials, split in 12 blocks of 60 trials, were presented.

There were five different types of search displays. The display consisted either of three target letters in the left (3Tl), three target letters in the right hemi-field (3Tr), three targets in the left hemi-field together with three non-targets in the right hemi-field (3Tl-3N), three targets in the right and three non-targets in the left hemi-field (3N-3Tr), or six target letters (6Tlr; three in the left and three in the right hemi-field). (See Figure 2 for examples.)

In order to ensure reliable parameter estimates, pairs of trials were defined for the three intertrial transition conditions (feature-repetition, one-dimension change, two-dimension change) and each of the five display types. Each of the resulting 15 intertrial transition conditions was repeated 48 times (24 pairs).

---

[8] As lowercase letters contain fewer strokes than uppercase letters, the fewer pixels are required to display lowercase than uppercase letters on the monitor. Consequently, the signal intensity is smaller for lowercase than for uppercase letters.

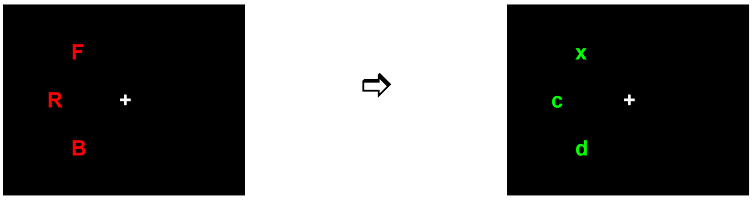
Table 2. Intertrial transition conditions of Experiment 3a.

	Intertrial Transition			
	Feat. Repetition	1-Dim Change	2-Dim Change	
Display				
3Tl	6	6	6	
	6	6	6	
	6	6	6	
	6	6	6	
	24	24	24	
3Tr	6	6	6	
	6	6	6	
	6	6	6	
	6	6	6	
	24	24	24	
3Tl-3N	6	6	6	
	6	6	6	
	6	6	6	
	6	6	6	
	24	24	24	
3N-3Tr	6	6	6	
	6	6	6	
	6	6	6	
	6	6	6	
	24	24	24	
6Tlr	6	6	6	
	6	6	6	
	6	6	6	
	6	6	6	
	24	24	24	
	120	120	120	360

Experiment 3a was designed to examine recognition performance in pairs of consecutive trials for the three intertrial transitions (Example Figure 4) while precluding confounding effects of location changes, particularly negative priming effects in conditions in which target and non-target hemi-fields changed across trials; the location (left vs. right hemi-field) remained the same across consecutive trials (see Table 2 for all possible inter-trial transitions). Note that this restriction only applies to intertrial transitions that were predefined before the experiment, randomly interspersing predefined pairs of trials involves hemi-field changes. As comparable numbers of accidentally resulting location repetitions and changes are expected to occur, effects of target location changes are expected to be cancelled out.

The target letters in Experiment 3a were presented for the presentation time determined in individual pretest immediately before the main experiment. Search items were masked in all trials.

The participants were instructed to report the identities of (green or red) target letters they were certain to have identified and to ignore (blue) non-target letters.



N-1 N

Figure 4. Example for the condition different dimension and different feature (colour and form) in pairs of consecutive trials (N-1→N).

Experiment 3b - Partial report with randomly changing target position

Experiment 3b (partial report) was designed to examine effects of repetitions or changes in stimulus features on the parameters *α* (allocation to targets versus non-targets), *w* (attentional weight to an object in the display compared to the other objects), and *A* (sensory effectiveness), in pairs of consecutive trials.

As in Experiment 3a, targets were either red or green (dimension colour) and uppercase or lowercase (dimension form), non-targets were always blue (lowercase or uppercase). Observers were instructed to report the identity of the red or green target letters and to always ignore the blue non-target letters (if non-targets appeared together with targets). In contrast to Experiment 3a, in Experiment 3b, the locations of targets (and non-targets) in consecutive trials changed randomly (or remained the same) in order to control for effects of implicit top-down knowledge and to investigate potential explanations for the result of Experiment 3a that had shown that top-down control was better in all conditions, in the second compared to the first trial in consecutive trials. Experiment 3b consisted of a total of 720 trials.

Participants. Twelve observers (eleven female, one male) participated in Experiment 3b, all of them students of the University of Fribourg. Their age ranged between 19 and 26 years (M = 21.3 years; SD = 2.1 years). Participants received course credits or were paid 10 CHF. All observers had normal or a corrected-to-normal vision, including normal colour vision. They had no previous experience with the partial report method.

Apparatus. The apparatus of Experiment 3b was the same as in Experiment 3a.

Stimuli and timing. Stimuli and timing were exactly the same as in Experiment 3a.

Procedure. The procedure of Experiment 3b was exactly the same as in Experiment 3b, with the exception that locations (hemi-fields) of targets and non-targets were selected randomly, i.e., without any restrictions.

Experiment 3c - Partial report with target locations predictably changing across trials

Experiment 3c (partial report) was designed to examine effects of repetitions or changes in stimulus features changes or no changes in the parameters top-down control (α), attentional weight (w) to an object in the display compared to the other objects, and sensory effectiveness (A) in pairs of consecutive trials in which the dimension and feature stay the same or change were of interest.

The targets were either red or green and uppercase or lowercase, non-targets were always blue (lowercase or uppercase). Observers were instructed to report the identities of the red or green target letters and to ignore blue non-target letters (if blue non-target letters were presented together with target letters). The location (hemi-field) of the target letters in consecutive trials, changed from left to right or right to left in a predictable way. The manipulation was introduced to examine whether explicit top-down knowledge about the target location generates performance advantages. Experiment 3c comprised of 720 trials.

Participants. Thirteen observers (two male, eleven female) participated in Experiment 3c, all of them students of the University of Fribourg with ages ranging from 19 to 21 years (M = 20.0 years; SD = 0.9 years). Participants received course credits or were paid CHF 10. All observers had normal or a corrected-to-normal vision, including normal colour vision. They had no previous experience with the partial or whole report methods.

Apparatus. The apparatus of Experiment 3c was exactly the same as in Experiments 3a and 3b.

Stimuli and timing. Stimuli and timing were exactly the same as in the Experiments 3a and 3b.

Procedure. The procedure of Experiment 3c was exactly the same as in the Experiments 3a and 3b, with the exception that consecutive pairs of trials of the condition with three targets combined with three non-targets appeared always in opposite hemi-fields.

5.1.3.1.4 Experiment 4 – Whole Report

Experiment 4 (whole report) was designed to examine the effects of feature repetitions and changes in the letter stimuli on processing speed (*C)* and visual short-term memory capacity (*K)*.

The targets were either red or green and uppercase or lowercase. Observers' task was to report the identities of the red or green letters (only target letters were presented). Experiment 4 consisted of a total of 1152 trials and recognition performance for subsets of trials N was analysed dependent on the featural definition of the search items in the preceding trials N-1. Three types of intertrial transitions were examined. In feature repetition trials, the colour (red, green) and form (lowercase, uppercase) of the search stimuli was the same as in the previous trial; in one-dimension change trials, the feature of one of the defining dimensions changed while the other remained the same; and in two-dimension change trials, the features of both dimensions changed.

Participants. Nine observers (four female, five male) participated in Experiment 4, all of them students of the University of Fribourg with ages ranging from 20 to 27 years (M = 23.1 years; SD = 2.2 years). Participants received course credits or were paid CHF 10. All observers had normal or a corrected-to-normal vision, including normal colour vision. They had no previous experience with the whole report method.

Apparatus. The apparatus was exactly the same as in Experiment 3.

Stimuli and timing. The experimental setup was based on the procedure introduced by Duncan et al. (1999). The search display consisted of five letters presented either in the left or right hemi-field relative to a central fixation cross (0.7° x 0.7°). Unlike in Duncan et al.'s (1999) study, stimuli were positioned in a semi-circular arrangement with each item location equidistant (4.9 degrees of visual angle) from the central fixation position. The distance between all of the search items was identical (36° of visual angle). All letters subtended an area of 0.6 x 0.5 degrees of visual angle and were either red or green (isoluminant at 1.6 cd/m^2) in either uppercase or lowercase. Letters were presented on a black background. The letters were picked randomly from the set of {BCDFGHJKLNPQRSTVXYZ} without replacement (i.e., each letter was presented once per trial).

A trial started with the onset of the fixation cross, after 500 ms fixation was replaced by the display of five target letters, presented either in the left or right hemi-field. The targets were presented very briefly for three different exposure durations. Exposure times were determined individually for each observer in a pretest conducted before the experiment. To avoid visual persistence of the stimuli in iconic memory and the resulting longer effective exposure durations of up to several hundred milliseconds (Sperling, 1960), presentation of letters was followed by masks (presented for 200ms) in half of the experimental trials, in the other half of the trials the display remained unmasked. After the letters or masks had disappeared, the screen remained blank (black) while the observer reported the identified letters, which were entered and saved on the computer by the experimenter. Letter names were reported verbally, in any order by the participant and entered into the computer by the examiner using the keyboard. The keyboard was hidden from the observer so as not provide any visual cues (by the key legends). After the participant was certain to have reported all the letter identities and was ready to carry on, the next trial was started by the examiner.

Procedure. Experiment 4 was run in two separate sessions, each of which took about one hour to complete. A total of 1152 trials were presented, one session comprised of eight blocks of 72 trials (making for 576 trials per session).

A pretest was run to determine individual exposure durations. The presentation time yielding the criterion accuracy of 20-30% was determined in a step procedure. The resulting presentation time corresponds to the medium presentation time of Experiment 4.

The five letters were presented either in the left or in the right hemi-field with an equal number of left- and right-hemi-field trials with respect to the entire experiment (see Figure 5 for examples). Search displays were presented for three different presentation times. In the pretest the medium presentation time was determined (corresponding to a criterion accuracy of 20-30%). Short and long presentation times correspond to half and double, respectively, the medium duration. Search displays were masked in half of the trials; they remained unmasked in the other half of trials. The resulting six effective exposure durations cover a broad range of performance, tracking early and late parts of the exposure duration function (Finke et al., 2005).

The trial number was chosen so as to ascertain a minimum of 16 trials[9] for each of the different experimental conditions (2 hemi-fields x 3 exposure durations x 2 masking conditions) and the three different manipulations (feature repetition, one-dimension change, two-dimension change; see Figure 5 for examples). The combinations of conditions and intertrial transitions yield 36 different trial types (2 hemi-fields x 3 exposure durations x 2 masking conditions x 3 manipulations). Each of the trial types was repeated 32 times (16 pairs for each type).

The participants were instructed to report the identity of those letters they were certain to have identified.

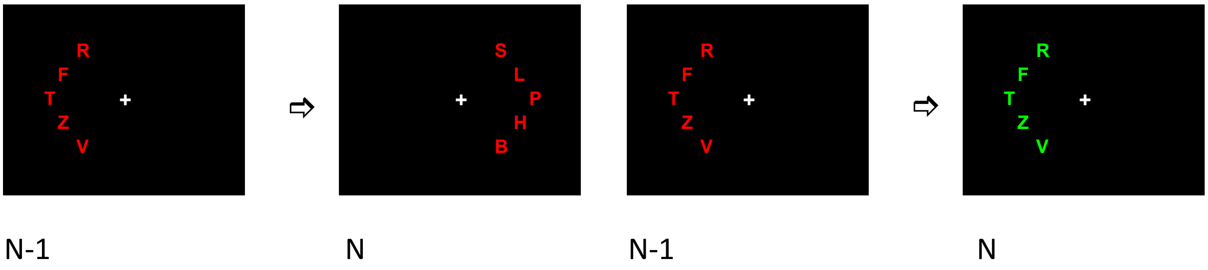


Figure 5. Different trial-types of the whole report experiment. Five targets in the left hemi-field or in the right hemi-field were presented. Examples for the conditions same dimension and same feature and same dimension and different feature in pairs of consecutive trials (N-1 ⟶ N) are shown.

---

[9] According to Finke et al. (2005), the minimum number of trials required for reliable parameter estimates is 16 trials (per condition).

5.1.3.2 Results

In this section, the results of Experiments 1 and 2, in which bottom-up feature changes were induced, are reported. In Experiment 1 and 2 the effects of changes or no changes in target feature were analysed for pairs of consecutive trials. The parameters reflecting the different attentional components of the TVA were estimated using the estimation software by Kyllingsbæk (2006).

5.1.3.2.1 Experiment 1 – Partial Report

Exposure durations varied within a range of 22 and 316 ms, with a median duration of 98.5 ms (individual exposure durations for the participants of Experiment 1 are given in Table 5). Exposure durations did not correlate with participants' age ($r = -.09$; $p = .76$).

The partial report procedure allows for the estimation of three parameters reflecting performance of the component attentional functions of lateralised sensory effectiveness (A), object-related distribution of attentional weight (w) and the top-down control (α) (see Table 3 and 4 for all parameter values).

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of feature repetitions or changes across trials).

Lateralised sensory effectiveness is based on perception accuracy at each stimulus location and computed by weighting accuracy values of targets presented in the left hemi-field to the accuracy of left hemi-field and right hemi-field targets according to $A = A_l / (A_l + A_r)$. Equal distributions of sensory effectiveness over the left and right hemi-fields yield a value of $A = .5$, values larger or smaller than .5 indicate improved effectiveness in the left and right hemi-fields, respectively.

Mean lateralised sensory effectiveness in Experiment 1 was at .45 (SD = .05). That is, processes of sensory perception were significantly more efficient for targets presented in the right hemi-field as revealed by a t-test ($t(13) = -3.18$; $p < .01$) comparing A values of Experiment 1 with the predicted equal distribution of .5.

In the partial report task used in Experiment 1, observers are instructed to report target items and to ignore non-target items. To perform the task efficiently, observers need to allocate processing resources to the items the relevant feature of which corresponds to the target category; that is, target items should receive more attentional weight than non-target items. Estimates of attentional weight allocated to targets or non-target items at the different display locations can be derived using a maximum likelihood fitting procedure (Kyllingsbaek, 2006).

The lateralised weight parameter w_λ indicates whether attentional weight attributed to objects is distributed evenly across the visual field (lateralised weights are space-based, i.e., averaged across target and non-target objects). Lateralised weights are calculated according to $w_\lambda = w_L / (w_{L\,+}\, w_R\,)$. Even distribution of weights is reflected by $w_\lambda = .5$; values below and above .5 reflect greater weight (attentional bias) in the right and left hemi-fields, respectively.

Average distribution of attentional weights, $w_\lambda = .43$ (SD = .08), in Experiment 1 is significantly biased to the right hemi-field as revealed by a t-test ($t(13) = -3.19$; $p = .007$) comparing observed ($w_\lambda = .43$) to predicted w_λ values (around .5).

Top-down control indicates whether attentional resources are allocated to target objects or non-target objects, independent of their display locations. Top-down control is defined as the ratio of weight attributed to target and non-target objects $\alpha = (w_D / w_T)$, that is, the lower the value of α the more weight is attributed to targets, i.e., the more efficient top-down control of the selection process is.

In Experiment 1, the average of the top-down control parameter was .72 (SD = .38). That is, overall, observers were able to efficiently select target and deselect non-target items. A t-test of α values revealed that they were significantly different from 1 ($t(13) = -2.76$; $p = .02$), the value corresponding to the equal weight attributed to target and non-target items.

In the second analysis step, potential effects of the experimental manipulation, feature repetitions and feature changes, were analysed for the first and second trial of sequences of two consecutive trials.

All trial pairs for each of the five conditions were analysed for each observer. The spatial distribution of attentional weights (laterality index w_λ) and the spatial distribution of sensory effectiveness (A_λ) did not differ significantly in pairs of consecutive trials (N-1→N) where the feature stayed the same or changed.

Sensory effectiveness (A_λ) in the feature repetition condition was for the first trial on average at .45 (SD = .10), and for the second trial at .49 (SD = .07); in the feature change condition, parameter A_λ revealed in the first trial values at .44 (SD = .06) and for the second trial at .43 (SD = .11).

The spatial distribution of the attentional weights (w_λ) was in the feature repetition condition for the first trial on average at .45 (SD = .16), and for the second trial at .42 (SD = .12); in the feature change condition parameter w_λ was for the first trial at .42 (SD = .11) and for the second trial at .43 (SD = .16).

Top-down control (α) revealed for the feature repetition condition for the first trial on average at .74 (SD = .54) and for the second trial at .52 (SD = .39); in the feature change condition parameter α was for the first trial at .67 (SD = .33) and for the second trial at .51 (SD = .59). The analysis of all pairs of trials in which the target feature was repeated revealed significantly better values of the top-down control (α) (paired-samples t-tests: $t(13) = 1.78$; $p = .098$), i.e., a tendency for a facilitated selection ability if the feature stays the same.

Table 3. Values of parameter A_λ and w_λ for all subjects of Experiment 1.

A_λ

Participant	Feature Repetition		Feature Change	
	1. value	2. value	1. value	2. value
1	0.57	0.50	0.47	0.45
2	0.42	0.43	0.43	0.39
3	0.38	0.42	0.44	0.42
4	0.40	0.46	0.44	0.43
5	0.45	0.48	0.44	0.48
6	0.51	0.56	0.56	0.56
7	0.33	0.53	0.51	0.58
8	0.41	0.62	0.33	0.47
9	0.42	0.47	0.49	0.51
10	0.59	0.51	0.46	0.41
11	0.42	0.43	0.41	0.46
12	0.66	0.57	0.31	0.18
13	0.31	0.36	0.41	0.26
14	0.36	0.50	0.44	0.38

wλ

Participant	Feature Repetition		Feature Change	
	1. value	2. value	1. value	2. value
1	0.32	0.50	0.48	0.45
2	0.46	0.42	0.34	0.33
3	0.45	0.46	0.36	0.42
4	0.46	0.40	0.41	0.44
5	0.54	0.38	0.40	0.62
6	0.51	0.53	0.41	0.59
7	0.59	0.38	0.39	0.36
8	0.43	0.32	0.59	0.30
9	0.56	0.54	0.50	0.45
10	0.21	0.18	0.38	0.18
11	0.23	0.31	0.23	0.14
12	0.19	0.49	0.64	0.70
13	0.69	0.64	0.31	0.60
14	0.61	0.36	0.42	0.47

Table 4. Values of parameter *α* for all subjects of Experiment 1.

α Participant	Feature Repetition 1. value	 2. value	Feature Change 1. value	 2. value
1	0.53	0.57	0.66	0.51
2	0.42	0.64	0.39	0.20
3	0.61	0.50	0.63	0.36
4	0.56	0.26	0.63	0.32
5	0.65	0.35	0.78	0.55
6	2.21	1.20	1.07	2.40
7	0.45	0.52	0.35	0.33
8	0.89	0.33	1.23	0.56
9	1.08	1.17	1.26	0.69
10	0.23	0.01	0.66	0.00
11	0.54	1.09	0.39	0.15
12	1.40	0.14	0.15	0.05
13	0.10	0.06	0.67	0.33
14	0.73	0.39	0.44	0.68

Table 5. Exposure durations (in ms) for all subjects in the partial report Experiment 1.

Participant	Exposure duration [ms]
1	60
2	22
3	26
4	100
5	128
6	100
7	100
8	165
9	48
10	316
11	71.8
12	83
13	196
14	96.9

5.1.3.2.2 Experiment 2 – Whole Report

Mean masked exposure durations varied within a range of 13 and 100 ms with a medium duration of 72.21ms (SD = 34.33). The three different individual exposure durations for each subject of Experiment 2 are given in Table 7. Exposure durations did not correlate with participants' age (r = 15; *p* = .64).

The whole report procedure allows for the estimation of three parameters reflecting performance of the component attentional functions of the vSTM capacity (*K*), the processing speed (*C*) and the detection threshold (t_0) (see all parameter values in Table 6).

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of feature repetitions or changes across trials).

The capacity of vSTM is reflecting the total number of elements processed simultaneously, i.e., the maximum number of letters reported on any single trial at any exposure duration. The vSTM is assumed to be a stable measure of the general information processing efficiency. For any value of targets bigger than four, performance reaches an asymptote of about 3 to 4 elements reported (Sperling, 1967). Average values of the capacity of vSTM in Experiment 2 are at 2.60 elements (SD = .61).

The overall processing speed is a measure of identification rate in elements per second. *C* is constant across variations in number of elements and their attentional weights. The total processing capacity is shared out among different elements and computed by the sum of the individual speeds for each element in the display. Average values of the overall processing speed in Experiment 2 are at 37.06 elements per second (SD = 27.79).

The detection threshold reflects the time it takes for each subject to perceive an element in the display. Average values of the detection threshold in Experiment 2 are at 14.10 ms (SD = 36.00 ms).

In the second analysis step, potential effects of the experimental manipulation, feature repetitions and feature changes, were analysed for the first and second trial of sequences of two consecutive trials. A total number of 20 trial pairs for each condition were analysed for each observer. The processing speed (parameter *C*) did not differ significantly in pairs of consecutive trials (N-1 → N) where the feature stayed the same or changed. In feature repetition trials, the processing speed for the first trial was on average at 37.98 (SD = 29.63), for the second trial at 39.64 (SD = 31.09); in the feature change condition, parameter *C* revealed in the first trial values at 36.99 (SD = 28.77) and for the second trial values at 37.55 (SD = 25.86).

The analysis of all pairs of trials in which the target feature was repeated revealed significantly higher values of the capacity of vSTM (*K)* (*t*(11)= -2.57; *p* = .026 [two-tailed]) in the second trial of consecutive trials. The values for the vSTM capacity for feature repetition trials were in the first trial on average at 3.81 (SD = .70), for the second trial at 4.12 (SD = .68). In pairs of trials with changes in target feature no significant difference could be found. The values for the vSTM capacity for feature change trials were in the first trial on average at 3.79 (SD = .59), for the second trial at 3.92 (SD = .64).

In pairs of trials with changes in target feature, a tendency for a higher detection threshold (*t0*) values (*t*(11) = -2.00; *p* = .07 [two-tailed]) was found in the second trials of consecutive pairs, implicating a higher detection threshold through feature changes. The values for the detection threshold for feature change trials were in the first trial on average at 6.21 (SD = 14.51), for the second trial at 48.93 (SD = 78.96). If the feature stayed the same, no significant difference could be observed. The values for the detection threshold were in the first trial on average at 16.43 (SD = 42.95), for the second trial at 36.44 (SD = 72.57).

Table 6. Values of parameter *K* and *C* for all subjects of Experiment 2.

K

Participant	Feature Repetition		Feature Change	
	1. value	2. value	1. value	2. value
1	3.79	3.50	3.82	3.91
2	3.83	4.47	3.79	4.00
3	2.49	2.80	2.61	2.61
4	3.00	3.86	3.49	3.65
5	4.90	4.94	4.85	4.82
6	3.46	3.53	3.43	3.46
7	3.72	3.72	3.44	3.84
8	4.82	4.94	4.72	4.95
9	3.72	4.39	3.73	3.71
10	4.49	4.33	3.73	4.61
11	3.52	3.90	3.82	3.64
12	3.98	5.00	4.00	3.88

C

Participant	Feature Repetition		Feature Change	
	1. value	2. value	1. value	2. value
1	105.33	106.84	87.17	89.85
2	58.67	50.71	53.40	56.43
3	15.50	14.37	14.37	18.08
4	12.45	13.63	12.22	12.31
5	30.75	31.91	32.40	30.82
6	13.27	13.57	14.21	13.35
7	14.51	16.09	14.87	13.20
8	59.83	58.00	65.30	57.12
9	19.00	25.76	18.55	24.74
10	73.01	89.70	87.63	73.28
11	28.21	22.10	20.74	23.45
12	25.17	33.04	23.01	37.92

Table 7. The three exposure durations (in ms) for all subjects of Experiment 2.

Participant	time 1	time 2	time 3
1	7	13	26
2	11	21.5	43
3	50	100	200
4	50	100	200
5	40	80	160
6	50	100	200
7	50	100	200
8	19	38	76
9	40	80	160
10	19	38	76
11	50	100	200
12	48	96	192

5.1.3.2.3 Experiment 3 (a, b, c) – Partial Report

The results for all three partial report experiments (3a, b, c) and the results of the whole report Experiment 4 were reported. In Experiment 3 (a, b, c) and Experiment 4 dimensional changes were induced.

For all four experiments we analysed effects of feature repetitions, 1-dimensional changes and 2-dimensional changes for pairs of consecutive trials (N-1 $\rightarrow$ N).

Experiment 3a - Partial report with repetition of target positions

Exposure durations varied within a range of 84.40 ms and 230.40 ms with a medium duration of 147.08 ms (SD = 47.35 ms). Individual exposure durations for the participants of Experiment 3a are given in Table 17. Exposure durations did not correlate with participants' age (r = -.04; *p* = .91).

The partial report procedure allows for the estimation of three parameters reflecting performance of the component attentional functions of lateralised sensory effectiveness (*A*), object-related distribution of attentional weight (*w*) and the top-down control (α) (see all parameter values in Tables 8 - 10).

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of feature repetitions, 1-dimensional or 2-dimensional changes across trials).

Lateralised sensory effectiveness is based on perception accuracy at each stimulus location and computed by weighting accuracy values of targets presented in the left hemi-field to the accuracy of left hemi-field and right hemi-field targets according to $A = A_l / (A_l + A_r)$. Equal distributions of sensory effectiveness over the left and right hemi-fields yield a value of $A = .5$, values larger or smaller than .5 indicate improved effectiveness in the left and right hemi-field, respectively.

Mean lateralised sensory effectiveness in Experiment 3a was at .45 (SD = .07). That is, processes of sensory perception were significantly more efficient for targets presented in the right hemi-field as revealed by a t-test ($t(9) = -2.38$; $p = .04$) comparing A values of Experiment 3a with the predicted equal distribution of .5.

The lateralised weight parameter w_λ indicates whether attentional weight attributed to objects is distributed evenly across the visual field (lateralised weights are space-based, i.e., averaged across target and non-target objects). Lateralised weights are calculated according to $w_\lambda = w_L / (w_{L +} w_R)$. Even distribution of weights is reflected by $w_\lambda = .5$; values below and above .5 reflect greater weight (attentional bias) in the right and left hemi-fields, respectively.

Average distribution of attentional weights, $w_\lambda = .51$ (SD = .15), in Experiment 3a are unbiased to any hemi-field as revealed by a t-test ($t(9) = .18$; $p = .86$) comparing observed to predicted w_λ values ($w_\lambda = .5$).

Top-down control indicates whether attentional resources are allocated to target objects or non-target objects, independent of their display locations. Top-down control is defined as the ratio of weight attributed to target and non-target objects $\alpha = (w_D / w_T)$, that is, the lower the value of α the more weight is attributed to targets, i.e., the more efficient top-down control of the selection process is.

In Experiment 3a, the average of the top-down control parameter was $\alpha = .40$ (SD = .21). That is, overall, observers were able to efficiently select target and deselect non-target items. A t-test of α values revealed that they were significantly different from 1 ($t(9) = -9.12$; $p < .001$), the value corresponding to the equal weight attributed to target and non-target items.

In the second analysis step, potential effects of the experimental manipulation, feature repetitions, 1-dimensional changes and 2-dimensional changes, were analysed for the first and second trial of sequences of two consecutive trials.

A total number of 24 trial pairs for each condition was analysed for each observer. The spatial distribution of sensory effectiveness (A_λ) did not differ significantly in pairs of consecutive trials (N-1→N) weather or not the feature was repeated, 1- or 2-dimensional changes took place. Sensory effectiveness (A_λ) in the feature repetition condition was for the first trial on average at .42 (SD = .11), for the second trial at .46 (SD = .11); in the 1-dimensional change condition, parameter A_λ revealed in the first trial values at .43 (SD = .09) and for the second trial at .42 (SD = .08); in the 2-dimensional change condition, parameter A_λ revealed in the first trial values at .43 (SD = .10) and for the second trial at .46 (SD = .11).

The spatial distribution of attentional weights (laterality index w_λ) also did not differ significantly. The spatial distribution of the attentional weights (w_λ) in the feature repetition condition was for the first trial on average at .54 (SD = .12), for the second trial at .51 (SD = .18); in the 1-dimensional change condition parameter w_λ was for the first trial at .53 (SD = .15) and for the second trial at .51 (SD = .21); in the 2-dimensional change condition parameter w_λ was for the first trial on average at .54 (SD = .13) and for the second trial at .50 (SD = .21).

Top-down control (α) was significantly better in second trials (N) compared to preceding trials (N-1) of all conditions (paired-samples t-test: feature repetition: *t*(9) = 3.76; *p* = .004; 1-dimensional change: *t*(9) = 3.93; *p* = .003; 2-dimensional change: *t*(9) = 3.19; *p* = .011 [all two-tailed]).

The top-down control revealed for the feature repetition condition for the first trial on average values at .69 (SD = .39) and for the second trial at .15 (SD = .16); in the 1-dimensional change condition parameter α was for the first trial at .83 (SD = .51) and for the second trial at .22 (SD = .22); in the 2-dimensional change condition parameter α was for the first trial at .45 (SD = .31) and for the second trial at .17 (SD = .14).

Table 8. Values of parameter A_λ for all subjects of Experiment 3a.

Aλ

Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	1.10	0.25	0.30	0.30	0.26	0.40
2	0.29	0.49	0.27	0.40	0.45	0.48
3	0.35	0.49	0.49	0.45	0.42	0.31
4	1.50	0.38	0.55	0.32	0.47	0.52
5	0.86	0.56	0.44	0.49	0.44	0.45
6	0.54	0.51	0.47	0.47	0.50	0.48
7	0.88	0.33	0.38	0.33	0.30	0.39
8	0.57	0.60	0.53	0.50	0.63	0.74
9	0.34	0.50	0.47	0.41	0.44	0.44
10	0.44	0.46	0.41	0.53	0.43	0.44

Table 9. Values of parameter *w_λ* for all subjects of Experiment 3a.

wλ

Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	0.32	0.11	0.26	0.07	0.25	0.05
2	0.76	0.50	0.73	0.53	0.48	0.55
3	0.58	0.61	0.59	0.48	0.52	0.68
4	0.55	0.68	0.48	0.85	0.58	0.59
5	0.58	0.49	0.56	0.51	0.63	0.58
6	0.60	0.64	0.75	0.65	0.57	0.68
7	0.46	0.37	0.36	0.28	0.46	0.26
8	0.50	0.68	0.43	0.63	0.68	0.59
9	0.44	0.40	0.52	0.59	0.66	0.35
10	0.57	0.56	0.62	0.53	0.61	0.69

Table 10. Values of parameter *α* for all subjects of Experiment 3a.

α

Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	1.10	0.07	1.63	0.04	0.41	0.06
2	0.29	0.07	0.37	0.01	0.22	0.06
3	0.35	0.06	0.52	0.38	0.64	0.13
4	1.50	0.18	1.56	0.25	1.12	0.17
5	0.86	0.14	1.19	0.40	0.62	0.35
6	0.54	0.34	0.73	0.32	0.49	0.44
7	0.88	0.00	0.49	0.10	0.52	0.16
8	0.57	0.00	0.27	0.00	0.01	0.00
9	0.34	0.52	1.14	0.66	0.27	0.17
10	0.44	0.11	0.34	0.09	0.22	0.12

To investigate if the better selection performance in pairs of consecutive trials of all conditions is due to implicit knowledge of the subjects that a repetition of the target location is highly probable, or that the location of the targets stays bottom-up activated in the sense of some kind of saliency signal, Experiments 3b and 3c were conducted.

Experiment 3b - Partial report with randomly changing target position

Exposure durations varied within a range of 72 ms and 260 ms with a mean duration of 162.47 ms (SD = 58.28). Individual exposure durations for the participants of Experiment 3b are given in Table 17. Exposure durations did not correlate with participants' age (r = .40; *p* = .19).

The partial report procedure allows for the estimation of three parameters reflecting performance of the component attentional functions of lateralised sensory effectiveness (*A*), object-related distribution of attentional weight (*w*) and the top-down control (α). (See all parameter values in Tables 11 - 13)

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of feature repetitions or changes across trials).

Mean lateralised sensory effectiveness in Experiment 3b was at .43 (SD = .05). That is, processes of sensory perception were significantly more efficient for targets presented in the right hemi-field as revealed by a t-test (*t*(11) = -4.85; *p* = .001) comparing *A* values of Experiment 3b with the predicted equal distribution of .5.

The average distribution of attentional weights, w_λ = .46 (SD = .11) in Experiment 3b is unbiased to any hemi-field as revealed by a t-test (*t*(11) = -1.27; *p* = .23) comparing observed to predicted w_λ values.

Top-down control indicates whether attentional resources are allocated to target objects or non-target objects, independent of their display locations. In Experiment 3b, the average of the top-down control parameter was .74 (SD = .19). That is, overall, observers were able to efficiently select target and deselect non-target items. A t-test of α values revealed that they were significantly different from 1 (*t*(11) = -4.72; *p* = .001), the value corresponding to the equal weight attributed to target and non-target items.

In the second analysis step, potential effects of the experimental manipulation, feature repetitions, 1-dimensional changes and 2-dimensional changes, were analysed for the first and second trial of sequences of two consecutive trials.

A total number of 24 trial pairs for each condition were analysed for each observer. Analysing the different conditions (feature repetition, 1-dimensional change, 2-dimensional change) in pairs of consecutive trials, interestingly no significant difference in all components (sensory effectiveness, attentional weight and top-down control) could be found.

The spatial distribution of sensory effectiveness (A_λ) in the feature repetition condition was for the first trial on average at .43 (SD = .05), for the second trial at .44 (SD = .09); in the 1-dimensional change condition, parameter A_λ revealed in the first trial values at .44 (SD = .07) and for the second trial at .43 (SD = .07); in the 2-dimensional change condition, parameter A_λ revealed in the first trial values at .41 (SD = .12) and for the second trial at .41 (SD = .07).

The spatial distribution of the attentional weights (w_λ) was in the feature repetition condition for the first trial on average at .42 (SD = .11), for the second trial at .47 (SD = .14); in the 1-dimensional change condition parameter w_λ was for the first trial at .44 (SD = .17) and for the second trial at .50 (SD = .16); in the 2-dimensional change condition w_λ was for the first trial at .49 (SD = .13) and for the second trial at .47 (SD =. 12).

The top-down control revealed for the feature repetition condition for the first trial on average values at .66 (SD = .37) and for the second trial at .66 (SD = .26); in the 1-dimensional change condition parameter α was for the first trial at .72 (SD = .26) and for the second trial at .85 (SD = .33); in the 2-dimensional change condition parameter α was for the first trial at .70 (SD = .25) and for the second trial at .78 (SD = .30).

Table 11. Values of parameter A_λ for all subjects of Experiment 3b.

Aλ

Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	0.41	0.41	0.42	0.37	0.38	0.37
2	0.45	0.59	0.56	0.56	0.59	0.47
3	0.42	0.47	0.52	0.44	0.39	0.45
4	0.36	0.34	0.38	0.43	0.13	0.23
5	0.56	0.48	0.38	0.45	0.51	0.44
6	0.43	0.59	0.48	0.41	0.46	0.47
7	0.40	0.39	0.45	0.39	0.36	0.42
8	0.42	0.49	0.40	0.46	0.46	0.48
9	0.38	0.32	0.34	0.39	0.33	0.35
10	0.41	0.37	0.45	0.49	0.38	0.39
11	0.43	0.45	0.39	0.28	0.52	0.47
12	0.46	0.44	0.48	0.45	0.40	0.41

Table 12. Values of parameter w_λ for all subjects of Experiment 3b.

wλ

Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	0.48	0.60	0.35	0.46	0.47	0.43
2	0.43	0.36	0.43	0.38	0.31	0.52
3	0.19	0.28	0.17	0.39	0.34	0.18
4	0.46	0.49	0.44	0.36	0.68	0.58
5	0.48	0.45	0.57	0.51	0.41	0.51
6	0.25	0.26	0.38	0.41	0.41	0.36
7	0.55	0.58	0.46	0.51	0.55	0.41
8	0.36	0.35	0.28	0.72	0.43	0.57
9	0.39	0.58	0.47	0.42	0.41	0.39
10	0.57	0.44	0.37	0.50	0.52	0.49
11	0.44	0.66	0.87	0.89	0.69	0.54
12	0.47	0.59	0.51	0.52	0.61	0.66

Table 13. Values of parameter *α* or all subjects of Experiment 3b.

α

Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	0.35	0.80	0.93	0.56	0.30	0.80
2	1.43	0.90	0.78	1.06	0.61	0.52
3	0.47	0.52	0.30	0.62	0.46	0.13
4	0.70	0.68	0.76	0.71	1.01	0.81
5	1.16	1.07	0.90	0.99	0.82	1.07
6	0.61	0.64	0.59	0.81	0.69	1.01
7	0.41	0.78	0.82	1.22	0.73	0.93
8	0.25	0.18	0.38	0.26	0.46	1.05
9	0.84	0.77	1.08	1.48	1.08	1.10
10	0.27	0.84	0.97	0.56	0.49	0.81
11	0.94	0.43	0.78	0.97	0.97	0.42
12	0.46	0.29	0.37	0.92	0.83	0.67

*Experiment 3*c *- Partial report with target locations predictably changing across trials*

Exposure durations varied within a range of 70ms and 250ms with a mean duration of 135.92 (SD = 57.10). Individual exposure durations for the participants of Experiment 3c are given in Table 17. Exposure durations did not correlate with participants' age (r = -.40; *p* = .17).

The partial report procedure allows for the estimation of three parameters reflecting performance of the component attentional functions of lateralised sensory effectiveness (*A*), object-related distribution of attentional weight (*w*) and the top-down control (α). (See all parameter values in Tables 14-16)

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of feature repetitions, 1-dimensional or 2-dimensional changes across trials).

Mean lateralised sensory effectiveness in Experiment 3c was at .46 (SD = .07). That is, processes of sensory perception were equally efficient for targets presented in the right hemi-field as in the left hemi-field revealed by a t-test (*t*(12) = -1.91; *p* = .08) comparing *A* values of Experiment 3c with the predicted equal distribution of .5.

The lateralised weight parameter w_λ indicates whether attentional weight attributed to objects is distributed evenly across the visual field (lateralised weights are space-based, i.e., averaged across target and non-target objects). The average distribution of attentional weights, w_λ = .49 (SD = .12) in Experiment 3c is unbiased to any hemi-field as revealed by a t-test (*t*(12) = -.35; *p* = .73) comparing observed to predicted w_λ values.

Top-down control indicates whether attentional resources are allocated to target objects or non-target objects, independent of their display locations. In Experiment 3c, the average top-down control parameter was at .90 (SD = .41). That is, overall, observers were able to efficiently select target and deselect non-target items. A t-test of α values revealed that they were significantly different from 1 (*t*(12) = -.89; *p* = .39), the value corresponding to equal weighting of target and non-target items.

In the second analysis step, potential effects of the experimental manipulation, feature repetitions, 1-dimensional changes and 2-dimensional changes, were analysed for the first and second trial of sequences of two consecutive trials.

A total number of 24 trial pairs for each condition were analysed for each observer. Analysing the different conditions (feature repetition, 1-dimensional change, 2-dimensional change) revealed no significant difference in the distribution of attentional weights (w_λ). The distribution of the attentional weights was in the feature repetition condition for the first trial on average at .49 (SD = .15), for the second trial at .48 (SD = .15); in the 1-dimensional change condition parameter w_λ was for the first trial at .52 (SD = .15) and for the second trial at .48 (SD = .14); in the 2-dimensional change condition w_λ was for the first trial at .47 (SD = .15) and for the second trial at .53 (SD =. 15).

In pairs of consecutive trials a tendentially significant reduced top-down control (α) in the 2-dimensional change condition was found (paired t-tests: $t(12) = -1.85$; $p = .08$ [two-tailed]). The top-down control revealed for the feature repetition condition for the first trial on average values at .76 (SD = .43) and for the second trial at .95 (SD = .73); in the 1-dimensional change condition parameter α was for the first trial at .94 (SD = .57) and for the second trial at 1.00 (SD = .60); in the 2-dimensional change condition parameter α was for the first trial at .93 (SD = .44) and for the second trial at 1.33 (SD = .90).

Also, a significantly better sensory effectiveness (A) in pairs with 1-dimensional change ($t(12) = -2.31$; $p = .04$ [two-tailed]) was found. The spatial distribution of sensory effectiveness (A_λ) in the feature repetition condition was for the first trial on average at .45 (SD = .09), for the second trial at .47 (SD = .11); in the 1-dimensional change condition, parameter A_λ revealed in the first trial values at .44 (SD = .08) and for the second trial at .48 (SD = .08); in the 2-dimensional change condition, parameter A_λ revealed in the first trial values at .46 (SD = .09) and for the second trial at .44 (SD = .09).

Interestingly a worse overall top -down control than in the partial report Experiment 3a (ANOVA: $F(2,18) = 11.78$; $p = 001$; pair-wise comparisons: $p = .007$) and Experiment 3b (pair-wise comparisons: $p = .002$) could be found. Mean α values for Experiment 3c were at .90 (SD = .41), for Experiment 3b at .74 (SD = .19) and for Experiment 3a at .40 (SD = .21).

Table 14. Values of parameter A_λ for all subjects of Experiment 3c.

Aλ						
Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	0.31	0.35	0.35	0.42	0.37	0.40
2	0.47	0.39	0.39	0.50	0.34	0.27
3	0.54	0.48	0.45	0.54	0.48	0.51
4	0.42	0.41	0.46	0.44	0.38	0.45
5	0.34	0.62	0.44	0.34	0.46	0.50
6	0.47	0.49	0.45	0.46	0.43	0.52
7	0.65	0.62	0.47	0.57	0.58	0.46
8	0.37	0.24	0.31	0.39	0.43	0.47
9	0.49	0.51	0.47	0.45	0.45	0.44
10	0.54	0.58	0.62	0.63	0.66	0.63
11	0.44	0.39	0.41	0.45	0.55	0.39
12	0.43	0.45	0.39	0.43	0.44	0.38
13	0.39	0.58	0.49	0.57	0.43	0.32

Table 15. Values of parameter w_λ for all subjects of Experiment 3c.

wλ						
Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	0.34	0.11	0.27	0.20	0.20	0.22
2	0.29	0.53	0.51	0.44	0.55	0.50
3	0.46	0.45	0.48	0.38	0.39	0.51
4	0.46	0.50	0.32	0.35	0.48	0.38
5	0.85	0.49	0.74	0.70	0.70	0.76
6	0.55	0.71	0.62	0.57	0.56	0.50
7	0.51	0.70	0.83	0.66	0.76	0.79
8	0.46	0.53	0.49	0.46	0.46	0.37
9	0.56	0.51	0.52	0.63	0.51	0.60
10	0.71	0.53	0.45	0.58	0.36	0.49
11	0.34	0.40	0.52	0.43	0.38	0.54
12	0.40	0.43	0.56	0.50	0.37	0.63
13	0.50	0.37	0.39	0.33	0.38	0.53

Table 16. Values of parameter α for all subjects of Experiment 3c.

α						
Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	0.56	0.13	0.57	0.65	0.55	0.55
2	0.82	0.70	0.56	0.68	0.46	1.07
3	0.46	0.99	0.86	1.14	1.18	1.90
4	1.57	1.56	1.53	1.83	1.57	2.68
5	1.63	2.81	2.42	2.32	0.87	3.13
6	0.24	0.08	0.37	0.39	0.35	0.18
7	0.92	1.14	1.23	0.89	1.17	2.31
8	0.96	1.14	1.16	1.67	1.37	0.99
9	0.81	0.45	0.96	0.42	0.79	0.82
10	0.28	1.56	0.50	1.04	1.66	1.21
11	0.61	0.70	1.00	0.66	0.54	1.18
12	0.59	0.42	0.62	0.43	0.52	0.33
13	0.50	0.66	0.41	0.95	1.09	0.98

Table 17. Exposure durations (in ms) for all subjects of the three partial report experiments (3 a, b, and c).

Exp. 3a		**Exp. 3b**		**Exp. 3c**	
Participant	time	Participant	time	Participant	time
1	140	1	96	1	145
2	196	2	120	2	84
3	120	3	201.6	3	120
4	120	4	174.2	4	129
5	96	5	185.8	5	250
6	86.4	6	160	6	70
7	132	7	80	7	240
8	230.4	8	260	8	75
9	150	9	190	9	120
10	200	10	72	10	145
		11	210	11	113
		12	200	12	140
				13	100

5.1.3.2.4 Experiment 4 –Whole Report

Mean middle masked exposure durations varied within a range of 80 ms and 147.50 ms with a mean duration of 116.83 ms (SD = 22.45). The three different individual exposure durations for each subject of Experiment 4 are given in Table 21. Exposure durations did not correlate with participants' age (r = .09; *p* = .83).

The whole report procedure allows for the estimation of three parameters reflecting performance of the component attentional functions of the vSTM capacity (*K*), the processing speed (*C*) and the detection threshold (t_0). (See all parameter values in Tables 18-20)

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of feature repetitions, 1-dimensional or 2-dimensional changes across trials).

The capacity of vSTM is reflecting the total number of elements processed simultaneously, i.e., the maximum number of letters reported on any single trial at any exposure duration. Average values of the capacity of vSTM in Experiment 4 are at 3.38 elements (SD = .47).

The overall processing speed is a measure of identification rate in elements per second. Average values of the overall processing speed are at 19.59 elements per second (SD = 5.81).

The detection threshold (t_0) is reflecting the time it takes for each subject to perceive an element in the display. Average values of the detection threshold are at 21.93 ms (SD = 18.38).

In the second analysis step, potential effects of the experimental manipulation, feature repetitions, 1-dimensional or 2-dimensional changes, were analysed for the first and second trial of sequences of two consecutive trials. A total number of 16 trial pairs for each condition was analysed for each observer.

No significant difference in the capacity of vSTM in pairs of trials with feature repetition, 1-dimensional change and 2-dimensional change could be found. The values for the vSTM capacity for feature repetition trials were in the first trial on average at 3.09 (SD = .38), for the second trial at 3.28 (SD = .52). The values for the vSTM capacity for 1-dimensional change trials were in the first trial on average at 3.31 (SD = .46), for the second trial at 3.23 (SD = .46). The values for the vSTM capacity for 2-dimensional change trials were in the first trial on average at 3.09 (SD = .53), for the second trial at 3.14 (SD = .50).

In feature repetition trials, the processing speed (parameter *C*) shows a significant acceleration in second trials of pairs of consecutive trials (paired-samples t-test: *t*(8) = -2.790; *p* = .048 [two-tailed]). In feature repetition trials the processing speed for the first trial was on average at 19.35 (SD = 5.46), for the second trial at 23.38 (SD = 8.78). In the 1-dimensional change condition, parameter *C* revealed in the first trial values at 20.86 (SD = 7.12) and for the second trial values at 21.79 (SD = 5.60). In the 2-dimensional change condition, parameter *C* revealed in the first trial values at 22.05 (SD = 7.19) and for the second trial values at 21.51 (SD = 7.75).

No significant differences in the values for the detection threshold could be found for feature repetition, 1-dimensional changes or 2-dimensional changes. For feature repetition trials the value of t_0 was in the first trial on average at 22.76 (SD = 20.35), for the second trial at 28.09 (SD = 19.93). The values for the detection threshold on 1-dimensional change trials was in the first trial on average at 24.59 (SD = 17.53), for the second trial at 27.00 (SD = 18.73). For the 2-dimensional changes values were for the first trial at 23.95 (SD = 22.58) and for the second at 27.84 (SD = 16.97).

Table 18. Values of parameter *K* for all subjects of Experiment 4.

K						
Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	2.82	3.73	3.79	2.91	2.83	2.99
2	3.00	4.00	3.80	4.00	4.00	4.00
3	2.99	2.95	2.91	2.82	2.92	3.00
4	2.98	2.70	2.97	3.00	2.80	2.88
5	3.59	3.43	3.67	3.52	2.71	2.67
6	3.86	4.00	3.90	3.94	4.00	4.00
7	2.97	3.00	2.98	2.98	2.99	2.94
8	2.96	3.00	2.96	3.00	2.90	3.00
9	2.66	2.74	2.85	2.91	2.63	2.80

Table 19. Values of parameter C for all subjects of Experiment 4.

C						
Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	14.66	13.14	15.71	19.95	14.34	18.06
2	18.49	20.27	19.69	22.15	18.32	17.93
3	14.44	15.33	13.31	19.02	17.71	14.14
4	24.27	32.33	31.69	26.87	25.18	29.76
5	13.98	16.11	15.74	15.92	14.42	16.37
6	30.72	37.23	26.94	28.00	34.32	34.87
7	21.63	29.52	30.79	23.42	25.95	30.01
8	18.62	29.38	19.21	28.61	30.40	16.40
9	17.35	17.12	14.64	12.22	17.82	16.04

Table 20. Values of parameter t_0 for all subjects of Experiment 4.

t0						
Participant	Feature Repetition		1-Dim Change		2-Dim Change	
	1. value	2. value	1. value	2. value	1. value	2.value
1	11.84	3.52	10.92	30.19	10.63	16.51
2	39.70	52.80	40.28	49.06	35.84	36.98
3	22.87	26.18	23.54	18.23	22.57	25.66
4	0.00	15.54	20.45	18.62	6.37	13.24
5	34.17	34.28	34.88	32.74	9.14	39.41
6	61.43	65.25	59.52	60.56	77.48	64.00
7	7.75	21.47	15.64	0.00	11.14	24.95
8	0.00	23.56	2.83	22.49	30.82	8.18
9	27.07	10.21	13.30	11.08	11.54	21.61

Table 21. The three exposure durations (in ms) for all subjects of Experiment 4.

Participant	time 1	time 2	time 3
1	50	100	200
2	55	110	220
3	60	120	240
4	40	80	160
5	70	140	280
6	70	140	280
7	57.5	115	230
8	73.5	147	294
9	49.5	99	198

5.1.3.3 Discussion

The aim of Experiments 1 and 2 was to investigate effects of feature changes and repetitions on parameters of Bundesen’s (1990) TVA. In the partial report task of Experiment 1 and the whole report task of Experiment 2 the colour of the target items repeated or changed, in a pseudo-random fashion, in consecutive trials. In Experiment 1, lateralised sensory effectiveness, average distribution of attentional weight, and the effectiveness of top-down control were estimated. In Experiment 2, visual short-term memory capacity and processing speed were analysed. In both Experiments 1 and 2, overall values were derived first, and in a second step, the effects of intertrial repetitions or changes of the target-defining colour were examined.

In Experiment 1, mean lateralised sensory effectiveness was slightly, but significantly, higher in the right hemi-field. Processes of sensory perception were more efficient for targets presented in the right hemi-field. Similarly, the average distribution of attentional weights showed a significant bias towards the right hemi-field. Sensory effectiveness did not vary across trials, irrespective of whether the feature was repeated or changed. Similarly, there was no effect of feature repetition or change in the spatial distribution of attentional weights.

The average of the parameter of top-down control effectiveness (α = .72) indicated that, overall, observers were able to efficiently select target and deselect non-target items. Analysis of top-down control effectiveness revealed a significant advantage in the second relative to the first of two consecutive trials, if the target feature was repeated; in feature change trials, although there was a benefit in the second compared to the first trial also, the difference was not significant.

In Experiment 2, average short-term memory capacity was 2.6 items and average processing speed estimates indicate that about 37 elements per second are processed on average.

Analysis of feature change and repetition trials shows that processing speed was not affected by inter-trial transition. However, the detection threshold was increased through changes in target features. Importantly, analysis of the visual short-term capacity across trials revealed a significant capacity increase in the second of two consecutive trials in feature repetition conditions: capacity was 3.81 items in the first and 4.12 items in the second trial.

Normally, values of the vSTM capacity are lower than the values found in the present experiment (at around 3.5). The high values are probably due to the spatial arrangement of the targets in the whole report experiment. The letters were presented in both hemifields and always on the same six positions. Subjects always knew at which positions the letters were presented and could top-down prepare their system resulting in higher capacity limits. Most likely the results can be interpreted in line with Alvarez and Cavanagh (2005). In their study they found that twice as many targets could be successfully tracked when targets were presented in the left and right hemifield compared to when all targets were presented within the same hemifield. Alvarez and Cavanagh (2005) concluded that their results rule out a single attentional focus. Therefore, independent (and independently limited) resources account for attentional tracking in the left and in the right hemifield. The present results could argue for two independent capacities – one in the right and one in the left hemisphere – contributing to the overall high vSTM capacity found in Experiment 2. If in further research the assumption of two independent capacities can be maintained then the method for getting the vSTM capacity values in TVA, namely computing the mean out of the capacity in the left and in the right hemifield, has to be corrected.

Overall, Experiments 1 and 2 suggest that the repetition of target features across consecutive trials improves and facilitates the ability to top-down set weight to target items and to ignore non-target items. Put differently, if the features defining the targets change, the selective system needs to attribute weights to the changed target feature, a process that is associated with costs. Importantly, short-term memory capacity is increased if the target feature remains the same across trials. This suggests, in accordance with recent findings in the literature, that short-term memory capacity is variable (e.g., Alvarez and Cavanagh, 2004) rather than stable (Bundesen, 1990). Further, variability of short-term memory capacity occurs in a very short temporal frame in the range a few seconds.

In sum, theories of visual search and visual selection that neglect effects of short term-memory require amendments. On the other hand, the present findings provide further support for the Dimension Weighting account (Müller, Heller & Ziegler, 1995; Found &

Müller, 1996) that assumes that processing on the level of generation of feature-based saliency signals is subjected to limitations in processing resources. In addition, the results are in line with Maljkovic and Nakayama's (1994) findings of better performance through repetition of features.

Experiments 3a, b and c (partial report) and 4 (whole report), were designed to examine the effects of single (as in Experiments 1 and 2) versus multiple feature changes on parameters of Bundesen's (1990) TVA. In Experiment 3a, 3b, 3c and 4 targets were either red or green (dimension colour) and uppercase or lowercase (dimension form) letters, non-targets were always blue (lowercase or uppercase) letters. In Experiment 3a, target positions were repeated across trials, in Experiment 3b, positions changed randomly across trials, and in Experiment 3c, positions changed in a predictable fashion across trials.

As in Experiment 1, in Experiment 3 the right hemi-field sensory effectiveness was slightly higher then left hemi-field sensory processing. Attentional weight, however, is evenly attributed to objects in the left and right visual hemi-field.

Effectiveness of top-down control varied with condition in Experiment 3. In Experiment 3a α = .40, in Experiment 3b α = .74, and in Experiment 3c α = .90. Recall that lower values indicate higher effectiveness of top-down control. Repetition of target location across trials is mirrored in high top-down effectiveness (Experiment 3a), random variations in target locations produce an average α-value similar to the one observed in Experiment 1. Importantly, predictability, i.e., (implicit) knowledge of the target location in the upcoming trial (Experiment 3c), does not improve top-down control effectiveness, rather, if anything, top-down control is worse compared to conditions in which target location varies randomly. This finding might reflect a difficulty in shifting, voluntarily, the location where a target is expected to appear relative to the location where the target appeared (physically) in the current trial. The present finding confirms a result reported by Maljkovic and Nakayama (1994, 1996), who also showed that the ability to predict target characteristics does not improve search performance.

Analyses of inter-trial changes and repetitions did not affect sensory effectiveness in any of the conditions of Experiment 3, neither was the spatial distribution of attentional weights.

Top-down control was affected by intertrial transition in Experiment 3a in which target location was repeated; top-down control increases in all conditions, irrespective of feature change or repetition across trials. The (implicit) knowledge of the target location increases the ability to allocate top-down processing resources. Probably the location of the target in the actual trial stays bottom-up activated in the sense of some kind of saliency signal and facilitates selection in the consecutive trial.

Different to Experiment 3a, in Experiment 3b in which target location changed randomly across trials, no significant difference was observed between consecutive trials in any of the change conditions

Interestingly, the worst intertrial transition effect was observed in Experiment 3c in which the target locations changed predictably. Recall that location change in Experiment 3 was associated with the repetition versus change in one or two features (colour, shape). If features were repeated, there was an increase in top-down control across consecutive trials. If one feature changed, top-down control was essentially the same in the first and second trial in a pair of trials. If both features changed, top-down control was worse in the second than in the first of two trials.

To sum, the effectiveness of top-down control is massively affected by the constant versus variable target locations. The breakdown of top-down control in Experiment 3c is probably due to interference between spatial and feature-based components of resource allocation (allocation of resources to the predicted stimulus location and allocation of resources to the predicted feature).

In Experiment 4, effects of single feature changes and dual feature changes on processing speed and short-term memory capacity were examined. Overall average processing speed was at about 20 items per second and overall short-term memory capacity was at 3.4 items.

Short-term memory capacity remained basically unaffected in Experiment 4 by both feature repetition and change trials.

Importantly, in feature repetition trials the processing speed is significantly accelerated in second trials of pairs of consecutive trials relative to first trials. In contrast, in feature change trials, neither the change of one feature nor the change of two features affected processing speed significantly.

Taken together, the findings suggest that the effectiveness of top-down control of resource allocation is affected by the presentation condition. Repetitions of target locations improve top-down control, while random selection of target locations and predictable target locations, together with changes in the target-defining features severely impair top-down control.

Further, repeating the target feature across trials in conditions in which the target feature may vary in one dimension (colour) increase visual short-term memory capacity in a short temporal frame of a few seconds (i.e., across consecutive trials). In conditions in which the target-defining features change in multiple dimensions (colour, shape), processing speed, rather than short-term memory capacity, is affected by intertrial repetitions versus changes.

Therefore, general information processing components such as the vSTM capacity and the processing speed as well as the components of the spatial distribution of attention such as the top-down control are affected by bottom-up changes in target features.

In terms of models of visual search, the present findings support the concept that bottom-up changes in target features entail the requirement of adjustments in processing resources at an early level of feature encoding and/or saliency computation (e.g., Müller, Heller & Ziegler's 1995, Dimension Weighting account).

In terms of models of working memory, the present findings suggest that short-term memory capacity is adjustable rather than fixed, and that the adjustment occurs in a fine-grained temporal frame.

5.1.4 **Experiment 5 & 6: Top-down Influences**

Müller, Reimann and Krummenacher (2003) found in visual search tasks that dimensional changes or repetitions can be influenced by top-down information in terms of a semantic cue presented previous to every search trial. For testing the top-down modulation capability of the vSTM a valid, invalid or neutral semantic cue was introduced indicating the likely feature of the display items previous to every trial of partial and whole report.

5.1.4.1 Method

5.1.4.1.1 Experiment 5 - Partial Report

In Experiment 5 (the partial report) the focus lay on the influence of top-down information on the components of the TVA. In this partial report experiment the effects of a symbolic cue, indicating the likely feature of the target letters, on the top-down control (α), attentional weight (w) to an object in the display compared to the other objects, and sensory effectiveness (A) of the TVA was investigated. The cue was valid, invalid or neutral. In the valid condition the presented cue indicated the real colour of the targets, in the invalid condition the wrong colour. The neutral cue gave no hint in which feature the target letters were defined. For the analysis the valid, invalid and neutral conditions were compared with each other. The targets were either red or green and the non-targets always blue. The observers had to report the identity of the red or green (target) letters and to ignore the blue (non-target) letters (if appearing in the same trial). A total of 600 trials were presented.

Participants. In Experiment 5, 13 students participated (four male, nine female), all of them from the University of Munich or the University of Fribourg. Participants' age ranged between 20 and 29 (M = 24.62 years; SD = 2.50 years). They received course credits or were paid 8 € or 10 CHF. All observers had normal or corrected-to-normal vision, including normal colour vision. They had no previous experience with the partial report method.

Apparatus. The apparatus of Experiment 5 was the same as in Experiment 2 or Experiment 1.

Stimuli and timing. Stimuli and timing were exactly the same as in Experiment 1, except for the cue at the beginning of each trial. The symbolic cue was a word (‘colour’ for neutral conditions, ‘green’ or ‘red’ for valid or invalid conditions), written in a neutral colour (white) in the center of the display. It was written in the font ‘arial’ and in uppercase letters (font size 40). The cue was presented for 700 ms and followed by the central fixation cross for 700 ms. Afterwards, the letters were presented for the individually determined brief presentation times (same pretest procedure as in Experiment 1).

Procedure. Individual exposure durations were determined in a pretest run immediately before the experiment. For equating the baseline performance across the different observers the aim of the pretest was to find the presentation time that yielded criterion accuracy between 60% and 70% correctly reported letters in the conditions in which three letters presented either in the left or the right hemi-field.

Experiment 5 consisted of one session lasting one and a half hours. A total of 600 trials were presented, split into twelve blocks with ten blocks of 50 valid and invalid trials (40 valid, 10 invalid) and two blocks with 50 neutral trials. Altogether the experiment consisted of 400 valid, 100 invalid and 100 neutral trials. For invalid and neutral trials in each condition 20 trials were presented.[10] One neutral block was positioned at the beginning of the experiment and the other one at the end. In the valid condition, the presented cue indicated the real colour of the targets (example see Figure 6), in the invalid condition the wrong colour. The neutral cue gave no hint in which feature the target letters were defined. On different trials the display consisted of three target letters in the left (3Tl) or in the right hemi-field (3Tr), three targets on the left accompanied by three non-targets in the right hemi-field (3Tl-3N) and the other way round (3N3Tr) and six target letters (6Tlr; three on the right and three on the left) (see Figure 2) with an equal number of trials for all conditions throughout the experiment. The letters were presented for one presentation time (identified individually through the pretest) and always masked.

The participants were requested to report the identity of those target letters (red or green) they were quite sure to have identified and to ignore the non-targets (blue letters).

---

[10] According to Finke et al. (2005), the minimum number of trials required for reliable parameter estimates is 18 trials (per condition).

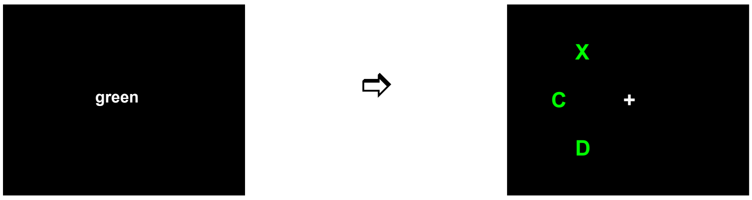


Figure 6. Example for a valid cue condition.

5.1.4.1.2 Experiment 6 – Whole Report

In Experiment 6 (the whole report) the focus was on the influence of top-down information on the components of the TVA. The effects of a symbolic cue, indicating the likely feature (colour) of the target letters, on the capacity of vSTM and speed of processing was investigated. The cue was valid, invalid or neutral. For the analysis the valid, invalid and neutral conditions were compared with each other. In the valid condition the presented cue indicated the real colour of the upcoming targets, in the invalid condition the wrong colour. The neutral cue gave no hint in which feature the target letters were defined. The targets were either red or green. The observers had to report the identity of all red or green letters. A total of 720 trials were presented.

Participants. In Experiment 6, eleven students participated (three male, eight female), all of them from the University of Munich or the University of Fribourg. Participants' age ranged between 19 and 29 (M = 23.73 years; SD = 3.00 years). They received course credits or were paid 8 € or 10 CHF. All observers had normal or corrected-to-normal vision, including normal colour vision. They had no previous experience with the whole report method.

Apparatus. The apparatus of Experiment 6 was the same as in Experiment 2 or Experiment 1.

Stimuli and timing. Stimuli and timing were exactly the same as in Experiment 2, except for the cue at the beginning of each trial. The symbolic cue was a word ('colour' for neutral conditions, 'green' or 'red' for valid or invalid conditions), written in a neutral colour (white) in the center of the display. It was written in the font 'arial' and in uppercase letters (font size 40). The cue was presented for 700 ms and followed by the central fixation cross for 700 ms. Subsequently, the letters were presented for the individually determined brief presentation times (same pretest procedure as in Experiment 2).

Procedure. The procedure was almost the same as in Experiment 2 except for the cue presentation at the beginning of each trial.

Experiment 6 consisted of one session lasting one and a half hours. A total of 720 trials were presented, split into twelve blocks with 10 blocks of 60 valid and invalid trials (48 valid, 12 invalid) and two blocks with 60 neutral trials. Altogether 480 valid, 120 invalid and 120 neutral trials were presented. For invalid and neutral trials and for each condition 20 trials were presented.[11] One neutral block was positioned at the beginning of the experiment and the other one at the end. In the valid condition the presented cue indicated the real colour of the upcoming targets, in the invalid condition the wrong colour (example see Figure 7). The neutral cue gave no hint in which feature the target letters were defined. The six letters were presented for three different presentation times (double and half the presentation time resulting from the pretest).

The participants were requested to report the identity of those letters they were quite sure to have identified.

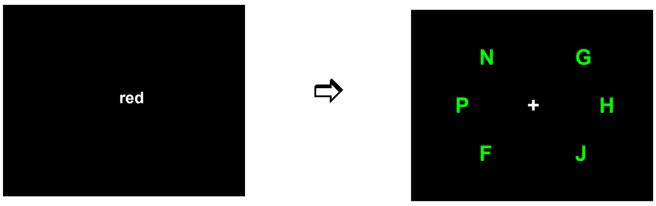


Figure 7. Example for the invalid cue condition.

5.1.4.2 Results

Effects of top-down information on the components of the TVA were investigated. In Experiments 5 and 6 the effects of valid, invalid and neutral cues on the components of the TVA were analysed.

TVA parameters reflecting the different attentional components were estimated using the estimation software developed by Kyllingsbæk (2006).

---

[11] According to Finke et al. (2005), the minimum number of trials required for reliable parameter estimates is 16 trials (per condition).

5.1.4.2.1 Experiment 5 – Partial Report

Exposure durations varied within a range of 22 ms and 168 ms with a mean duration of 86.77 ms (SD = 38.85). Individual exposure durations for the participants of Experiment 5 are given in Table 24. Exposure durations did not correlate with participants' age (r = .13; *p* = .68).

As mentioned above, the partial report procedure allows for the estimation of three parameters reflecting performance of the component attentional functions of lateralised sensory effectiveness (*A*), object-related distribution of attentional weight (*w*) and the top-down control (α). (See all parameter values in Table 22 and 23.)

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of the three different cue conditions).

Equal distributions of sensory effectiveness over the left and right hemi-fields yield a value of *A* = .5, values larger or smaller than .5 indicate improved effectiveness in the left and right hemi-fields, respectively. Mean lateralised sensory effectiveness in Experiment 5 was at .45 (SD = .05). That is, processes of sensory perception were significantly more efficient for targets presented in the right hemi-field as in the left hemi-field revealed by a t-test (*t*(12) = -3.33; *p* = .006) comparing *A* values of Experiment 5 with the predicted equal distribution of .5.

The lateralised weight parameter w_λ indicates whether attentional weight attributed to objects is distributed evenly across the visual field. Even distribution of weights is reflected by w_λ = .5; values below and above .5 reflect greater weight (attentional bias) in the right and left hemi-fields, respectively. The average distribution of attentional weights, w_λ = .40 (SD = .03), in Experiment 5 is significantly biased to the right hemi-field as revealed by a t-test (*t*(12) = -3.05; *p* =.01) comparing observed to predicted w_λ values.

Top-down control indicates whether attentional resources are allocated to target objects or non-target objects, independent of their display locations. Top-down control is defined as the ratio of weight attributed to target and non-target objects $\alpha = (w_D / w_T)$, that is, the lower the value of α the more weight is attributed to targets, i.e., the more efficient top-down control of the selection process is. In Experiment 5, the average of the top-down control parameter was $\alpha = .68$ (SD = .51). That is, overall, observers were able to efficiently select target and deselect non-target items. A t-test of α values revealed that they were significantly different from 1 ($t(12) = -2.29$; $p = .04$), the value corresponding to the equal weighting of target and non-target items.

Additionally, values of the vSTM capacity were analysed. Since there is not a sufficient number of trials for a stable estimation of this component, results concerning this component out of the partial report experiment can only serve as a hint. In Experiment 5 the average values of parameter K were at 3.10 elements (SD = .72).

In the second analysis step, potential effects of the experimental manipulation, the neutral, valid or invalid cues, were analysed.

A total number of 20 trials for each condition were analysed for each observer. Analysing the different conditions (neutral, invalid and valid cue) revealed no significant difference between the three different cue conditions in the lateralised sensory effectiveness (A_λ), spatial distribution of attentional weights (w_λ), and the top-down control (α). The lateralised sensory effectiveness for the neutral cue condition was at .44 (SD = .09), for the valid cue condition at .45 (SD = .06) and for the invalid at .43 (SD = .06). Values of the spatial distribution of attentional weights were at .42 (SD = .16) for neutral, at .41 (SD = .13) for valid and at .40 (SD = .15) for invalid trials. The top-down control showed in the neutral cue condition values of 1.01 (SD = .74), in the valid condition .64 (SD = .48) and in the invalid condition values at .85 (SD = .76).

The results indicate a significant difference in the capacity of vSTM (K) between the valid, neutral and invalid condition (Analysis of variance [ANOVA]; $F(2,24) = 4.83$; $p = .017$). Pair-wise comparisons revealed a significantly higher capacity value in the valid condition ($K = 3.18$; SD = .69) compared to the invalid condition ($K = 2.91$; SD = .71; $p = .009$). There was no significant difference compared to the neutral cue condition ($K = 2.92$; SD = .61). However, these estimates of vSTM are not very valid due to the few trials for estimating the capacity of vSTM in partial report. It can serve as a hint or tendency and has to be confirmed by the whole report experiment.

Table 22. Values of parameter A_λ and w_λ for all subjects of Experiment 5.

A_λ

Participant	Cue neutral	valid	invalid
1	0.43	0.37	0.35
2	0.48	0.35	0.38
3	0.53	0.56	0.49
4	0.45	0.42	0.43
5	0.43	0.42	0.40
6	0.33	0.49	0.54
7	0.47	0.53	0.52
8	0.56	0.46	0.51
9	0.54	0.45	0.41
10	0.52	0.44	0.37
11	0.35	0.39	0.39
12	0.37	0.43	0.41
13	0.25	0.48	0.44

wλ

Participant	Cue neutral	valid	invalid
1	0.39	0.49	0.53
2	0.24	0.31	0.32
3	0.43	0.35	0.48
4	0.40	0.51	0.57
5	0.51	0.47	0.50
6	0.29	0.39	0.18
7	0.45	0.12	0.11
8	0.61	0.52	0.49
9	0.34	0.33	0.41
10	0.28	0.43	0.48
11	0.19	0.27	0.26
12	0.75	0.60	0.32
13	0.55	0.53	0.51

Table 23. Values of parameter α for all subjects of Experiment 5.

α

Participant	Cue neutral	valid	invalid
1	1.19	0.69	1.08
2	0.45	0.29	0.41
3	1.12	0.51	1.03
4	0.71	0.86	0.78
5	0.44	0.22	0.27
6	0.70	0.78	0.49
7	2.86	0.13	0.38
8	0.15	0.53	0.64
9	1.44	0.60	1.00
10	1.87	2.00	3.22
11	0.20	0.28	0.56
12	0.82	0.42	0.53
13	1.18	0.99	0.70

*Table 24***.** Exposure durations (in ms) for all subjects of Experiment 5.

Participant	time
1	80
2	80
3	120
4	90
5	22
6	120
7	100
8	46
9	84
10	100
11	48
12	168
13	50

5.1.4.2.2 Experiment 6 – Whole Report

The three different exposure durations for each subject can be seen in Table 27 and all parameter values in Table 25 and 26.

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of the three different cue conditions). The capacity of vSTM is reflecting the total number of elements processed simultaneously, i.e., the maximum number of letters reported on any single trial at any exposure duration. Average values of the capacity of vSTM in Experiment 6 are at 4.54 elements (SD = .96).

The overall processing speed is a measure of identification rate in elements per second. Average values of the overall processing speed are at 67.27 elements per second (SD = 47.34).

The detection threshold (t_0) is reflecting the time it takes for each subject to perceive an element in the display. Average values of the detection threshold are at 3.11 ms (SD = 4.14).

In the second analysis step, potential effects of the experimental manipulation, the neutral, valid or invalid cues, were analysed.

A total number of 20 trials for each condition were analysed for each observer. Analysing the different conditions (neutral, invalid and valid cue) revealed no significant difference concerning the processing speed (parameter *C*). The processing speed in the neutral cue condition was at 63.92 (SD = 41.35), for the valid cue condition at 64.65 (SD = 43.14) and for the invalid at 64.36 (SD = 32.09).

However, a significant difference in the capacity of the vSTM between the valid, neutral and invalid condition (ANOVA; *F*(2,20) = 10.31; *p* = .001) could be found. Pair-wise comparisons revealed a significantly higher capacity in the valid condition (*K* = 4.72; SD = .98) compared to both the neutral (*K* = 4.15; SD = .78; *p* = .002) and the invalid (*K* = 4.16; SD = .77; *p* = .027) conditions.

Table 25. Values of parameter *K* and *C* for all subjects of Experiment 6.

K

Participant	Cue neutral	valid	invalid
1	4.59	4.87	4.58
2	3.91	4.39	3.80
3	3.62	4.56	3.82
4	3.94	3.84	3.86
5	5.00	6.00	4.22
6	5.00	5.89	5.00
7	5.00	5.88	4.97
8	4.57	4.70	4.59
9	2.45	2.68	2.43
10	3.81	4.65	4.93
11	3.75	4.42	3.58

C

Participant	Cue neutral	valid	invalid
1	45.34	43.43	49.14
2	67.18	54.17	74.72
3	14.16	27.41	21.58
4	91.03	86.14	86.25
5	151.94	163.33	99.63
6	46.00	41.25	49.56
7	65.22	55.16	67.57
8	109.96	114.92	117.74
9	11.58	13.61	13.98
10	61.20	72.23	83.75
11	39.56	39.46	44.03

Table 26. Values of parameter t_0 for all subjects of Experiment 6.

t0

Participant	Cue neutral	valid	invalid
1	0.00	0.00	0.00
2	3.95	5.14	9.88
3	0.00	0.00	0.00
4	3.45	3.75	2.60
5	1.97	0.58	4.72
6	0.00	0.00	0.00
7	9.63	5.42	11.28
8	0.00	0.00	0.00
9	8.86	13.22	17.67
10	0.00	1.82	10.34
11	2.22	0.00	0.00

Table 27. The three exposure durations (in ms) for all subjects of Experiment 6.

Participant	time 1	time 2	time 3
1	40	80	160
2	10.5	21.6	43.2
3	40	80	160
4	12.9	25.8	51.6
5	6.5	13	26
6	40	80	160
7	20	40	80
8	11.5	23	46
9	50	100	200
10	25.5	51	102
11	25.6	51.2	102.4
12	40	80	160

5.1.4.3 Discussion

In Experiment 5 (partial report) and 6 (whole report), the focus was on the influence of top-down information on the components of the TVA. The effects of a symbolic cue, indicating the likely feature (colour) of the target letters, on the lateralised sensory effectiveness, top-down control, spatial weighting, capacity of VSTM and speed of processing was investigated. The cue was either valid or invalid or neutral. For the analysis the valid, invalid and neutral conditions were compared with each other. In the valid condition the presented cue indicated the real colour of the targets, in the invalid condition the wrong colour. The neutral cue gave no hint in which feature the target letters were defined.

In Experiment 5 the cue could neither influence the lateralised sensory effectiveness, nor the spatial distibution of attentional weights, nor the selection effectiveness (top-down control). Therefore, the parameters, reflecting spatial aspects of attention seem not to be affected by top-down information. Interestingly, although due to the non-sufficient number of trials for stable estimation of the parameter K is not really reliable, estimates of the vSTM capacity were affected by the top-down information (cue). Valid cues significantly increased the capacity of vSTM and subjects could report significantly more items compared to invalid cue conditions. The results concerning the vSTM can serve as a hint and have to be confirmed by the whole report experiment (Experiment 6).

Experiment 6 revealed no significant difference in the processing speed if the dimensions of the upcoming target letters were validly, invalidly or neutrally cued. Therefore, top-down information does not help to speed up or slow down the system. However, valid cues significantly affected the capacity of vSTM (K = 4.72) compared to both, neutral (K = 4.15) and invalid (K = 4.16) cue trials. To conclude, the vSTM can be influenced and enhanced remarkably by top-down information about the upcoming target dimension. The system is set for the dimension of the upcoming targets and this facilitates the storing of more items in vSTM. This suggests, in accordance to recent findings in the literature, that vSTM capacity is variable (e.g., Alvarez & Cavanagh, 2004) rather than stable (Bundesen, 1990) depending on the specific setting.

The untypically high values of the vSTM capacity at 4.72 elements (normally around 3.5) and the processing speed with values around 60 elements per second (normally at around 30). The high values are probably due to the spatial arrangement of the targets in the whole report experiment. The letters were presented in both hemifields and always on the same six positions. Subjects always knew at which positions the letters were presented and could top-down prepare their system resulting in higher capacity limits. Most likely the results can be interpreted in line with Alvarez and Cavanagh (2005). In their study they found that twice as many targets could be successfully tracked when targets were presented in the left and right hemifield compared to when all targets were presented within the same hemifield. Alvarez and Cavanagh (2005) concluded that their results rule out a single attentional focus. Therefore, independent (and independently limited) resources account for attentional tracking in the left and in the right hemifield. The present results could argue for two independent capacities – one in the right and one in the left hemisphere – contributing to the overall high vSTM capacity and processing speed found in Experiment 6. If in further research the assumption of two independent capacities can be maintained then the method for getting the vSTM capacity values in TVA, namely computing the mean out of the capacity in the left and in the right hemifield, has to be corrected.

Summing up the Experiments 1-6, top-down and bottom-up information can influence the categorisation process and therefore the attentional components of TVA, repeatedly the capacity of vSTM. Variability and enhancement of the vSTM in specific situations is therefore possible. Since vSTM is a very important component for everyday normal functioning and if the short-term memory capacity can be increased by certain experimental manipulations it is highly probable that it can be increased by training. Therefore it is very important to train children's brains while they are still developing. Furthermore, it is possible to train and improve short-term memory capacity in people suffering from short-term memory problems (Gathercole & Alloway, 2006).

5.1.5 **Experiment 7 – 9: Specific Characteristics of the TVA**

Besides investigating through the combination of the implementation of the TVA with the DW ideas, the above mentioned question of how some components of the TVA can be affected by bottom-up changes or top-down information, specific properties of the TVA (Bundesen, 1990) are investigated in Experiment 7 and 8. In Experiment 7 the influences of one letter presented twice in one trial on the capacity of vSTM and on the processing speed were investigated. Experiment 8 aims at testing effects of different spatial positions of the letter presentations on the attentional components of top-down control, lateralised sensory effectiveness, spatial distribution of attentional weights, processing speed and capacity of vSTM. The effects of exactly the same letters on exactly the same positions presented in pairs of consecutive trials (N-1 → N) on the attentional components of the TVA were tested in Experiment 9.

Since the whole and partial report methods were the same as in the experiments reported before in this chapter, I will only briefly describe the methods.

5.1.5.1 **Experiment 7**

In the first experiment, the processing of target repetitions in one and the same trial is investigated. The influences of target repetitions on the attentional components proposed by the TVA are tested by using the whole report procedure. In one trial with five target letters on the left or right of a central fixation cross one letter was repeated, i.e., presented twice. Performance on these trials is compared to standard whole report trials with each letter presented only once in a given trial. Repetition of exactly the same letter should facilitate and improve selection performance. The probability for every other letter presented in the display to be reported correctly should increase.

5.1.5.1.1 Method

Participants. In Experiment 7, fourteen students participated (one male, thirteen female), all of them from the University of Fribourg. Participants' age ranged between 19 and 24 years (M = 21.00 years; SD = 1.57 years). They received course credits or were paid 10 CHF. All observers had normal or corrected-to-normal vision, including normal colour vision. They had no previous experience with the whole report method.

Apparatus and stimuli. The apparatus were the same as in Experiment 3; stimuli were the same as in Experiment 4, except for the repetition of one letter in one and the same trial.

Procedure. The procedure was similar to all reported whole report experiments. Again five letters were presented in semi-circles to the left or right of a central fixation cross. Three different presentation times (resulting from the pre-test conducted previous to the Experiment 7), masked and unmasked presentations of letters and two different colours resulted in 12 different conditions. For each of the trials in which one target letter was presented twice in one and the same trial, either on position 2 and 3, 2 and 4 or 3 and 4 (numbered from top to bottom), 192 trials were presented (resulting in a total of 576 trials with the same target twice presented in one trial). In the other 576 trials each letter was presented only once in each trial. For each of the trials with one letter presented twice a corresponding trial with the same letter, but presented once in the trial at one of the two positions was presented. For example, if two Ls were on positions 2 and 3, there was a corresponding trial with the L on position 2 and one with the L on position 3.

For each of the 12 conditions (3 presentation times x 2 mask conditions x 2 different colours) multiplied by the 6 different target presentations (3 single target letter on either position 1, 2 or 3 and 3 twice target letters on positions 2 and 3, 2 and 4 or 3 and 4) 16 trials (necessary for a stable estimation of the components) were presented, resulting in 1152 trials. The total of 1152 trials (16 blocks with 72 trials) were presented split into two test sessions lasting approximately 45 minutes.

5.1.5.1.2 Results

Using the same procedure as in the whole report experiments reported before, the components of the capacity of vSTM and processing speed are estimated. The number of items processed simultaneously in visual short-term memory, i.e. vSTM capacity, is estimated on the basis of the performance in the whole report task. In adult observers, processing is limited to about 3 to 4 items (letters). The second important component, the processing speed, estimated on the basis of performance in the whole report task is, reflects the number of items processed per unit time (second).

Mean masked exposure durations varied within a range of 110.00 ms and 160 ms with a mean duration of 140.71 ms (SD = 16.74 ms).

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of the singly or twice presented letter in one trial).

The capacity of vSTM is reflecting the total number of elements processed simultaneously, i.e., the maximum number of letters reported on any single trial at any exposure duration. Average values of the capacity of vSTM in Experiment 7 are 3.31 correctly reported elements (SD = .51).

The overall processing speed is a measure of identification rate in elements per second. Average values of the overall processing speed in Experiment 7 are at 24.28 elements per second (SD = 7.02).

In the second analysis step, potential effects of the experimental manipulation were analysed. Analysing the influences of the repetition of one letter in a trial, in a first step, the conditions with double letters were compared with trials containing each letter only once.

The comparison of percent correct values of all trials, in which each letter was presented once (single trial) with all trials, in which one letter was presented twice (double trial) revealed a significantly better performance in single trials (M = 44.85; SD = 4.38) compared to double trials (M = 43.74; SD = 4.81) (paired-samples t-test: *t*(13) = 4.00; *p* = .002).

Comparing the single trials with double trials revealed no significant differences in all components of the TVA. The capacity of vSTM was slightly lower in the trials, in which one letter was presented twice (M = 3.22; SD = .53) compared to the single trials (M = 3.36; SD = .52), but not significantly different (*t*(13) = 1.21; *p* = .247). The processing speed also did not differ between single (M = 23.76; SD = 7.00) or double trials (M = 25.14; SD = 7.08; *t*(13) = -1.35; *p* = .201).

In the next step, trials with double presented letters were compared with trials, in which the same letter was presented on one of the positions, at which the two letters were presented. For example, if two Ls were on positions 2 and 3, there was a corresponding trial with the L on position 2 and one with the L on position 3. The effects on the components of the capacity of vSTM and the processing speed are analysed.

If the same letter was presented twice at positions 3 and 4 (M = 3.10; SD = .48) and the same letter singularly on position 4, the capacity was significantly higher in the latter condition (M = 3.45; SD = .52), when the letter was only presented once (*t*(13) = 2.57; *p* = .023).

Furthermore, in conditions where a letter was presented twice at position 2 and 4 (M = 3.21; SD = .51), there was a tendency of a significantly higher capacity again, when this letter was only presented once a trial at position 4 (M = 3.45; SD = .52) (*t*(13) = 2.03; *p* = .063).

Between all other conditions there was no significant difference reflected in the capacity of the vSTM.

Concerning the processing speed, the second important component, a significantly higher speed could be found in trials in which a letter is presented twice, at position 2 and 3 (M = 29.88; SD = 10.74) compared to conditions with this letter presented once in the trial on position 3 (M = 25.50; SD = 7.07).

All other comparisons did not reveal any significant difference.

5.1.5.1.3 Discussion

In Experiment 7 the processing of target repetitions in one and the same trial was investigated. Influences of target repetitions on the categorisation process were tested by using the whole report procedure. In one trial with five target letters, one letter was repeated (i.e., presented twice) and compared to trials in which letters were presented once a trial.

Increasing percent correct values were assumed to arise if the same target was presented twice in one trial. The probability of detecting one of the two targets at a certain point in time should be bigger than to detect one of one target. Interestingly, this does not seem to be the case in Experiment 7.

Concerning the components of the TVA (capacity of vSTM and the processing speed) the capacity of vSTM was decreasing in trials, in which one target was presented twice. In other words, the capacity of vSTM was higher if the target was presented once a trial. It seems that all available slots in vSTM are occupied by target items, however, the total amount of information was reduced by the doubled letter. One explanation might be that the neighbouring same targets masked each other and therefore participants were not able to name them both. Furthermore, there is maybe an additional task for the system to briefly store two same stimuli, which goes then on the expense of the vSTM capacity. The two same stimuli seem to remove a huge amount of capacity which is then not available anymore for the remaining targets.

Contrary to the capacity of vSTM, the processing speed was increased whenever two same targets in one trial were presented. This finding was as expected that the processing of the system was facilitated by repeating one and the same stimulus. Interestingly, although there was a higher processing speed, the vSTM capacity was decreased if two same stimuli were presented. Since all components of the TVA (Bundesen, 1990) are assumed to be independent (theoretically as well as empirically (Finke et al., 2005) this result is consistent with the TVA: one component can be enhanced and the other decreased.

5.1.5.2 **Experiment 8**

Experiment 8 consists of two parts - one partial report and one whole report experiment. In both experiments effects of different spatial positions of the letter presentations on the attentional components claimed by the TVA (Bundesen, 1990) were tested. The different spatial positions were presented according to the presentation of visual search stimuli in the study by Carrasco and Frieder (1997).

According to Carrasco, Evert, Chang and Katz (1995) detection of targets in feature or conjunction search tasks becomes increasingly less efficient as the target is presented at more distant field eccentricities. However, if the stimuli are cortically magnified this effect could be flattened out (Carrasco & Frieder, 1997). Using the same computation of the cortical magnification factors as Carrasco & Frieder (1997) the size of letters on the three different spatial positions increased. Following the paper of Carrasco & Frieder (1997) no effects on the performance reflected in percent correct values and the different attentional components should be found.

5.1.5.2.1 Method – Partial Report

Participants. In the partial report of Experiment 8, fifteen students participated (one male, fourteen female), all of them from the University of Fribourg. Participants' age ranged between 19 and 25 years (M = 21.27 years; SD = 1.49 years). They received course credits or were paid 10 CHF. All observers had normal or corrected-to-normal vision, including normal colour vision. They had no previous experience with the partial report method.

Apparatus and stimuli. The apparatus was the same as in Experiment 7 and stimuli were the same as in Experiment 1, except for the three different distances the stimuli (letters) were presented at. The spatial positions of the letters were computed by a cortical magnification factor (M) at each eccentricity by holding the viewing distance constant at approximately 50 cm. Following Carrasco and Frieder (1997), the magnification factor was computed by averaging the equations proposed by Rovamo and Virsu (1979) and Virsu and Rovamo (1979).

M(superior visual field) = $M_0(1+.42E + .00012E^3)^{-1}$ and

M(inferior visual field) = $M_0(1+.42E + .000055E^3)^{-1}$, where E refers to degrees of eccentricity, and M_0 is the magnification value (7.99mm/deg) for the central fovea.

The resulting magnification factor between the first and second spatial position was at 1.13 and between the first and third spatial position 1.24. The first spatial position is the one nearest to the fixation cross and the third the one with the biggest distance to the fixation cross.

Procedure. The procedure was similar to all previously reported partial report experiments. Again either three or six letters were presented in semi-circles to the left and/or right of a central fixation cross at one brief presentation time (resulting form the pre-test conducted previous to the partial report). Again, five different conditions were presented. The display consisted either of three (red) target letters in the left (3Tl), three (red) target letters in the right hemi-field (3Tr), three (red) targets in the left hemi-field together with three (green) non-targets in the right hemi-field (3Tl-3N), three (red) targets in the right and three (green) non-targets in the left hemi-field (3N-3Tr), or six (red) target letters (6Tlr; three in the left and three in the right hemi-field).

Like in all previously presented partial report experiments, all letters were followed by masks.

For each of the five conditions multiplied by the three different spatial positions 20 trials (necessary for a stable estimation of the components) were presented, resulting in 300 trials. The total of 300 trials (5 blocks with 60 trials) were presented in one test session lasting approximately 45 minutes.

5.1.5.2.2 Results – Partial Report

Using the same procedure as in the partial report experiments reported before, the components of the lateralised sensory effectiveness, the spatial distribution of attentional weights, and the top-down control are estimated. Lateralised sensory effectiveness is based on perception accuracy at each stimulus location and computed by weighting accuracy values of targets presented in the left hemi-field to the accuracy of left hemi-field and right hemi-field targets according to $A = A_l / (A_l + A_r)$. Equal distributions of sensory effectiveness over the left and right hemi-fields yield a value of $A = .5$, values larger or smaller than .5 indicate improved effectiveness in the left and right hemi-fields, respectively. The lateralised weight parameter w_λ indicates whether attentional weight attributed to objects is distributed evenly across the visual field (lateralised weights are space-based, i.e., averaged across target and non-target objects). Lateralised weights are calculated according to $w_\lambda = w_L / (w_L + w_R)$. Even distribution of weights is reflected by $w_\lambda = .5$; values below and above .5 reflect greater weight (attentional bias) in the right and left hemi-fields, respectively. Top-down control indicates whether attentional resources are allocated to target objects or non-target objects, independent of their display locations. Top-down control is defined as the ratio of weight attributed to target and non-target objects $\alpha = (w_D / w_T)$, that is, the lower the value of α the more weight is attributed to targets, i.e., the more efficient top-down control of the selection process is.

Exposure durations varied within a range of 65.00 ms and 200.00 ms with a medium duration of 139.27 ms (SD = 34.47 ms).

In the first step, the parameters and percent correct values were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of the three different spatial positions of the presented letters).

The overall mean performance in percent correct was at 37.37% correctly reported items (SD = 5.64).

The spatial distribution of attentional weights was at .48 (SD = .07) and not different from .5 arguing for equal weighting ($t(14) = -1.17$; $p = .26$) of both hemifields. The overall mean of the lateralised sensory effectiveness was at .43 (SD = .07), and significantly different from .5 ($t\ (14) = -3.71$; $p = .002$). There was a slight preference for targets on the right side.

Average values of the top-down control parameter were at .39 (SD = .19). That is, overall, observers were able to efficiently select target and deselect non-target items. A t-test of α values revealed that they were significantly different from 1 (the value of equal selecting of targets and non-targets) ($t(14) = -12.35$; $p < .001$).

In the second analysis step, potential effects of the experimental manipulation – the three different spatial positions of the letters – were analysed.

Analysing the influences of the different target positions, a repeated measures ANOVA, revealed neither for the spatial distribution of attentional weights, nor for the lateralised sensory effectiveness, nor for the top-down control significant differences between the three different spatial positions (*F*(2,28) = .94; *p* = .404; *F*(2,28) = .85; *p* = .438; *F*(2,28) = .15; *p* = .862). (All parameter values can be seen in Table 28.)

Table 28. Mean values for the spatial distribution of attentional weights, for the lateralised sensory effectiveness and for the top-down control for the three spatial positions (standard deviations in brackets).

	pos 1	pos 2	pos 3
Aλ	.44 (.10)	.40 (.15)	.42 (.07)
wλ	.46 (.12)	.50 (.17)	.52 (.12)
α	.35 (.21)	.37 (.29)	.39 (.21)

However, analysing the percent correct performance, subjects performed significantly better if targets were presented in the second (38.19%; SD = 5.72) or third (38.87%; SD = 4.82) spatial position and compared to the first (35.05%; SD = 7.11) (the one nearest to the fixation cross) (*F*(2,28) = 11.15; *p* < .001; third and first: *p* = .005; second and first: *p* = .004, third and second: *p* = 1.000;).

5.1.5.2.3 Method – Whole Report

Participants. The same subjects as in the partial report of Experiment 8 participated in the whole report experiment.

Apparatus and stimuli. The apparatus was the same as in Experiment 7; stimuli were the same as in Experiment 4, except for the three different distances the stimuli (letters) were presented at. The spatial positions of the letters were computed by a cortical magnification factor (M) at each eccentricity by holding the viewing distance constant at approximately 50 cm. Following Carrasco and Frieder (1997), the magnification factor was computed by averaging the equations proposed by Rovamo and Virsu (1979) and Virsu and Rovamo (1979).

M(superior visual field) = $M_0(1+.42E + .00012E^3)^{-1}$ and

M(inferior visual field) = $M_0(1+.42E + .000055E^3)^{-1}$, where E refers to degrees of eccentricity, and M_0 is the magnification value (7.99mm/deg) for the central fovea.

The resulting magnification factor between the first and second spatial position was at 1.12 and between the first and third spatial position 1.21.

Procedure. The procedure was similar to all reported whole report experiments. Again five letters were presented in semi-circles to the left or right of a central fixation cross. Three different presentation times (resulting from the pre-test conducted previous to the whole report), masked and unmasked presentations of letters and two different colours resulted in 12 conditions.

For each of the 12 conditions multiplied by the three different spatial positions 20 trials (necessary for a stable estimation of the components) were presented, resulting in 720 trials. The total of 720 (12 blocks with 60 trials) trials were presented in one test session lasting approximately one hour.

5.1.5.2.4 Results – Whole Report

Using the same procedure as in the whole report experiments reported before, the components of the capacity of vSTM and processing speed are estimated. The number of items processed simultaneously in visual short-term memory, i.e. vSTM capacity, is estimated on the basis of the performance in the whole report task. The second important component, the processing speed, reflects the number of items processed per unit time (second).

Mean masked exposure durations varied within a range of 70 ms and 200 ms with a medium duration of 146.67 ms (SD = 42.03 ms).

In the first step, the parameters were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of the three different spatial positions of the presented letters).

The overall mean performance in percent correct was at 39.41% correctly reported items (SD = 5.16). The overall mean of vSTM capacity was at 3.02 correctly reported elements (SD = .38) and of the processing speed at 21.13 elements per second (SD = 9.95).

In the second analysis step, potential effects of the experimental manipulation – the three different spatial positions of the letters – were analysed.

Analysing the influences of the different target positions, a repeated measures ANOVA revealed no significant difference in the capacity of vSTM between the first (M = 3.04; SD = .38), second (M = 2.98; SD = .34) or third spatial position (M = 2.86, SD = .28) ($F(2,28) = 2.86$; $p = .074$).

The processing speed was significantly higher in the spatial position nearest to the fixation cross (position 1) and at spatial position two (position 2) compared to the farthest spatial position (position 3) ($F(2,28) = 7.13$; $p = .003$; first compared to third: $p = .004$; first compared to second: $p = 1.000$; second compared to third: $p = .006$). Mean values can be seen in Table 29.

Table 29. Mean values for the capacity of vSTM and for the processing speed for the three spatial positions (standard deviations in brackets).

	pos 1	pos 2	pos 3
K	3.04 (.38)	2.98 (.34)	2.86 (.28)
C	23.84 (11.28)	23.59 (11.61)	19.88 (9.42)

A repeated measures ANOVA revealed significant differences in the performance reflected in percent correct ($F(2,28) = 42.45$; $p < .001$). The performance was significantly higher at the first position compared to the third position ($p < .001$) and significantly higher on the second compared to the third position ($p < .001$) (no difference between first and second position: $p = .743$).

5.1.5.2.5 Discussion

The effects of different spatial positions of the stimuli of the whole and partial report tasks on the components of the TVA were investigated in Experiment 8. Analysing the partial report data, neither in top-down control, nor in the lateralised sensory effectiveness, nor in the spatial distribution of attentional weights, different spatial positions had an effect on performance. Spatial variations therefore cannot influence the spatial parameters of the TVA. In whole report, the processing speed was significantly higher in the nearest position to the fixation cross compared to the other two spatial positions.

According to Carrasco, Evert, Chang and Katz (1995) detection of targets in feature or conjunction search tasks becomes increasingly less efficient as the target is presented at more distant field eccentricities. However, if the stimuli are cortically magnified this effect could be flattened out (Carrasco & Frieder, 1997). Using the same computation of the cortical magnification factors as Carrasco & Frieder (1997) the size of letters on the three different spatial positions increased. Following the paper of Carrasco & Frieder (1997) no effects on the performance reflected in percent correct values and the different attentional components should be found. However, the general information processing components of the TVA were affected by different spatial positions although corrected by cortical magnification. More precisely, the processing speed was significantly higher in the nearest position to the fixation cross compared to the farthest spatial position. Therefore, it seems that the spatial position of targets has a remarkable influence on performance in the attentional components of the TVA (Bundesen, 1990) and that the components are not as independent from spatial variations as assumed. This detoriation effect with increasing distance from fixation cross should be even more pronounced if the stimuli are not magnified. To confirm these findings the same experiments have to be made without the magnification correction.

5.1.5.3 **Experiment 9**

In the last two experiments (partial and whole report) discussed in this section, two specific questions - again concerning the TVA (Bundesen, 1990) - were investigated. Like in Experiments 1 – 4 the whole and partial report methods were used in combination with inter-trial analysis of pairs of consecutive trials. The effects of exactly the same letters on exactly the same positions presented in pairs of consecutive trials (N-1 → N) on the components of the TVA were tested. For controlling if these possible effects are due to only the same letters or to the exactly same positions, same letters were presented at different positions in two consecutive trials.

The second question the experiments dealt with was if a difference in the size of the used (letter-)stimuli (uppercase or lowercase) influenced the effects of presenting same letters on same positions or same letters on different positions in pairs of consecutive trials. If there is no difference if the size is changed it would argue for processing of the stimuli on conceptual stages (i.e., it does not matter if a letter is written in upper or lower case, because the the concept of a ‘T’ (e.g.) is enough for recognising it), differences would argue for processing of purely visual features.

5.1.5.3.1 Method – Partial Report

In both whole and partial report the same possible intertrial transitions in pairs of consecutive trials (N-1 → N) could occur. Table 30 shows all possibilities.

Table 30. All possible intertrial transitions and the number of trial pairs

N-1	**N**		
size	size	position	trials
lower case	lower case	same	8
upper case	upper case	same	8
lower case	lower case	different	8
upper case	upper case	different	8
lower case	upper case	same	8
lower case	upper case	different	8
upper case	lower case	same	8
upper case	lower case	different	8

Participants. In the partial report of Experiment 9, thirteen students participated (two male, eleven female), all of them from the University of Fribourg. Participants’ age ranged between 19 and 42 years (M = 24.15 years; SD = 6.91 years). They received course credits or were paid 10 CHF. All observers had normal or corrected-to-normal vision, including normal colour vision. They had no previous experience with the partial report method.

Apparatus and stimuli. The apparatus was the same as in Experiment 7; stimuli and spatial arrangement were the same as in Experiment 3 (without changes in the colour).

Procedure. The procedure was similar to all reported partial report experiments. Again either three or six letters were presented in semi-circles to the left and/or right of a central fixation cross at one brief presentation time (resulting form the pre-test conducted previous to the partial report). Again, five different conditions were presented. The display consisted either of three (red) target letters in the left (3Tl), three (red) target letters in the right hemi-field (3Tr), three (red) targets in the left hemi-field together with three (green) non-targets in the right hemi-field (3Tl-3N), three (red) targets in the right and three (green) non-targets in the left hemi-field (3N-3Tr), or six (red) target letters (6Tlr; three in the left and three in the right hemi-field).

Like in all previously presented partial report experiments, all letters were followed by masks.

The eight possible intertrial transitions (Table 30) can be reduced to four different, because there should be no difference e.g., if lower case letters were repeated on the same position or upper case letters were repeated on the same position in pairs of consecutive trials. For each of the five conditions multiplied by the 8 trials for the four different intertrial transitions ([1] same size, same position; [2] same size, different position; [3] different size, same position; [4] different size, different position); 18 trials (necessary for a stable estimation of the components) were presented (5 x 8 x 18), resulting in 720 trials. The total of 720 trials (12 blocks with 60 trials) was presented in one test session lasting approximately one hour.

5.1.5.3.2 Results – Partial Report

Using the same procedure as in the partial report experiments reported before, the components of the lateralised sensory effectiveness, the spatial distribution of attentional weights, and the top-down control are estimated.

Equal distributions of sensory effectiveness over the left and right hemi-fields yield a value of $A = .5$, values larger or smaller than .5 indicate improved effectiveness in the left and right hemi-fields, respectively. The lateralised weight parameter w_λ indicates whether attentional weight attributed to objects is distributed evenly across the visual field. Even distribution of weights is reflected by $w_\lambda = .5$; values below and above .5 reflect greater weight (attentional bias) in the right and left hemi-fields, respectively. Top-down control indicates whether attentional resources are allocated to target objects or non-target objects, independent of their display locations. Top-down control is defined as the ratio of weight attributed to target and non-target objects $\alpha = (w_D / w_T)$, that is, the lower the value of α the more weight is attributed to targets, i.e., the more efficient top-down control of the selection process is.

Exposure durations varied within a range of 89.60 ms and 317.00 ms with a mean duration of 175.28 ms (SD = 64.48 ms).

In the first step, the parameters and percent correct values were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of the size or position changes or repetitions).

The overall mean performance in percent correct was at 51.42% correctly reported items (SD = 7.60).

The overall mean of the lateralised sensory effectiveness was at .45 (SD = .05) and significantly different from .5 ($t(12) = -3.70$; $p = .003$) arguing for a slight preference for targets on the right side. The spatial distribution of attentional weights was at .48 (SD = .10) and not significantly different from .5 arguing for equal weighting ($t(12) = -.77$; $p = .46$).

Finally, the top-down control was at .23 (SD = .13). That is, overall, observers were very well able to efficiently select target and deselect non-target items. A t-test of α values revealed that they were significantly different from 1 (the value of equal selecting of targets and non-targets) ($t(12) = -21.09$; $p < .001$).

In the second analysis step, potential effects of the experimental manipulation – changes or repetitions of position or size in pairs of consecutive trials – were analysed.

Analysing the pairs of consecutive trials in the four different possibilities ([1] same size, same position; [2] same size, different position; [3] different size, same position; [4] different size, different position), the top-down control was significantly higher in all second trials (N) compared to the first trials (N-1). Therefore, top-down control was better if the position and the size of the letters stayed the same, if the same letters in the same size were presented but on different positions, if size changed, but same letters were presented at the same position and if the position as well as the size of the letters changed (paired-samples t-test: no change: $t(12) = 4.49$; $p = .001$; position change: $t(12) = 5.71$; $p < .001$; size change: $t(12) = 4.44$; $p = .001$; position and size change: $t(12) = 2.83$; $p = .015$). Mean values of the top-down control can be extracted from Table 31. This overall better top-down control in all second trials is possibly due to the attempt to avoid location and negative priming effects with the presentation of 3Tl-3N in trial N-1 and condition 3N-3Tr in trial N (or the other way round). The same effect could be observed in Experiment 3a.

Table 31. Mean values of the top-down control for the pairs of consecutive trials (N-1 → N) for all four different possibilities (SD in brackets).

	N-1	N
no change	0.39 (0.22)	0.18 (0.17)
position change	0.39 (0.26)	0.10 (0.13)
size change	0.45 (0.24)	0.12 (0.17)
change	0.26 (0.17)	0.09 (0.13)

The distribution of attentional weights and the lateralised sensory effectiveness did not differ if the size or the position of the letters stayed the same or changed across consecutive trials (see Table 32).

Table 32. Mean values of the distribution of attentional weights (w_λ) and the lateralised sensory effectiveness (A_λ) for the pairs of consecutive trials (N-1 → N) for all four different possibilities (standard deviations in brackets).

	w_λ		**A_λ**	
	N-1	N	N-1	N
no change	0.48 (0.18)	0.45 (0.14)	0.45 (0.10)	0.46 (0.14)
position change	0.49 (0.14)	0.47 (0.22)	0.46 (0.09)	0.45 (0.14)
size change	0.56 (0.13)	0.52 (0.14)	0.38 (0.10)	0.43 (0.09)
change	0.49 (0.22)	0.51 (0.15)	0.40 (0.11)	0.44 (0.08)

Concerning performance in percent correct, values (see Table 33) were significantly higher in all second trials of the pairs (no change: $t(12) = -7.53$; $p < .001$; position change: $t(12) = -5.72$; $p < .001$; size change: $t(12) = -7.07$; $p < .001$; all changed: $t(12) = -3.69$; $p = .003$) (see Table 33).

Table 33. Mean values of performance (percent correct) for the pairs of consecutive trials (N-1 → N) for all four different possibilities (SD in brackets).

	N-1	N
no change	47.52 (6.60)	56.60 (8.14)
position change	46.79 (7.60)	53.18 (8.56)
size change	49.11 (7.80)	56.85 (7.93)
change	48.35 (8.47)	52.98 (9.10)

5.1.5.3.3 Method – Whole Report

Participants. In the whole report of Experiment 9, nine students participated (four male, five female), all of them from the University of Fribourg. Participants' age ranged between 19 and 27 years (M = 22.00 years; SD = 2.87 years). They received course credits or were paid 10 CHF. All observers had normal or corrected-to-normal vision, including normal colour vision. They had no previous experience with the whole report method.

Apparatus and stimuli. The apparatus was the same as in Experiment 7; stimuli and spatial arrangement were the same as in Experiment 4.

Procedure. The procedure was similar to all reported whole report experiments. Again five letters were presented in semi-circles to the left or right of a central fixation cross. Three different presentation times (resulting from the pre-test conducted previous to the whole report), masked and unmasked presentations of letters and two different colours resulted in 12 conditions.

The eight possible intertrial transitions (Table 30) can be reduced to four different, because there should be no difference e.g., if lower case letters were repeated on the same position or upper case letters were repeated on the same position in pairs of consecutive trials. For the resulting four different intertrial transitions (i.e., 8 trials) and for the twelve different conditions in whole report 16 trials were presented (necessary for stable estimation of the whole report components) (8 x 12 x 16 = 1538 trials).

A total of 32 blocks with 48 trials (1538 trials) split in two sessions lasting approximately 50 minutes, were presented.

5.1.5.3.4 Results – Whole Report

Using the same procedure as in the whole report experiments reported before, the components of the capacity of vSTM and processing speed are estimated. The vSTM capacity corresponds to the number of items processed simultaneously in visual short-term memory. The second important component, the processing speed reflects the number of items processed per unit time (second).

Mean masked exposure durations varied within a range of 57.50 ms and 120 ms with a mean duration of 100.83 ms (SD = 20.92 ms).

In the first step, the parameters and percent correct values were calculated, individually for each observer, independent of the experimental manipulation (i.e., independent of the size or position changes or repetitions).

The overall mean performance in percent correct was at 37.87% correctly reported elements (SD = 4.27). The overall mean of the capacity of vSTM was at 3.42 correctly reported elements (SD = .48) and of the processing speed at 24.66 elements/second (SD = 11.11).

In the second analysis step, potential effects of the experimental manipulation – changes or repetitions of position or size in pairs of consecutive trials – were analysed.

Analysing the influences of size or position repetitions or changes on the capacity of vSTM, a significantly higher capacity in the second trials (M = 3.36; SD = .49) compared to the first trials (M = 3.01; SD = .34) of pairs could be found if the same letters were presented at the same position in the same size (*t*(8) = -2.42; *p* = .042). The capacity was slightly (but not significantly) lower if the position (*t*(8) = .32; *p* = .755) or the size (*t*(8) = .92; *p* = .384) of the letters changed and if both changed slightly higher (*t*(8) = -.35; *p* =.736) (see Table 34).

Table 34. Mean values of the capacity of vSTM and the processing speed for the pairs of consecutive trials (N-1 ⟶ N) for all four different possibilities (SD in brackets).

	K		**C**	
	N-1	N	N-1	N
no change	3.01 (0.34)	3.36 (0.49)	23.44 (10.66)	30.13 (12.65)
position change	3.11 (0.40)	3.06 (0.33)	27.64 (14.38)	25.69 (10.26)
size change	3.11 (0.45)	3.05 (0.37)	25.66 (13.38)	28.19 (12.90)
change	3.07 (0.41)	3.13 (0.48)	24.87 (11.89)	28.19 (12.91)

The processing speed was significantly higher in the second trials (N) if the size as well as the position of the same letters in pairs of consecutive trials was repeated (*t*(8) = -2.52; *p* =.036). Values were at 23.44 items/second (SD = 10.66) in the first trials and in the second at 30.13 items/second (SD = 30.13). All changes did not have a significant effect on the second trials (position change: *t*(8) = 1.00; *p* = .342; size change: *t*(8) = -1.17; *p* = .276; all changed: *t*(8) = -1.77; *p* = .115).

Percent correct performance (see Table 35) was significantly higher in the second trials if neither the size nor the position changed (*t*(8) = -5.72; *p* < .001) and if the size of the letters changed but not their position (*t*(8) = -3.93; *p* = .004). The change of the position or of both – position and size – did not change performance (position: *t*(8) = -1.75; *p* = .117; all changed: *t*(8) = -.54; *p* = .601).

Table 35. Mean values of performance (percent correct) for the pairs of consecutive trials (N-1 → N) for all four different possibilities (SD in brackets).

	N-1	N
no change	36.61 (4.41)	39.73 (4.55)
position change	37.58 (4.52)	38.09 (4.11)
size change	37.29 (4.32)	38.99 (4.45)
change	37.18 (4.30)	37.48 (4.24)

5.1.5.3.5 Discussion

In the partial and whole report of Experiment 9 two specific questions - again concerning the TVA (Bundesen, 1990) - were investigated. Like in Experiments 1 – 4, the whole and partial report methods were used in combination with inter-trial analysis of pairs of consecutive trials. The effects of exactly the same letters on exactly the same positions presented in pairs of consecutive trials (N-1 → N) on the components of the TVA were tested. For controlling if these possible effects are due to only the same letters or to the exactly same positions, same letters were presented at different positions in two consecutive trials.

The second question the experiments dealt with was if the size of the used (letter-) stimuli (uppercase or lowercase) influences the effects of presenting same letters on same positions or same letters on different positions in pairs of consecutive trials. If there is no difference when the size changed it would argue for processing of the stimuli on conceptual stages (i.e., it does not matter if a letter is written in uppercase or lowercase, because the the concept of a 'T' (for example) is enough for recognising it), differences would argue for processing of purely visual features.

In partial report, top-down control was significantly better in second trials of all possible inter-trial transitions. This overall better top-down control in all second trials is possibly due to the attempt to avoid additional location and negative priming effects with the presentation of 3Tl-3N in trial N-1 and condition 3N-3Tr in trial N (or the other way round). The same effect was observed and discussed in Experiment 3a. The distribution of attentional weights and the lateralised sensory effectiveness did not differ, if the size or the position of the letters stayed the same or changed across consecutive trials.

Analysing the whole report performance, there was a significant higher capacity of vSTM and processing speed in second trials of the pairs if the same letters were presented at the same location in pairs of consecutive trials. The general information processing components can be enhanced through the repetition of exactly the same letters. The system seems to be able to maintain the activation for the stimuli and their position on the actual trial facilitating the selection performance in the following trial. Since neither size nor position changes affected the performance reflected in the different attentional components of the TVA (Bundesen, 1990) the results argue for processing of the experimental stimuli on high conceptual processing stages. The concept of a certain letter is enough for recognising the letter regardless of the upper or lower case.

5.1.6 General Discussion

The aim of Experiments 1 and 2 was to investigate effects of feature changes and repetitions on parameters of Bundesen's (1990) TVA. In the partial report task of Experiment 1 and the whole report task of Experiment 2, the colour or the target items repeated or changed, in a pseudo-random fashion, in consecutive trials. In Experiment 1, lateralised sensory effectiveness, average distribution of attentional weight, and the effectiveness of top-down control were estimated. In Experiment 2, visual short-term memory capacity and processing speed were analysed. In both Experiments 1 and 2, overall values were derived first, and in a second step, the effects of intertrial repetitions or changes of the target-defining colour were examined.

In Experiment 1, mean lateralised sensory effectiveness was slightly, but significantly, higher in the right hemi-field. Processes of sensory perception were more efficient for targets presented in the right hemi-field. Similarly, the average distribution of attentional weights showed a significant bias towards the right hemi-field. Sensory effectiveness did not vary across trials, irrespective of whether the feature was repeated or changed. Similarly, there was no effect of feature repetition or change in the spatial distribution of attentional weights.

The average of the parameter of top-down control effectiveness (α = .72) indicated that, overall, observers were able to efficiently select target and deselect non-target items.

Analysis of top-down control effectiveness revealed a significant advantage in the second relative to the first of two consecutive trials, if the target feature was repeated; in feature change trials, although there was a benefit in the second compared to the first trial also, the difference was not significant.

In Experiment 2, average short-term memory capacity was 2.6 items and average processing speed estimates indicate that about 37 elements per second are processed on average.

Analysis of feature change and repetition trials shows that processing speed was not affected by inter-trial transition. Importantly, analysis of the visual short-term capacity across trials revealed a significant capacity increase in the second of two consecutive trials in feature repetition conditions: the capacity was 3.81 items in the first and 4.12 items in the second trial.

Normally, values of the vSTM capacity are lower than the values found in the present experiment (at around 3.5). The high values are probably due to the spatial arrangement of the targets in the whole report experiment. The letters were presented in both hemifields and always on the same six positions. Subjects always knew at which positions the letters were presented and could top-down prepare their system resulting in higher capacity limits. Most likely the results can be interpreted in line with Alvarez and Cavanagh (2005). In their study they found that twice as many targets could be successfully tracked when targets were presented in the left and right hemifield compared to when all targets were presented within the same hemifield. Alvarez and Cavanagh (2005) concluded that their results rule out a single attentional focus. Therefore, independent (and independently limited) resources account for attentional tracking in the left and in the right hemifield. The present results could argue for two independent capacities – one in the right and one in the left hemisphere – contributing to the overall high vSTM capacity found in Experiment 2. In line with Alvarez and Cavanagh (2005), Kraft et al. (2005) showed that if participants have to compare the identity of two out of four stimuli in a difficult condition, performance of the subjects was always better when the stimuli were presented in both hemifields indicating a bilateral field advantage. They proposed a model which permits the hemispheres to maintain and control simultaneous attentional foci. Chakravarthi and Cavanagh (2009) found a bilateral field advantage as well. Their results revealed a better target identification when two precued targets were presented in different hemifields than when they were within the same hemifield. They argued in favor of separate attentional resources in the left and right hemifield. If in further research the assumption of two independent capacities can be maintained then the method for getting the vSTM capacity values in TVA, namely computing the mean out of the capacity in the left and in the right hemifield, has to be corrected.

Overall, Experiments 1 and 2 suggest that the repetition of target features across consecutive trials improves and facilitates the ability to top-down set weight to target items and to ignore non-target items. Put differently, if the features defining the targets change, the selective system needs to attribute weights to the changed target feature, a process that is associated with costs. Importantly, short-term memory capacity is increased if the target feature remains the same across trials. This suggests, in accord with recent findings in the literature, that short-term memory capacity is variable (e.g., Alvarez and Cavanagh, 2004) rather than stable (Bundesen, 1990). Further, variability of short-term memory capacity occurs in a very short temporal frame in the range a few seconds.

In sum, theories of visual search and visual selection that neglect effects of short term-memory required amendments. On the other hand, the present findings provide further support for the Dimension Weighting account (Müller, Heller & Ziegler, 1995; Found & Müller, 1996) that assumes that processing on the level of generation of feature-based saliency signals is subjected to limitations in processing resources. In addition, the results are in line with Maljkovic and Nakayama's (1994) findings of better performance through repetition of features.

Experiments 3a, b and c (partial report) and 4 (whole report), were designed to examine the effects of single (as in Experiments 1 and 2) versus multiple feature changes on parameters of Bundesen's (1990) TVA. In Experiment 3a, 3b, 3c and 4 targets were either red or green (dimension colour) and uppercase or lowercase (dimension form) letters, non-targets were always blue (lowercase or uppercase) letters. In Experiment 3a, target positions were repeated across trials, in Experiment 3b, positions changed randomly across trials, and in Experiment 3c, positions changed in a predictable fashion across trials.

As in Experiment 1, in **Experiment 3** the right hemi-field sensory effectiveness was slightly higher then left hemi-field sensory processing. Attentional weight, however, is evenly attributed to objects in the left and right visual hemi-field.

Effectiveness of top-down control varied with condition in Experiment 3. In Experiments 3a α = .40, in Experiment 3b α = .74, and in Experiment 3c α = .90. Recall that lower values indicate higher effectiveness of top-down control. Repetition of target location across trials is mirrored in high top-down effectiveness (Experiment 3a), random variations in target locations produce an average α-value similar to the one observed in Experiment 1. Importantly, predictability, i.e., (implicit) knowledge of the target location in the upcoming trial (Experiment 3c), does not improve top-down control effectiveness, rather, if anything, top-down control is worse compared to conditions in which target location varies randomly. This finding might reflect a difficulty in shifting, voluntarily, the location where a target is expected to appear relative to the location where the target appeared (physically) in the current trial. The present finding confirms a result reported by Maljkovic and Nakayama (1994, 1996), who also showed that the ability to predict target characteristics does not improve search performance.

Analyses of inter-trial changes and repetitions did not affect sensory effectiveness in any of the conditions of Experiment 3, neither was the spatial distribution of attentional weights affected.

Top-down control was affected by intertrial transition in **Experiment 3a** in which target location was repeated; top-down control increases in all conditions, irrespective of feature change or repetition across trials. The (implicit) knowledge of the target location increases the ability to allocate top-down processing resources. Probably the location of the target in the actual trial stays bottom-up activated in the sense of some kind of saliency signal and facilitates selection in the consecutive trial.

Different to Experiment 3a, in **Experiment 3b** in which target location changed randomly across trials, no significant difference was observed between consecutive trials in any of the change conditions

Interestingly, the worst intertrial transition effect was observed in **Experiment 3c** in which the target locations changed predictably. Recall that location change in Experiment 3 was associated with the repetition versus change in one or two features (colour, shape). If features were repeated, there was an increase in top-down control across consecutive trials. If one feature changed, top-down control was essentially the same in the first and second trial in a pair of trials. If both features changed, top-down control was worse in the second than in the first of two trials.

To sum, the effectiveness of top-down control is massively affected by the constant versus variable target locations. The breakdown of top-down control in Experiment 3c is probably due to interference between spatial and feature-based components of resource allocation (allocation of resources to the predicted stimulus location and allocation of resources to the predicted feature).

In **Experiment 4**, effects of single feature changes and dual feature changes on processing speed and short-term memory capacity were examined. Overall average processing speed was at about 20 items per second and overall short-term memory capacity was at 3.4 items.

Short-term memory capacity remained basically unaffected in Experiment 4 by both feature repetition and change trials.

Importantly, in feature repetition trials the processing speed is significantly accelerated in second trials of pairs of consecutive trials relative to first trials. In contrast, in feature change trials, neither the change of one feature nor the change of two features affected processing speed significantly.

Taken together the findings suggest that the effectiveness of top-down control of resource allocation is affected by the presentation condition. Repetitions of target locations improve top-down control, while random selection of target locations and predictable target locations, together with changes in the target-defining features severely impair top-down control.

Further, repeating the target feature across trials in conditions in which the target feature may vary in one dimension (colour) increase visual short-term memory capacity in a short temporal frame of a few seconds (i.e., across consecutive trials). In conditions in which the target-defining features change in multiple dimensions (colour, shape) processing speed, rather than short-term memory capacity, is affected by intertrial repetitions versus changes.

Therefore, general information processing components such as the vSTM capacity and the processing speed as well as the components of the spatial distribution of attention such as the top-down control are affected by bottom-up changes in target features.

In terms of models of visual search, the present findings support the concept that bottom-up changes in target features entail the requirement of adjustments in processing resources at an early level of feature encoding and/or saliency computation (e.g., Müller, Heller & Ziegler's 1995, Dimension Weighting account).

In terms of models of working memory, the present findings suggest that short-term memory capacity is adjustable rather then fixed, and that the adjustment occurs in a fine-grained temporal frame.

In Experiment 5 (partial report) and 6 (whole report) the focus was on the influence of top-down information on the components of the TVA. The effects of a symbolic cue, indicating the likely feature (colour) of the target letters, on the lateralised sensory effectiveness, top-down control, spatial weighting, capacity of VSTM and speed of processing was investigated. The cue was either valid or invalid or neutral. For the analysis the valid, invalid and neutral condition were compared with each other. In the valid condition the presented cue indicated the real colour of the targets, in the invalid condition the wrong colour. The neutral cue gave no hint in which feature the target letters were defined.

In **Experiment 5** the cue could neither influence the lateralizend sensory effectiveness, nor the spatial distibution of attentional weights, nor the selection effectiveness (top-down control). Therefore, the parameters, reflecting spatial aspects of attention seem not to be affected by top-down information. Interestingly, although due to the insufficient number of trials for stable estimation of the parameter K is not really reliable, estimates of the vSTM capacity were affected by the top-down information (cue). Valid cues significantly increased the capacity of vSTM and subjects could report significantly more items compared to invalid cue conditions. The results concerning the vSTM can serve as a hint and have to be confirmed by the whole report experiment (Experiment 6).

Experiment 6 revealed no significant difference in the processing speed if the dimensions of the upcoming target letters were validly, invalidly or neutrally cued. Therefore, top-down information does not help to speed up or slow down the system. However, valid cues significantly affected the capacity of vSTM (K = 4.72) compared to both, neutral (K = 4.15) and invalid (K = 4.16) cue trials. To conclude, the vSTM can be influenced and enhanced remarkably by top-down information about the upcoming target dimension. The system is set for the dimension of the upcoming targets and this facilitates the storing of more items in vSTM. This suggests, in accordance to recent findings in the literature, that vSTM capacity is variable (e.g., Alvarez & Cavanagh, 2004) rather than stable (Bundesen, 1990) depending on the specific setting.

The untypically high values of the vSTM capacity at 4.72 elements (normally around 3.5) and the processing speed with values around 60 elements per second (normally at around 30) are probably due to the spatial arrangement of the targets in the whole report experiment. The letters were presented in both hemifields and always on the same six positions. Subjects always knew at which positions the letters were presented and could top-down prepare their system resulting in higher capacity limits. Most likely the results can be interpreted in line with Alvarez and Cavanagh (2005). In their study they found that twice as many targets could be successfully tracked when targets were presented in the left and right hemifield compared to when all targets were presented within the same hemifield. Alvarez and Cavanagh (2005) concluded that their results rule out a single attentional focus. Therefore, independent (and independently limited) resources account for attentional tracking in the left and in the right hemifield. The present results could argue for two independent capacities – one in the right and one in the left hemisphere – contributing to the overall high vSTM capacity and processing speed found in Experiment 6. If in further research the assumption of two independent capacities can be maintained then the method for getting the vSTM capacity values in TVA, namely computing the mean out of the capacity in the left and in the right hemifield, has to be corrected.

Summing up Experiments 1-6, top-down and bottom-up information can influence the categorisation process and therefore the attentional components of TVA, repeatedly the capacity of vSTM. Variability and enhancement of the vSTM in specific situations is therefore possible. Since vSTM is a very important component for everyday normal functioning and if the short-term memory capacity can be increased by certain experimental manipulations it is highly probable that it can be increased by training. Therefore it is very important to train children’s brains while they are still developing. Furthermore it is possible to train and improve short-term memory capacity in people suffering from short-term memory problems (Gathercole & Alloway, 2006).

Overall, results from Experiments 1-6 revealed significant influences of bottom-up and top-down information on the components of the TVA (Bundesen, 1990). Therefore, the idea of the automatic and relatively independent categorisation process, proposed by Bundesen cannot be maintained.

In a series of further experiments (Experiment 7-9), I wanted to further investigate specific questions with regard to the characteristics of the TVA (Bundesen, 1990). The question was if different spatial arrangements of the experimental stimuli (Experiment 8), repetitions of exactly the same stimuli in consecutive trials (Experiment 9) or repetitions of the same stimulus within the same trial (Experiment 7) affect the categorisation process and therefore the four attentional components of the TVA (Bundesen, 1990).

In **Experiment 7**, the processing of target repetitions in one and the same trial was investigated. Influences of target repetitions on the categorisation process were tested by using the whole report procedure. In one trial with five target letters, one letter was repeated (i.e., presented twice) and compared to trials in which letters were presented once per trial.

Increasing percent correct values were assumed to arise if the same target was presented twice in one trial. The probability of detecting one of the two targets at a certain point in time should be bigger than to detect one of one target. Interestingly, this does not seem to be the case in Experiment 7.

Concerning the components of the TVA (capacity of vSTM and the processing speed) the capacity of vSTM was decreasing in trials, in which one target was presented twice. In other words, the capacity of vSTM was higher if the target was presented once per trial. It seems that all available slots in vSTM are occupied by target items, however, the total amount of information was reduced by the doubled letter. One explanation might be that the neighbouring same targets masked each other and therefore participants were not able to name them both. Furthermore, there is possibly an additional task for the system to briefly store two same stimuli, which goes then on the expense of the vSTM capacity.

Contrary to the capacity of vSTM the processing speed was increased whenever two same targets in one trial were presented. This finding was as expected that the processing of the system was facilitated by repeating one and the same stimulus. Interestingly, although there was a higher processing speed, the vSTM capacity was decreased if two of the same stimuli were presented. The two same stimuli seem to remove a huge amount of capacity which is then not available anymore for the remaining targets.

The effects of different spatial positions of the stimuli of the whole and partial report tasks on the components of the TVA were investigated in **Experiment 8**. Analysing the partial report data, neither in top-down control, nor in the lateralised sensory effectiveness, nor in the spatial distribution of attentional weights, different spatial positions had an effect on performance. Spatial variations therefore cannot influence the spatial parameters of the TVA. In whole report, the processing speed was significantly higher in the nearest position to the fixation cross compared to the other two spatial positions.

According to Carrasco, Evert, Chang and Katz (1995) detection of targets in feature or conjunction search tasks becomes increasingly less efficient as the target is presented at more distant field eccentricities. However, if the stimuli are cortically magnified, this effect could be flattened out (Carrasco & Frieder, 1997). Using the same computation of the cortical magnification factors as Carrasco and Frieder (1997) the size of letters on the three different spatial positions increased. Following the paper of Carrasco and Frieder (1997) no effects on the performance reflected in percent correct values and the different attentional components should be found. However, the general information processing components of the TVA were affected by different spatial positions although corrected by cortical magnification. More precisely, the processing speed was significantly higher in the nearest position to the fixation cross compared to the farthest spatial position. Therefore, it seems that the spatial position of targets has a remarkable influence on performance in the attentional components of the TVA (Bundesen, 1990) and that the components are not as independent from spatial variations as assumed. This detoriation effect with increasing distance from fixation cross should be even more pronounced if the stimuli are not magnified. To confirm these findings the same experiments have to be made without the magnification correction.

In the last two experiments (partial and whole report) discussed in this section (**Experiment 9**) two specific questions - again concerning the TVA (Bundesen, 1990) - were investigated. Like in Experiments 1 – 4, the whole and partial report methods were used in combination with inter-trial analysis of pairs of consecutive trials. The effects of exactly the same letters on exactly the same positions presented in pairs of consecutive trials (N-1 → N) on the components of the TVA were tested. For controlling if these possible effects are due to only the same letters or to the exactly same positions, same letters were presented at different positions in two consecutive trials.

The second question the experiments dealt with was if there is a difference if the size of the used (letter-) stimuli (uppercase or lowercase) influenced the effects of presenting same letters on same positions or same letters on different positions in pairs of consecutive trials. If there is no difference if the size changed it would argue for processing of the stimuli on conceptual stages (i.e., it does not matter if a letter is written in uppercase or lowercase, because the the concept of a ‘T’, e.g., is enough for recognising it), differences would argue for processing of purely visual features.

In partial report, top-down control was significantly better in second trials of all possible inter-trial transitions. This overall better top-down control in all second trials is possibly due to the attempt to avoid additional location effects with the presentation of 3Tl-3N in trial N-1 and condition 3N-3Tr in trial N (or the other way round). The same effect was observed and discussed in Experiment 3a. The distribution of attentional weights and the lateralised sensory effectiveness did not differ, if the size or the position of the letters stayed the same or changed across consecutive trials.

Analysing the whole report performance, there was a significant higher capacity of vSTM and processing speed in second trials of the pairs if the same letters were presented at the same location in pairs of consecutive trials. The general information processing components can be enhanced through the repetition of exactly the same letters. The system seems to be able to maintain the activation for the stimuli and their position on the actual trial facilitating the selection performance in the following trial. Since neither size nor position changes affected the performance reflected in the different attentional components of the TVA (Bundesen, 1990) the results argue for processing of the experimental stimuli on high conceptual processing stages. The concept of a certain letter is enough for recognising the letter regardless of the upper or lower case.

Concluding the results of the last three experiments, the repetition of the same target in one trial, the spatial position of the stimuli and the repetition of exactly the same letters on exactly the same location could affect the components of the TVA. Testing with TVA based methods therefore requires carefulness in the selection of the stimuli, their arrangement and their features.

5.2 Project II: Visual Search Tasks Reveal Enhanced Selection Performance in Observers with the Asperger´s Syndrome

5.2.1 Summary

Recent research revealed performance benefits in visual search tasks in observers with autism compared to unimpaired observers. In visual search tasks, observers decide whether a target object is present among a variable number of distractor objects or not. Targets may be defined by a unique feature (a red apple among green apples) or a conjunction of features (a large red apple among small red and large or small green apples). Reaction times (RT) in feature search conditions are independent of the number of display items; RTs in conjunction search conditions increase linearly with the number of objects to be searched. Compared to controls, autistic children and adults showed faster search RTs than age-matched unimpaired controls in both feature and conjunction search conditions without trading speed for accuracy in either condition. Further, in conjunction search, participants with autism did not show an increase in RTs with an increasing number of search items – an effect characterizing conjunction search tasks.

In order to further contribute to the understanding of the mechanisms underlying search in autistic observers and to identify the component process(es) giving rise to the expedited search times in autistic observers, feature and conjunction search performance was investigated in participants with Asperger's syndrome – an autism spectrum disorder comparable to mild forms of autism.

Compared to a control group of healthy observers, in the (singleton) feature search task, mean RTs of observers with Asperger's syndrome were significantly faster. Search rates (search time per item, a measure of search efficiency) in target-present trials were also significantly faster in observers with Asperger's syndrome than in the control group. In conjunction search, mean RTs in the Asperger's group were again faster than in the control group. Dissimilar to the findings with autistic observers reported in the literature, search rates of participants with Asperger's syndrome were statistically reliably affected by the number of display items. However, while mean search rates differ significantly between the feature and conjunction search conditions in the sample of healthy controls, there was no significant task-dependent search rate difference in participants with Asperger's syndrome.

Further, controls required considerably more time for the completion of component processes not related to searching for the target item such as (visual) parsing of the display, or response selection / execution.

Overall, the present empirical results of Experiment 1 and 2 indicate that search performance in observers with Asperger's syndrome is significantly faster and more efficient than in age-matched healthy controls. However, apart from the overall expedition of search reaction times, the pattern of search performances is similar to that observed in the healthy observers.

Further experimental work (Experiments 3-5) was aimed at probing potential loci, i.e. component mechanisms of information processing and selection, underlying the performance benefits of the Asperger's group compared to the sample of healthy controls. In particular, it was examined whether the difference arises at an early (pre-selective stage of structuring of the visual scene or feature extraction) or later (selective or post-selective) stage of processing. Results rather point at a processing difference arising in later processing stages.

Finally, it was examined whether the complex stimuli – letters – commonly used in the literature might contribute to the observed advantage in autism and autism spectrum disorders. The Asperger's group and the control group did not differ in search for other complex stimuli (pseudo-letters). Therefore, the difference in processing performance between the two groups found in Experiment 1 and 2 are probably, at least partially, due to the fact that highly overlearned letters were used as stimuli.

5.2.2 Introduction

Recently, the performance of people suffering from one of different forms of autism in tasks involving selective visual processing has moved into the focus of research interest. The interest was mainly generated because people suffering from early childhood autism or Asperger's syndrome show significantly expedited search times compared to (age-matched) healthy control groups. Some of the differences are quantitative, others qualitative, in nature suggesting that, in people with autism, visual processing might be mediated by processes that are expedited and, possibly, by mechanisms different from those assumed to underlie visual selective processing in unimpaired observers.

The objectives of the present study are two-fold. The first aim is to describe performance in visual search tasks in people with a particular form of an autistic disorder, Asperger's syndrome. The second aim is to compare search performance of observers with Asperger's syndrome to search performance in healthy age-matched controls and to people with autism.

'Classical' or early childhood autism (ICD-10: F84; DSM-IV: 299.00) is a highly variable but profound developmental disorder with onset in early childhood. The course of the disease is stable without any noticeable amelioration. Autism is defined in terms of abnormalities in social interactions and the development of communication abilities, in the presence of marked repetitive behaviour, restricted interests and limited imagination. Certain disturbances in perception and information processing in the brain seem to cause autism. Early childhood autism can be seen as a 'spectrum disorder' with early childhood autism at the lower end and Asperger's syndrome at the upper end of the autistic spectrum (Ehlers et al., 1997).

Asperger's syndrome (ICD-10: F84.5; DSM IV: 299.80) is comparable to a mild form of autism with low severity of autistic symptoms. According to Klin (2006) Asperger's syndrome differs from autism in that language acquisition is not generally delayed and in there being no delay in cognitive development; Asperger's syndrome is further characterized by normal intellectual abilities and self-help skills as well as a lower prevalence (of two to four cases in

10,000) than early childhood autism (10 cases in 10,000). Persons with Asperger's syndrome show a substantial delay in the development of their abilities of social interaction and a development of very restricted, repetitive patterns of behaviours, interests and activities, including a persistent preoccupation with parts of objects. These abnormalities tend to persist into adulthood. Overall, it is not that clear which anomalies observed in people with Asperger's syndrome are specific to disorders in the autism spectrum (Happé & Frith, 2006).

Neuropsychological cardinal symptoms in autism are disturbances in executive functions (Ozonoff, Pennington & Rogers, 1991) such as planning of everyday activities and problem solving. The deficits in the executive functions have been suggested to reflect dysfunction of prefrontal cortical areas in many autistic cases (Ozonoff et al., 1991), resulting, in turn, in attentional problems and deficient planning of everyday activities (Ehlers et al., 1997). According to Schatz, Weimer and Trauner (2002) attentional problems in many individuals with autism spectrum disorders may be a significant component of the disorder. Perceptual anomalies (Frith, 1989; Happé, 1994; Mottron & Belleville, 1993) were found to affect the visual perceptual skills of persons with Asperger's syndrome (Klin, 2003, 2006). Visuo-perceptual disturbances seem to be a persistent feature of autism in the entire course of the disease and they can be found both in children and adults (O'Riordan, 2004).

The cognitive anomalies in autism are usually seen as deficits rather than as superior skills (Jolliffe & Baron-Cohen, 1997). Several recent studies, however, have provided evidence that particular abilities in observers with autism spectrum disorders may be superior compared to those of unimpaired observers. In particular, it was shown that basic perceptual processes such as low-level discrimination are not only intact in autism, but rather they seem to be enhanced (Mottron et al., 2006). For example, Mottron et al. (2006) showed that autistic observers have enhanced low-level discrimination and enhanced perception of first order static stimuli. On this account, autism should be viewed as a *different,* rather than an impaired, type of information processing in comparison to control groups (Jolliffe & Baron-Cohen, 1997). Importantly, the enhanced perceptual abilities found in autism spectrum disorder seem to give raise to 'positive symptoms' in disorders in the autism spectrum (Mottron et al., 2006).

The detailed investigation of perceptual processes thus constitutes a highly promising approach to the investigation of specific dissimilarities between different forms of autistic impairment.

Recently, a number of studies using several different tasks have revealed superior perceptual performance in subjects with autism or an autistic spectrum disorder compared to healthy controls (e.g., Frith, 1989; Plaisted, O'Riordan & Baron-Cohen, 1998a; Bertone et al., 2005; Mottron et al., 2003). Shah and Frith (1993) used a *block design* task in which the participant is required to take blocks with either all white sides, all red sides, or red and white sides and arrange them according to a given pattern. Participants with autism outperformed the healthy control group in this task by completing the task significantly faster. In a *perceptual learning* task Plaisted, O'Riordan and Baron-Cohen (1998a) found significantly better discrimination of novel, highly similar stimuli in adults with autism compared to the controls. Shah and Frith (1993) and Jolliffe and Baron-Cohen (1997) found that children with autism are more accurate and faster in the *Embedded Figures Test* (EFT; Spreen & Benton, 1969) in which observers are instructed to search for a simple shape embedded within a complex figure. In the *shape detection* task, stimuli can be analyzed at a global or local level, i.e. as whole shapes or in terms of individual features, respectively. Using a series of visual tasks involving global versus local analyses, Mottron et al. (2003) found faster search for embedded stimuli in a *dis-embedding* task in high-functioning autistic observers than in healthy controls. Jolliffe and Baron-Cohen (1997) extended the findings of superior performance of autistic children in the EFT with an experiment in which they collected response times, tested autistic adults with normal intellectual abilities and adults with Asperger's syndrome. Both clinical groups revealed significantly faster reaction times in the EFT compared to the control group.

The tasks discussed above (block design task, EFT, and discrimination task) require item discrimination: the appropriate block face forming part of a design in the block design test, the hidden figure in the embedded figures task, and the unique features of each stimulus in the discrimination task need to be compared to different items in the neighbourhood.

The finding that autistic participants revealed significantly better results on all of these tasks argues for a superior ability in item discrimination. Therefore, any such superior ability should also be evident in visual search tasks, in which subjects are required to decide on the presence or absence of a pre-defined target item that is embedded in an array of irrelevant distractor objects. In visual search experiments, in addition to accuracy, observers' reaction times are analyzed. Mean reaction times (RTs) provide a 'pure' measure of selective, i.e., attentional, processing (Nydén, Gillberg, Hjelmquist & Heiman, 1999), because RTs seem to be confounded only by simple motor speed. Reaction time measures the time elapsed between the onset of the presentation of a sensory (visual) stimulus and the subsequent behavioural response of the observer, indicating how quickly a particular stimulus display is processed. Processing includes several cognitive and motor components on the level of perception (feature extraction, feature representation), memory (matching of a seen stimulus with target template involving feature integration), and execution (selection, planning, and execution of a response).

Usually, in visual search, observers are presented with equal proportions of trials containing a variable number of display items (referred to as the 'set size'). Set size is varied in at least three stages and displays may or may not contain a target item. Set size variation allows reaction times to be analyzed as a function of set size. It was shown (e.g., Treisman & Gelade, 1980) that search for feature targets is independent of set size; in other words, the time it takes to detect a target that differs from distractors by a single feature (a red apple among green apples) is independent of the number of distractors. In contrast, if the target is defined by a feature conjunction (a small red apple among large red and small green or large green apples), search reaction times increase in a linear fashion with the number of items presented in the search display. Search reaction time functions relate search times with set size; usually search functions are given separately for target-present and target-absent conditions.

One important component of the search function is the y-axis-intercept. The y-axis intercept reflects the time necessary for the completion of the component processes not related to searching the display objects for the target; the non-search related components of the overall response time are comprised of perceptual analysis of the display (i.e., structuring of the display into units that underlie selection), and the selection and execution of the appropriate response. The intermediate processes of allocating attention to a particular display item and comparison of the selected item with the target template is referred to as the search process proper. Each search function is characterized by a particular slope. Feature searches produce flat slopes, as reaction times are independent of the number of display items; and slopes do not differ between target-absent and target-present conditions. Conjunction searches produce slopes that reflect dependency of reaction time and set size. In addition, in conjunction search, the ratio of slopes of target-absent to target present-trials is 2:1 reflecting exhaustive search in absent-trials (each item needs to be checked and rejected) and self-terminating search in present-trials (as soon as the target is detected, search is terminated). The slope of the search function can be used to derive the 'search rate', that is, the time it takes to process one display item. The search rate constitutes a measure of search efficiency. The flatter the search function of a given observer, the more efficient is the search (feature search); consequently, the steeper the search function, the less efficient is the search (conjunction search).

In a feature search task, as the time it takes to detect the target is independent of the number of distractors, display items are processed efficiently, in a parallel fashion, resulting in flat search functions with slopes of approximately 0 ms per item. In a conjunction search task, with increasing set sizes, the time it takes to detect the target increases linearly, indicating inefficient, serial processing of display items, resulting in steep(er) slopes. In feature search, search rates are at around 0 ms per item; generally, search rates below 10 ms per item are interpreted as indicative of efficient (parallel) search, while search rates of above 10 ms per item in combination with the 2:1 target-absent to target-present ratio of search slopes indicate inefficient (serial) search (Treisman & Gelade, 1980; Davis & Driver, 1998).

Plaisted, O'Riordan and Baron-Cohen (1998b) and O'Riordan et al. (2001) used a variant of the search conditions discussed above to test search performance in children with autism. In detail, in the feature task of Plaisted et al. (1998b), the target was a red letter 'S', distractors were red 'Ts' and green 'Xs'; that is, the target was unique in terms of shape, but it shared its colour with one set of distractors (the red T's) – the target was defined by one feature, namely the shape. In the conjunction search task, the target was a red 'X' and distractors were red 'Ts' and green 'Xs'; that is, the target shared its colour with one set (red T's) and its shape with the other set of distractors (green X's) – the target was defined by a unique conjunction of colour and shape.

The results showed that children with autism performed better both in feature and conjunction search tasks than healthy children of the same age; search reaction times in both search conditions were faster without any loss in accuracy. Importantly, in the conjunction task, observers with autism did not produce significantly higher RTs with increasing set size, an effect that usually characterizes conjunction search performance and that was observed in the sample of age-matched controls (Plaisted, O'Riordan and Baron-Cohen, 1998b). Moreover, O'Riordan et al. (2001) found the biggest difference between the groups of observers with autism and the control group in target-absent trials.

O'Riordan (2004) showed that adults with autism were superior in both search tasks, essentially replicating the findings of Plaisted, O'Riordan and Baron-Cohen (1998b) in adults. In interpreting their findings, Plaisted, O'Riordan and Baron-Cohen (1998b) and O'Riordan et al. (2001) argue that autistic persons seem to be extremely good at detecting unique items, an interpretation that is supported by results obtained in other visual perceptual tasks such as the Embedded Figures Task (Jolliffe & Baron-Cohen, 1997).

In a further experiment O'Riordan and Plaisted (2001) manipulated the similarity between the target and the distractor items. The autistic children showed an enhanced performance in visual search tasks and were not slowed to the same degree as the control children by an increase in target-distractor similarity (note that no differences between the groups of autistic and control children were found if target-distractor similarity was very low). In terms of the stimulus material used, it is interesting to note that, in almost all of the search tasks in which autistic observers outperformed the healthy controls, letters were used as stimuli.

The finding of a superior discrimination ability in visual search proposed by O´Riordan and Plaisted (2001) is consistent with the findings of the better discrimination between novel, highly similar stimuli (Plaisted et al., 1998b), better performance in the EFT (e.g. Shah & Frith, 1993; Jolliffe & Baron-Cohen, 1997) and in the faster RTs in the block design task (Shah & Frith, 1993).

Based on the findings in observers with autism (at the lower end of the autistic spectrum) discussed above, the present study aims at examining whether a similar pattern of results is also found in observers with Asperger's syndrome (at the upper end of the autistic spectrum). Data obtained in a group of participants with Asperger's syndrome will be compared to the data of age-matched controls, and on the level of patterns of search behaviour with the samples of autistic observers reported in the literature (Plaisted, O'Riordan & Baron-Cohen, 1998b; O'Riordan et al., 2001; O'Riordan, 2004). By these comparisons a contribution to a better differentiation of subtypes along the autistic spectrum is expected. In addition, the reaction time analyses performed in previous studies will be extended in the present approach.

If a difference in visual search performance between the Asperger's group and healthy controls is indeed observed, in a following step, the location (early or late) of the processing difference in the visual processing stream is investigated. Furthermore, potential processes giving raise to the difference will be investigated with respect to whether it is possible that the specific and complex features of the letters that are used as stimuli in a majority of the studies cited above mediate, at least in part, the advantage of people on the autistic spectrum. (One important characteristic of letters is that they are highly overlearned.) Thus, it can be hypothesized that the Asperger's group and the control group differ concerning their respective efficiencies of letter processing.

5.2.3 Experiment 1 & 2: Feature and Conjunction Search Task

5.2.3.1 Method

Two visual search tasks (singleton feature search and conjunction search) were conducted in separate sessions with the order of task counterbalanced within two groups of observers (Asperger's syndrome and control). All the experiments were conducted online.

Experiment 1: Singleton Feature Search

Experiment 1 was designed to replicate the findings in autistic children and autistic adults (Plaisted, O'Riordan & Baron-Cohen, 1998b; O'Riordan et al., 2001; O'Riordan, 2004) of superior performance in singleton feature search. In a singleton feature search task the results of a group of observers with Asperger's syndrome is compared with an age- and gender-matched control group. As in the studies of Plaisted, O'Riordan and Baron-Cohen (1998b) and O'Riordan et al. (2001) the observers were instructed to search for a feature target (red S) among two sets of distractors (red T's and green X's). That is, the target differs from non-targets by shape, while sharing colour with one subset of distractors. If the observers with Asperger's syndrome show the same performance pattern as the autistic observers (in the studies of Plaisted, O'Riordan & Baron-Cohen, 1998b; O'Riordan et al., 2001), faster overall reaction times and faster search rates (search times per item) but no trade-off between search speed and search accuracy should be found if the Asperger's groups' RTs are compared to the healthy control group.

Participants. 13 observers with Asperger's syndrome (6 male, 7 female) ranging in age between 17 and 57 years (M = 36.1 years, SD = 15.5 years) and 15 healthy (control) observers (6 male, 9 female) ranging in age between 18 and 59 years (M = 41.3 years, SD = 14.9 years) participated in Experiment 1. The experiment consisted of one session. Statistical analyses show that the two experimental groups did not differ in terms of age ($t(26) = -.916$; $p = .368$) or gender ($\chi^2(1) = .108$; $p = .743$). The observers with Asperger's syndrome were all diagnosed by experts and clinicians all of whom have extensive experience in diagnosing disorders in the autism spectrum according to the criteria specified in the ICD-10 (WHO, 1993). Further, all the observers with Asperger's syndrome were asked to provide their

Autism-Spectrum Quotient (AQ, Baron-Cohen et al., 2001). All of the participants reported AQs of above 26, the cut-off for clinically significant levels of autistic traits (Woodbury-Smith Robinson, Wheelwright & Baron-Cohen, 2005). Individual AQs for both the group of participants with Asperger's syndrome and controls are given in Appendix I at the end of this chapter. The AQ constitutes a measure for the degree to which an adult person with normal intelligence shows autistic traits. None of the participants had previous experience with visual search tasks. They reported normal or corrected-to-normal vision, including colour vision.

Apparatus. Because of the low prevalence of Asperger's syndrome, observers for the group with Asperger's syndrome were recruited in (German-speaking) Switzerland and Germany, and considering the fact that the internet removes the barriers of direct social interactions in persons with autistic spectrum disorders (Biever, 2007), the experiments were conducted online. The experiments were programmed with Adobe Macromedia Authorware 7.0 (Adobe Systems, 2009) in such a way as to make sure that the displays were always presented in the centre of the screen, irrespective of the diagonal and resolution at which individual monitors were run and independent of the internet browser used to run the experiments.

Search displays were presented on liquid crystal display (LCD) monitors ranging in screen diagonal between 14.1" to 24" (6 x 14.1", 16 x 17", 5 x 19", 1 x 24"), refresh rates varied between 60 Hz to 75 Hz (22 x 60 Hz, 6 x 75 Hz). Stimulus presentation and reaction time recording were controlled by the Adobe Macromedia Authorware Web Player on personal computers running the Windows operating system.

Observers were instructed to view the monitor from a distance of approximately 50 cm and to dimly illuminate their rooms. Distance was varied to adjust for screen size. Observers responded by pressing one of two alternative keys (left and right arrow keys on laptops or the C and M keys on desktops) with their left- and right-hand index fingers.

Stimuli and timing. The search display consisted of 5, 15, or 25 uppercase letter items (set size 5, 15, 25) arranged in the 16 x 16 cells (rows and columns, respectively) of a virtual matrix subtending approximately 16.5 degrees of visual angle in width and height. Each of the letters subtended approximately 0.6 degrees of visual angle in height and 0.5 degrees in width. The minimum distances between letters in any display were 0.4 degrees of visual angle between centres of gravity of individual letter locations vertically (row) and 0.3 degrees of visual angle horizontally (columns). Display letters were defined on two dimensions: colour (red, green) and form/shape (target: S; distractors: T or X) and were presented on a dark grey background. In target-absent trials (50% of all trials), half of the items plus one were T's, the other half X's or vice versa (equal proportions); in target-present trials, the item of the surplus distractor category was replaced with the target.

A trial started with the presentation, for 500 ms, of a central fixation point (a hash mark) and was followed by the search display. The display remained on the screen until a (target-present or target-absent) response was recorded. The response was followed by a blank screen intertrial interval of 500 ms (see example in Figure 1a).

Procedure. All observers were instructed on several occasions and were given the opportunity to ask questions, by email or telephone, if they were uncertain about particular issues. Great care was taken to instruct participants in as much detail as required without risking that the instructions were ignored. Instructions were delivered to participants by email; instructions were also available on the initial page of the online laboratory and also presented immediately before the experiment started. To make sure that participants read the instructions, they were presented on a sequence of pages with information on how to proceed to the next page being contained in the instruction. Half of the participants (N = 14) started with Experiment 1 (feature search), the other half (N = 14) with Experiment 2 (conjunction search, see below). Observers were instructed not to complete the experiments in direct succession; rather, they should carry on with the respective second experiment after a break of at least 2 hours or on the following day. (Note that compliance with the instruction could be established on the basis of the time stamps of the reaction time files.)

The observers were instructed to search for a red S target letter and to ignore the distractors letters (red T's and green X's). It was pointed out to the participants that the target was unique in terms of its form/shape. There were a total of 60 trials for each combination of the factors set size (3: 5, 15, 25 letters) and trial type (2: target present, target absent). Overall, the experiment comprised of a total of 360 trials, split into 10 blocks of 36 trials; Experiment 1 took about 30 minutes to complete.

The observers were instructed to respond as quickly and as accurately as possible by depressing the appropriate response key. They had to press the right-arrow key of a desktop keyboard, (M key on a laptop keyboard) with their right index finger to indicate target presence and the left-arrow key (C key on laptops) with their left index finger to indicate target absence. In order to become familiar with the search task, each observer had to complete at least one block of 24 practice trials. In the practice, but not the experimental, blocks, feedback on whether the response was correct or incorrect was provided.

Experiment 2: Conjunction Search

Experiment 2 was designed to replicate the findings in autistic children and autistic adults (e.g., Plaisted, O'Riordan & Baron-Cohen, 1998b; O'Riordan et al., 2001; O'Riordan, 2004) showing superior performance, relative to normal age-matched controls, in a conjunction search task. In the conjunction search task, the results of the group of observers with Asperger's syndrome were compared with an age- and gender-matched control group. The observers' task was to search for a conjunction target (a red X) among two sets of distractors (red T's and green X's). That is, the target was defined by a conjunction of colour and form and the colour of the target was shared with the subset of T distractors and the shape of the target was shared with the subset of X distractors – i.e., the target is made unique by its conjunction of features. If the observers with Asperger's syndrome show the same pattern of performance as the autistic observers (reported in the literature; see Plaisted, O'Riordan and Baron-Cohen, 1998b; O'Riordan et al., 2001), their mean search reaction times and search rates (search times per item) should be faster and accuracy should be no worse than the reaction times of the age-matched group of controls. Furthermore, for the performance pattern to be the same as in observers with autism (reported in the literature) no significant slowing of reaction times with increasing set size, particularly in target-absent trials, should be found. Recall that, in conjunction search tasks, search reaction functions are usually characterized by a linear increase in RTs with increasing set size and a 2:1 ratio of target-absent to target-present function slopes.

Participants. Participants of the group with Asperger's syndrome and the control group were the same as in Experiment 1. Individual AQs for both the group of participants with Asperger's syndrome and controls are given in Appendix II at the end of this chapter.

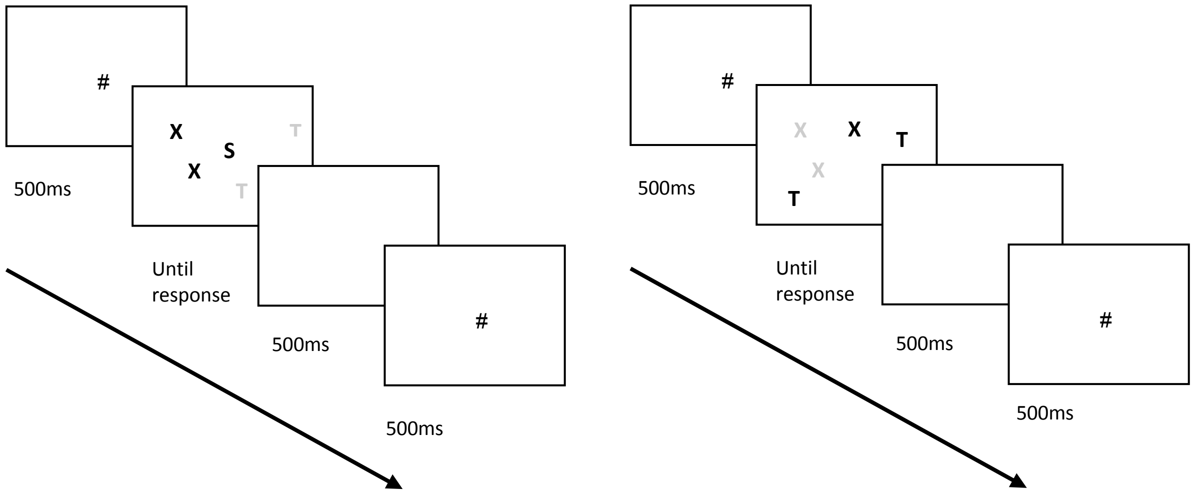
Apparatus. The apparatus was the same as in Experiment 1.

Stimuli and timing. Stimuli and timing were the same as in Experiment 1, with the following exceptions. Displays contained uppercase letters defined on the dimensions colour (red and green) and form (S, T and X), search items were presented on a dark grey background. The target was always a red X, distractors were red T's and green X's.

Procedure. The procedure was exactly the same as in Experiment 1, except for the search of a different target amongst different distractors as in Experiment 1.

The observers were instructed to search for a red X target and to ignore the distractors (red T's and green X's). It was pointed out to the observers that the target was unique in terms of the combination of colour (red) and form/shape (X). There were a total of 60 test trials per condition and each condition involved two crossed factors: set size (3: 5, 15, 25 letters) and trial type (2: target present, target absent). The number of trials per condition was equal, 60, for each factor combination. Altogether, Experiment 2 comprised of 360 trials, split into ten blocks of 36 trials. Experiment 2 took about 30 minutes to complete. (See example of the timing in Experiment 2 in Figure 1b)

Observers were instructed to respond as quickly and as accurately as possible. They were instructed to press the right-arrow keys (or the M key on laptops) with their right index finger to indicate that a target was present and the left-arrow key (C key on laptops) with their left index finger to indicate that a target was absent. In order to familiarize participants with the task, observers had to complete at least one block of 24 practice trials. In the practice block, but not the experimental blocks, feedback on the correctness of the response was provided.



a) b)

Figure 1. (a) Example for the timing and for a display of Experiment 1, feature search. The black S (a red S in the experimental displays) shows the target and the black X's (red X's) and grey T's (green T's) two sets of distractors. (b) Example for the timing and for a display in Experiment 2, conjunction search. The black X (a red X in the experimental displays) shows the target and the grey X's (green X's) and black T's (red T's) two sets of distractors.

5.2.3.2 Results

Search performance of the Asperger's group was compared to the matched control group in both tasks, feature and conjunction search. For each participant, reaction time data of all trials with correct target-present (hit) and target-absent (correct rejection) trials as well as accuracy data (i.e., misses on target-present and false alarms on target-absent trials) were averaged for each of the six (3 set sizes [5, 15, 25] and 2 trial types [present, absent]) conditions. A significance level of $p < .05$ was adopted for all statistical comparisons.

The overall reaction times, search times per item and error data were analyzed in ANOVAs with the between-subjects factor group (Asperger's, control) and the within-subjects factors task (feature search, conjunction search), trial type (target present, target absent) and set size (5, 15, 25). All simple effects reported in the following are adjusted according to the Bonferroni procedure where necessary.

Experiment 1: Feature Search

Errors. The error rates were below 1% for both the group of observers with Asperger's syndrome and control. Error rates were analyzed in an ANOVA with between-subjects factor group (Asperger's, control) and the within-subjects factors trial type (target present, target absent). Results revealed a significant main effect of trial type (*F*(1, 26) = 11.27; *p* = .002) with a significantly higher rate of errors in target-present (misses) compared to target-absent (false alarms) trials. The two groups did not differ significantly (no main effect of group) (*F*(1, 26) = .06; *p* = .817), neither was there a significant interaction between trial type and group (*F*(1, 26) = .15; *p* = .706). Planned comparisons revealed a significant difference, in the control group, between target-present and target-absent trials, i.e., the miss and false alarm rates (*F*(1,26) = 7.53, *p* = .011), with a higher error rate in target-present trials (M = 1.78%; SD = 2.13%) compared to target-absent trials (M = .49%; SD = .50%). In the Asperger's group the difference between miss (target-present) and false alarm (target-absent) rates, approached statistical significance (*F*(1,26)= 4.13, *p* =. 052), with a higher miss (target-present) (M = 1.56%; SD = 1.21%) than false alarm (target-absent) rate (M = .54%; SD = .48%). Neither in target-present nor in absent trials was there a significant difference between the groups (present: *F*(1,26) = .10; absent: *F*(1,26) = .07, both *p*s > .05).

Potential effects of set size on error rates were analyzed separately for the participants with Asperger's syndrome and the controls in ANOVAs with the within-subjects factors set size (5, 15, 25 items) and trial type (target-present, target-absent). The ANOVA of the control group revealed a significant main effect of trial type (*F*(1, 14) = 5.03; *p* = .042) with higher error (miss) rates in target-present compared to target-absent trials (false alarm), no significant main effect of set size (*F*(1.55, 21.68) = 2.218; *p* = .143; Huynh-Feldt-corrected *df*), but a significant interaction between the factors trial type and set size (*F*(2, 28) = 5.55; *p* = .009). The interaction is due to a significantly higher error rate in the largest set size (25 items) in target-present trials compared to target-absent trials (*F*(1,14) = 9.19; *p* = .009).

In the Asperger's group, the main effect of trial type was significant (*F*(1, 12) = 9.79; *p* = .009). Error rates (misses) were higher in target-present compared to target-absent trials. The main effect of set size was not statistically reliable (no set size effect) (*F*(2, 24) = 2.38; *p* = .114). The interaction between the factors trial type and set size was significant (*F*(2, 24) = 5.45; *p* = .011). The interaction revealed significantly higher error (miss) rates for target-present trials compared to target-absent trials (false alarms) in displays with set sizes 15 (F(1,12) = 7.26, p = .020) or 25 items (F(1,12) = 10.69, p = .007) compared to the set size of 5 items. Error rates are given in Figure 2.

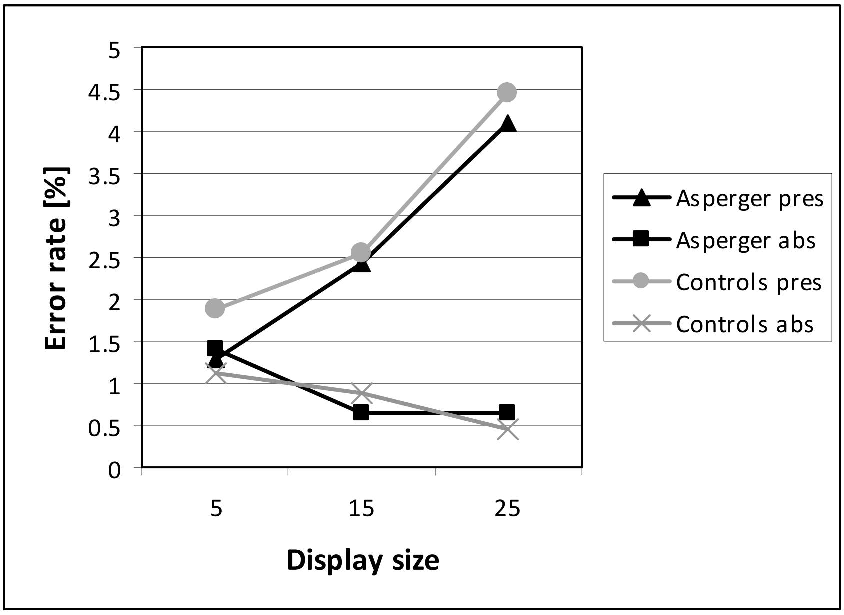


Figure 2. Error rates are plotted separately for the Asperger's and the control group for target- present and target-absent trials as a function of set size.

Reaction times. Mean overall reaction times in target-present and target-absent trials of Experiment 1 are shown in Figure 3 for the Asperger's and the control group. Individual overall mean reaction times of the feature search task of Experiment 1 were subjected to an ANOVA with the within-subjects factor trial type (target-present, target-absent) and the between-subjects factor group (Asperger's, control). The ANOVA revealed a significant main effect of trial type (F(1, 26) = 36.01; p < .001) with significantly higher reaction times for target-absent trials compared to target-present trials. There was a tendency of a significant main effect of group (F(1, 26) = 3.71; p = .065). In target-present trials, the Asperger's group (M = 756.82 ms; SD = 89.51 ms) produced significantly faster RTs (F(1,26) = 4.56, p = .042) than the control group (M = 932.35 ms; SD = 283.84 ms) and a tendency of being faster (M = 992.67 ms; SD = 156.94 ms) in target-absent trials (F(1,26) = 3.28, p = .082) than the control group (M = 1320.53 ms; SD = 635.15 ms). There was no significant interaction between the factors trial type and group (F(1, 26) = 2.15; p = .155), but the mean difference between the two groups is more pronounced in target-absent trials (Asperger's: 992.67 ms, control:

1320.53 ms for a difference of 327.86 ms) than in target-present trials (Asperger's: 756.82 ms, control: 932.35 ms for a difference of 175.53 ms).

Effects of set size on RTs were analyzed in an ANOVA with the within-subjects factors trial type (target-present, target-absent) and set size (5, 15, 25 items), and the between-subjects factor group (Asperger's, control). The ANOVA showed a significant main effect of trial type (*F*(1, 26) = 36.01; *p* < .001) and set size (*F*(1.08, 28.04) = 42.59; *p* < .001; Huynh-Feldt-corrected *df*); the main effect of group revealed a tendency towards significance (*F*(1, 26) = 3.71; *p* = .065). The two-way interaction of trial type and set size was significant (*F*(1.10, 28.57) = 21.68; *p* < .001; Huynh-Feldt-corrected *df*). The remaining two-way and three-way interactions were not statistically significant: trial type and group (*F*(1, 26) = 2.15; *p* = .155); set size and group (*F*(1.08, 28.04) = 2.82; *p* = .102; Huynh-Feldt-corrected *df*); trial type, set size and group (*F*(1.10, 28.57) = .89; *p* = .364; Huynh-Feldt-corrected *df*).

The significant main effects of trial type and set size, together with a tendency of significance of the group involved faster reaction times in target present trials compared to target absent trials (trial type), increasing reaction times with increasing set size (set size) and faster reaction times in the Asperger's compared to the control group (group). The significant interaction between trial type and set size implies an increasing difference in overall reaction times between target-present and target-absent trials with increasing set sizes.

The RTs of the Asperger's and control group were analyzed further in separate ANOVAs with the within-subjects factors trial type and set size.

For observers of the control group, the ANOVA revealed significant main effects of set size (*F*(1.04, 14.51) = 20.75; *p* < .001; Huynh-Feldt-corrected *df*) and trial type (*F*(1, 14) = 16.87; *p* = .001). RTs were significantly faster in trials with set size 5 (849.63 ms) compared to 15 (1147.31 ms) (*F*(2,13) = 9.78; *p* = .001) and 25 (1382.38 ms) (*F*(2,13) = 9.78; *p* = .001) and RTs were significantly faster in trials with set size 15 compared to 25 (*F*(2,13) = 9.78; *p* = .002). RTs were significantly faster in target-present compared to target-absent trials for all three set sizes (5 items: *F*(1,14) = 23.46, *p* < .001; 15: *F*(1,14) = 19.42, *p* = .001; 25: *F*(1,14) = 13.24, *p* = .003). The interaction between trial type and set size was significant (*F*(1.05, 14.63 = 9.73; *p* = .007; Huynh-Feldt-corrected *df*). Target-present and -absent trial reaction times for set size 5 were faster than for set sizes 15 (present: *F*(2,13) = 18.53, *p* = .001; absent: *F*(2,13) = 8.93, *p* = .003) and 25 (present: *F*(2,13) = 18.53, *p* < .001; absent: *F*(2,13) = 8.93, *p* = .003), respectively, and reaction times for set size 15 were significantly faster than for set size 25 (present: *F*(2,13) = 18.53, *p* < .001; absent: *F*(2,13) = 8.93, *p* = .008). The significant comparisons show, for the control group, a set size effect with an increase in overall reaction times with increasing display size (set size) for target-present and target-absent trials. The significant interaction between trial type and set size shows that the RT difference between target-present and target-absent trials increases with increasing set size.

In the Asperger's group, the ANOVA (with within-subject factors trial type and set size) revealed significant main effects of trial type (*F*(1, 12) = 105.01; *p* < .001) and set size (*F*(1.10, 13.16 = 85.24; p < .001; Huynh-Feldt-corrected *df*). RTs in target-present trials were significantly faster than in target-absent trials for all three set sizes (5: *F*(1,12) = 28.11, *p* < .001; 15: *F*(1,12) = 91.17, *p* < .001; 25: *F*(1,12) = 81.59, *p* < .001). The interaction between the factors trial type and set size (*F*(1.25, 15.02) = 44.01; *p* < .001; Huynh-Feldt-corrected *df*) was significant. For target-present and target-absent trials, reaction times for displays with set size 5 were faster than for set sizes 15 and 25, respectively, (15: present: *F*(2,11) = 40.26, *p* < .001, absent: *F*(2,11) = 36.75, *p* < .001, 25: present *F*(2,11) = 40.26, *p* < .001, absent *F*(2,11) = 36.75, *p* < .001), reaction times for 15 items were significantly faster than for 25 items (present: *F*(2,11) = 40.26, *p* < .001; absent: *F*(2,11) = 36.75, *p* < .001). The significant comparisons show, for the Asperger's group, a set size effect with an increase in overall reaction times with increasing set size for target-present and target-absent trials. The significant interaction between trial type and set size implies that the RT difference between target-present and target-absent trials increases with set size.

The analyses of the functions relating search RTs to trial type and set size in the feature search condition of Experiment 1 thus suggests that the mechanisms underlying search are the same in observers with Asperger's syndrome and the healthy controls.

However, overall search RTs are significantly faster in observers with Asperger's syndrome compared to healthy observers. Thus, in accordance with findings in the literature of a performance benefit in observers with autism (Plaisted, O'Riordan & Baron-Cohen, 1998b; O'Riordan et al., 2001), the present data show that participants with Asperger's syndrome complete feature search tasks significantly faster than controls.

Both groups, however, show a set size effect and significant RT differences between target-present and –absent trials for all set sizes. This finding suggests that, although people with Asperger's syndrome solve the search task faster than controls, the mechanism underlying search is the same in both groups of observers of Experiment 1.

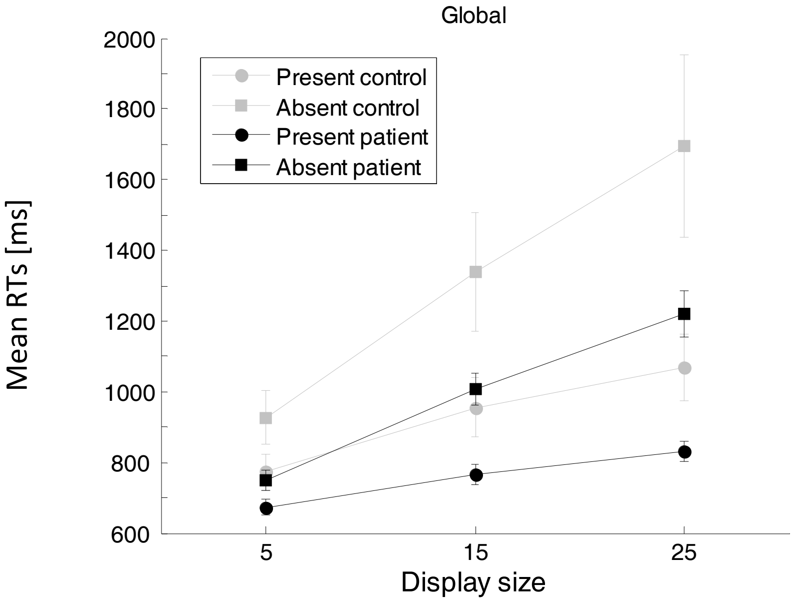


Figure 3. Mean overall reaction times in target-present and target-absent trials of Experiment 1 are shown for all observers of the Asperger's group and of the control group for all three set sizes.

The next analysis step is thus aimed to identify the component mechanism (or component mechanisms) mediating the observed search performance advantage in people with Asperger's syndrome.

The feature search task can be decomposed in three components: (1) structuring the display into an initial visual representation (in the sense of Marr's, 1982, primal sketch representation), (2) the search process, and (3) response selection and execution. Reaction time analyses allow identification of the time required for the search process (2) from the initial perceptual (1) and response-related processes (3). Search-related processing is reflected in the slope of the search function, in detail, in the time taken to process a single display item – that is, search time per item. Processing related to perception and response is reflected in the y-axis intercept of the search function. The next analysis step examines search time per item and y-axis intercepts in order to compare these measures between the groups of participants with Asperger's syndrome and healthy controls.

Search time per item. Search reaction times per item were analyzed in an ANOVA with the within-subjects factors trial type (target-present, target-absent) and the between-subjects factor group (Asperger's, control). Search times per item are calculated by solving the equality for the linear relationship between set size and search RT (the search function) RT = y + nx, with y representing the y-axis intercept, n the set size, and x the search time per item, respectively. Search times per item are shown in Table 1.

Table 1. Mean search times per item (left) and mean y-axis intercepts (right), separately for target-present and target-absent trials, and for participants with Asperger's syndrome and controls are displayed.

	Search times per item		Y-axis intercept	
	Asperger	Control	Asperger	Control
present	7.89	14.84	638.49	709.76
absent	23.59	38.44	638.80	744.00

The ANOVA revealed a significant main effect of trial type (*F*(1, 26) = 22.54; *p* < .001). Search rates were lower, i.e., items were processed faster in target-present (11.61 ms) than in target-absent (31.54 ms) trials. Search rates of participants with Asperger's syndrome (15.74 ms), though lower (10.90 ms) than rates of the controls (26.64 ms), did not differ; no significant main effect of group (*F*(1, 26) = 2.86; *p* = .103) and the interaction between trial type and group was not significant (*F*(1, 26) = .91; *p* = .349), either.

Detailed comparisons revealed significant differences, however, between participants with Asperger's syndrome and controls. In target-present trials, mean search times per item of the control group (M = 14.83 ms, SD = 9.66 ms) were significantly higher relative to the Asperger's group (M = 7.89 ms; SD = 3.08 ms) (*F*(1,26) = 6.16, *p* = .020). Search times per item, in target-present trials, of the control group were about twice those of the Asperger's group, as can be seen in the slopes of the search function in Figure 3. In target-absent trials, search RTs per item are 38.44 ms (SD = 36.50 ms) for the control and 23.59 ms (SD = 9.77 ms) for the Asperger's group; although the difference is quite marked numerically, it is not a statistically reliable difference (*F*(1,26) = 2.02, *p* = .168).

Search times per item thus clearly show that the search process is significantly faster in observers with Asperger's syndrome than in healthy controls.

Y-axis intercept. In order to complete the picture, the time required to complete processes that are not related to search process proper, that is, the time required to structure the display into a (primal) sketch providing the basis for the operation of the search process, as well as the time required to program and execute the appropriate (present or absent) response, needs to be determined. The non-search time is reflected by the y-axis intercept of the search function, i.e., the location on the (y-) axis representing search RT, where the search function cuts the y-axis (values see Table 1).

Y-axis intercepts were subjected to a two-way ANOVA with the within-subject factor trial type (target-present, target-absent) and the between-subject factor group (Asperger's, control). The analysis revealed no main effect of trial type ($F(1,26) = .74$; $p = .398$) and a tendency of a significant main effect of group ($F(1,26) = 3.21$; $p = .085$). The interaction was not significant ($F(1,26) = .711$; $p = .407$). Planned comparisons revealed a tendency of a significant difference between the two groups in target-absent trials ($F(1,26) = 3.46$; $p = .074$) with lower y-axis intercepts in the Asperger's group (638.80 ms) compared to the control group (744.00 ms) but not in target-present trials ($F(1,26) = 2.06$; $p = .163$; Asperger's: 638.49 ms; controls: 709.76 ms).

In the feature search task, non-search processes tend to differ between the groups of participants with Asperger's and controls only in target-absent trials with lower y-axis intercepts in the Asperger's group.

In summary, the results of the feature search task of the Asperger's and control group revealed a very similar picture. There are two notable exceptions, however: 1) overall reaction times are significantly faster in participants with Asperger's syndrome than in the control sample. 2) Search functions are significantly shallower in participants with Asperger's syndrome than in the control sample; put differently, search times per item are significantly lower in persons with Asperger's syndrome than in controls. Taken together, this is strong evidence that the component process of searching individual display items is expedited in people with Asperger's syndrome. The search process involves allocating focal attention to a particular display item, making available the visual information characterizing that item to cognitive processes mediating the comparison of the currently inspected item with a memory template of the target, as well as the decision whether there is a match between the currently inspected item and the template (i.e., whether to terminate the search process and to initiate response selection or to continue search with the next candidate item).

Pre-selective processes associated with the structuring of the visual scene for the selection mechanism and post-selective processes of response selection and execution take place in the same temporal range in both people with Asperger's syndrome and controls.

Experiment 2: Conjunction Search

Errors. Overall error rates were low; they were below 4% in the control group and below 2% in the Asperger's group.

Error rates were analyzed in an ANOVA with the between-subjects factor group (Asperger's, control) and the within-subjects factor trial type (target-present, target-absent). The ANOVA revealed a significant main effect of trial type ($F(1, 26) = 32.46$; $p < .001$) with higher error rates (misses: 4.54%) in target-present than target-absent (false alarms: .73%) trials. The main effect of group was significant ($F(1, 26) = 10.25$; $p = .004$); participants with Asperger's syndrome made overall fewer errors (1.43%) than controls (3.69%). The interaction between trial type and group was significant ($F(1, 26) = 10.48$; $p = .003$). In target-present trials there was a significant difference between the two groups ($F(1,26) = 11.03$; $p = .003$) with the control group (M = 3.93%; SD = 2.77%) producing higher error rates than the Asperger's group (M = 1.33%; SD = .53%); however, no significant difference was found in target-absent trials ($F(1,26) = .26$; $p = .613$). Further, a significant difference was revealed in the control group between target-present and target-absent trials ($F(1,26) = 42.97$, $p < .001$); participants of the control group produced higher error rates in target-present trials (M = 3.93%; SD = 2.77%) relative to target-absent trials (M = .49%; SD = .55%).

Error rates of the two groups were analyzed separately in ANOVAs with the within-subjects factors set size (5, 15, 25 items) and trial type (target-present, target-absent). In the control group, a significant main effect of trial type ($F(1, 14) = 23.77$; $p < .001$) was found; error rates were higher in target-present (6.56%) compared to target-absent (.81%) trials. The main effect of size was significant ($F(2, 28) = 6.76$; $p = .004$); higher error rates were observed in trials with set size 25 (3.20%) compared to set size 15 (1.87%) ($F(2,13) = 6.42$, $p =$

.023), error rates were not significantly higher in set size 15 (1.87%) than 5 (1.57%) (*F*(2,13) = 6.42, *p* = 1.000).

The interaction between the factors trial type and set size (*F*(2, 28) = 5.35; *p* =.011) was also significant. The significant interaction is due to the following pattern of effects: In target-present trials, the error rates were significantly higher in trials with set size 25 compared to trials with set size 5 (*F*(2,13) = 5.44, *p* = .029) or set size 15 (*F*(2,13) = 5.44, *p* = .026). Further, in the control group, significantly more errors were made in target-present trials of all three set sizes compared to target absent-trials (set size 5: *F*(2,13) = .07, *p* = .025; 15: *F*(2,13) = .07, *p* < .001; 25: *F*(2,13) = .07, *p* = .001) with error rates increasing with increasing set size (interaction).

In the Asperger's group, there was a significant main effect of trial type (*F*(1, 12) = 49.19; *p* <.001); error rates were higher in target-present (2.22%) compared to target-absent (.64%) trials. The main effect of size (*F*(2, 24) = 2.21; *p* = .131) was not significant. There was no significant interaction between the factors trial type and set size (*F*(2, 24) = 2.11; *p* = .143), either.

These effects suggest that, while in the controls the expected relation between set size and error rates is observed, error rates in observers with Asperger's syndrome are affected neither by trial type nor by set size.

Reaction times. Mean overall reaction times in target-present and target-absent trials of Experiment 2 are shown in Figure 4 for the Asperger's and control groups. Mean search reaction times were subjected to an ANOVA with the within-subjects factor trial type (target-present, target-absent) and the between-subjects factor group (Asperger's, control). The ANOVA revealed the main effect of trial type to be significant (*F*(1, 26) = 68.11; *p* < .001); RTs were higher in target-absent (M = 1249.91 ms; SD = 407.78 ms) than in target-present trials (M = 878.49 ms; SD = 180.80 ms). The main effect of group was significant (*F*(1,26) = 6.26; *p* = .019); RTs of participants with Asperger's syndrome (M = 929.46 ms; SD = 138.78 ms) were faster by about 250 ms than RTs of the control group (M = 1180.96 ms; SD = 344.01 ms). In both target-present and target-absent trials significantly higher overall reaction times were observed in the control (present: 951.26 ms, absent: 1410.65 ms) compared to the Asperger's (present: 794.52 ms, absent: 1064.43 ms) group (present: *F*(1,26) = 6.25, *p* = .019; absent: *F*(1,26) = 5.94, *p* = .022).

Further, the interaction between trial type and group was significant (*F*(1, 26) = 4.60; *p* = .042). The reaction time difference between target-absent and target-present trials was significantly smaller in the Asperger's group (M = 269.92 ms; SD = 92.43 ms) compared to the control group (M = 459.39 ms; SD = 306.08 ms; *t*(16.88) = 2.28, *p* = .036).

Reaction times were further analyzed in an ANOVA with the within-subjects factors trial type (target-present, target-absent) and set size (5, 15, 25 items) and the between-subjects factor group (Asperger's, control).

The ANOVA revealed significant main effects of trial type (*F*(1, 26) = 68.11; *p* < .001), set size (*F*(1.12, 29.12) = 108.06; *p* < .001; Huynh-Feldt-corrected *df*), and group (*F*(1, 26) = 6.26; *p* = .019). The main effects are due to faster reaction times in target-present (878.49 ms) compared to target-absent trials (1249.91 ms), increasing reaction times with increasing set size (5: 776.14 ms; 15: 1068.39 ms; 25: 1321.12 ms) and faster reaction times for the Asperger's (929.71 ms) compared to the control group (1180.96 ms).

The two-way interactions between trial type and set size (*F*(1.21, 31.38) = 58.40; *p* < .001; Huynh-Feldt-corrected *df*), between trial type and group (*F*(1, 26) = 4.60; *p* = .042), and between set size and group (*F*(1.12, 29.12) = 4.46; *p* = .039; Huynh-Feldt-corrected *df*) were all significant. The three-way interaction between trial type, set size and group (*F*(1.21, 31.38) = 2.65; *p* = .108; Huynh-Feldt-corrected *df*) was not significant.

The interaction between trial type and set size is due to an increasing difference between target-present and target-absent trial RTs as set size increases. The interaction between set size and group is due to an increasing difference in overall RTs between the two groups of observers with increasing set size. For all three set sizes, RTs of target-absent and target-present trials were significantly faster in the participants with Asperger's syndrome relative to controls (set size 5, present: *F*(1,26) = 5.00, *p* = .034, absent: *F*(1,26) = 6.68; 15, present: *F* (1,26) = 4.59, *p* = .042; absent: *F* (1,26) = 5.55, *p* = .026; 25, present: *F*(1,26) = 7.60, *p* = .011; absent: *F* (1,26) = 5.43, *p* = .028).

To follow up the results, RT data of the two groups of observers were analyzed in separate ANOVAs with the within-subject factors set size (5, 15, 25 items) and trial type (target-present, target-absent).

In the control group, the ANOVA revealed significant main effects of set size (*F*(1.04, 14.56) = 50.60; *p* < .001; Huynh-Feldt-corrected *df*) and trial type (*F*(1, 14) = 33.79; *p* < .001). RTs were significantly faster in target-present (951.26 ms) compared to target-absent (1410.65 ms) trials for all three set sizes (5: *F*(1,14) = 22.29, *p* < .001; 15: *F*(1,14) = 29.98; 25: *F*(1,14) = 33.67; *p* < .001). The interaction between the factors set size and trial type was significant (*F*(1.10, 15.43) = 28.57; *p* < .001; Huynh-Feldt-corrected *df*). Target-present and target-absent trial reaction times for set size 5 displays were faster than RTs for set sizes of 15 (*F*(2,13) = 24.57 , *p* < .001) and 25 items (*F*(2,13) = 24.57, *p* < .001), and reaction times for displays of set size 15 were significantly faster than set size 25 displays (*F*(2,13) = 24.57, *p* < .001). That is, in the control group, reaction times increase with increasing set size both in target-present and target-absent trials. The interaction shows that the difference between target-present and target-absent increases with increasing set size.

In the group of observers with Asperger's syndrome, significant main effects of set size (*F*(1.52, 18.19) = 142.11; p < .001; Huynh-Feldt-corrected *df*) and trial type (*F*(1, 12) = 110.86; *p* < .001) were found. Reaction times in target-present (794.52 ms) were significantly faster than in target-absent (1064.43 ms) trials in all three set sizes (5: *F*(1,12) = 35.60, *p* < .001; 15: *F*(1,12) = 71.54, *p* < .001; 25: *F*(1,12) = 98.90, *p* < .001). The interaction between the factors trial type and set size (*F*(2, 24) = 60.41; *p* < .001) was significant. RTs of target-present and target-absent trials of set size 5 were faster than for set sizes 15 (*F*(2,11) = 83.81; *p* < .001) and 25 (*F*(2,11) = 83.81; *p* < .001). However, reaction times of set size 15 displays were significantly faster than set size 25 displays only in target-absent trials (*F*(2,11) = 83.81, *p* < .001), but not in target-present trials (simple effect: *p* = .081).

Thus, in contrast to the set size effect of observers of the control group, a significant set size effect (increase of overall reaction times with increasing set size) is evident only in target-absent trials. In target-present trials, however, a set size effect is observed only for set sizes 5 and 15. The interaction revealed an increasing difference between target-present and target-absent trials with increasing set size.

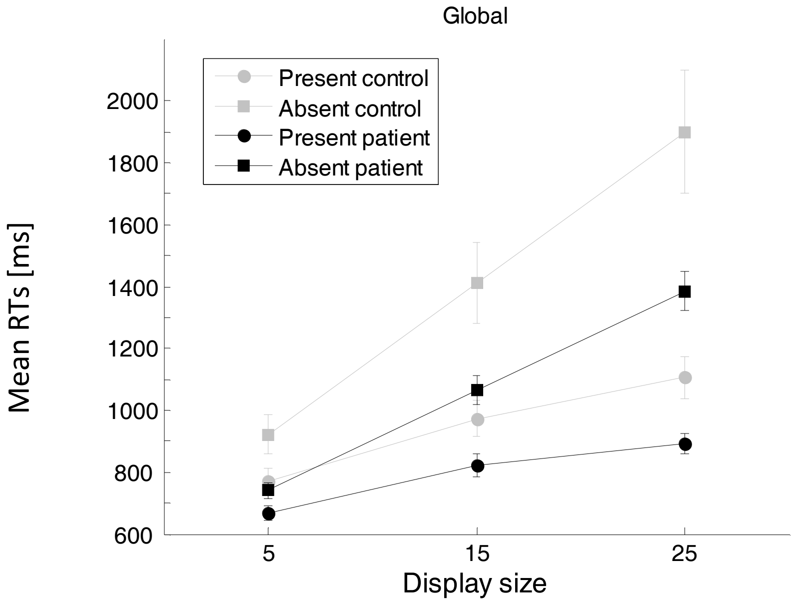


Figure 4. Mean overall reaction times in target-present and target-absent trials of Experiment 2 are shown for all observers of the Asperger's group and of the control group for all three set sizes.

Search time per item. Search times per item (the efficiency with which single display items are searched), reflected by the slope of the search function, were analyzed in an ANOVA with the within-subject factors trial type (target-present, target-absent) and the between-subjects factor group (Asperger's, control). The ANOVA revealed a significant main effect of trial type ($F(1, 26) = 62.24$; $p < .001$); search times per item of target-absent trials (M = 41.11 ms; SD = 23.39 ms) were significantly higher than in target-present trials (M = 14.18 ms; SD = 6.35 ms). The main effect of group was significant ($F(1, 26) = 4.63$; $p = .041$). Search times per item were significantly lower in the Asperger's group (M = 21.71 ms; SD = 6.49 ms) compared to the control group (M = 32.79 ms; SD = 18.12 ms). There was no significant interaction between the factors trial type and group ($F(1,26) = 2.84$; $p = .104$).

Comparisons to follow up the main effects showed that search times per item were significantly higher in the control compared to the Asperger's group in target-present trials ($F(1,26) = 6.03$, $p = .021$). In target-absent trials, there was a tendency of higher search times per item for the control group ($F(1,26) = 3.96$, $p = .057$).

Y-axis intercept. In order to complete the picture, the time required to complete processes that are not related to search process proper, that is, the time required to structure the display into a sketch providing the basis for the operation of the search processes, as well as the time required to program and execute the appropriate (present or absent) response, needs to be determined. The non-search time is reflected by the y-axis intercept of the search function, i.e. the location on the (y-) axis representing search RT, where the search function cuts the y-axis (values see Table 4).

Y-axis intercept times were subjected to a two-way ANOVA with the within-subject factor trial type (target-present, target-absent) and the between subject-factor group (Asperger's, control). The analysis revealed no main effect of trial type ($F(1,26) = 3.29$; $p = .081$) and a tendency of a significant main effect of group ($F(1,26) = 3.43$; $p = .075$). The interaction was not significant ($F(1,26) = .711$; $p = .407$). Planned comparisons revealed a tendency of a significant difference between the two groups in target-absent trials ($F(1,26) = 3.30$; $p = .081$) with lower y-axis intercepts in the Asperger's group (582.35 ms) compared to the control group (677.42 ms), but not in target-present trials ($F(1,26) = 2.62$; $p = .117$; Asperger's: 625.36 ms; controls: 700.78 ms).

In the conjunction search task, non-search processes tend to differ between the groups of participants with Asperger's and controls with lower intercepts in the Asperger's group.

The results pattern of both groups revealed a similar picture, except for the faster overall reaction times of the Asperger's group compared to the control group, no significant difference in reaction times between 15 or 25 display items in the Asperger's group in target present trials and the steeper search function (in target present and target absent trials) for the control group compared to the Asperger's group reflected by the significantly higher search times per item in target present and absent trials for the control group.

Furthermore the Asperger's group needed less time for the completion of search related processes like structuring the display or response execution, compared to the control group.

Comparison of feature search and conjunction search

Mean reaction times. Mean reaction times of the feature (Experiment 1) and conjunction (Experiment 2) search tasks (see Table 2) were subjected to ANOVAs with the within-subjects factors trial type (target-present, target-absent) and task (feature search, conjunction search), separately for the control group and the Asperger's group.

In the control group, there was no significant main effect of task (*F*(1, 14)= .99; *p* = .337), that is, overall reaction times did not differ between feature and conjunction search. The main effect of trial type (*F*(1, 14)= 24.46; *p* < .001) was significant with higher reaction times on target-absent trials compared to target-present trials in both search tasks. The interaction between trial type and task was significant (*F*(1, 14) = 5.14; *p* = .040). The interaction is due to a larger difference between the two search tasks in target-absent trials compared to target-present trials.

In the Asperger's group, the main effect of search task (*F*(1, 12) = 3.61; *p* = .082) was not significant; overall reaction times did not differ between search tasks. The main effect of trial type was significant (*F*(1, 12) = 118.40; *p* < .001); RTs were higher in target-absent trials compared to target-present trials in both search tasks. The interaction between trial type and task was significant (*F*(1, 12)= 5.43; *p* = .038). This interaction is due to a larger difference between feature and conjunction search in target-absent trials compared to target-present trials. Contrasts did not reveal a significant RT difference in target-present trials of the feature relative to the conjunction search task (*F*(1,12) = 2.22, *p* = .162); in target-absent trials a tendency of a significant difference between feature and conjunction search was revealed (*F*(1,12) = 4.56, *p* =.054); RTs were longer in absent (775.67 ms) than in present (1028.55 ms) trials.

Search rates. Search times per item (see Table 3) were analyzed in an ANOVA with the within-subjects factors trial type (target-present, target-absent) and search task (feature search, conjunction search), separately for the control group and the group with Asperger's syndrome.

In the control group, the ANOVA revealed a significant main effect of search task (*F*(1, 26) = 16.25; *p* < .001); search times were slower in the conjunction (27.65 ms) than in the feature (21.58 ms) task. The main effect of trial type was significant (*F*(1, 26) = 40.33; *p* <

.001) with higher search times per item in target-absent (36.33 ms) compared to target-present (12.90 ms) trials. The interaction between trial type and search task was significant (*F*(1, 26) = 11.83; *p* = .002); the RT difference between search tasks was larger in target-absent compared to target-present trials. In target-absent trials, search time per item was significantly higher in the conjunction compared to the feature search task (*F*(1,26) = 9.20, *p* < .001); in target-absent trials there was a significant difference between search tasks as well (*F*(1,26) = 6.81, *p* = .015).

In the Asperger's group, the ANOVA of the search times per item revealed a significant main effect for the factor search task (*F*(1, 12)= 21.61; *p* = .001) with higher search times per item in conjunction (21.71 ms) relative to feature (15.74 ms) search. The main effect of trial type (*F*(1, 12) = 81.20; *p* < .001) was significant; search times per item in target-absent (27.87 ms) trials were higher compared to target-present (9.58 ms) trials. The interaction was significant (*F*(1, 12) = 5.80; *p* = .033); the RT difference in target-absent compared to target-present trials was larger in conjunction than in feature search. Comparisons showed, that in target-present and target-absent trials, search time per item was significantly higher in the conjunction compared to the feature search task (present: *F*(1,12) = 16.24, *p* = .002; absent: *F*(1,12) = 14.95, *p* = .002).

Both groups showed significantly higher search times per item (steeper search function) in the conjunction compared to the feature search task.

Overall, results revealed an effect of the search task with higher search times per item in conjunction search compared to the feature search. In the Asperger's group, the difference in slopes between feature and conjunction search, in target-present (3.39 ms) and target-absent (8.55 ms) trials, was relatively small. However, in the control group, the difference in slopes between target-present (1.86 ms) and target-absent (10.44 ms) was comparably large.

Table 2. Overall mean search reaction times (M) and standard deviations (SD) for the control group and the Asperger's group, separately for the feature search and conjunction search task and for target-present and target-absent trials.

	Feature search				Conjunction search			
	present		absent		present		absent	
	M	SD	M	SD	M	SD	M	SD
Control group	932.35	283.84	1320.53	635.15	951.26	201.31	1410.65	486.71
Asperger group	756.82	89.51	992.67	156.94	794.52	109.61	1064.43	167.94

Table 3. Search times per item for the control group and the Asperger's group for the feature and conjunction search experiment for target-present and target-absent trials.

	Feature search					Conjunction search			
	present		absent			present		absent	
	M	SD	M	SD		M	SD	M	SD
Control group	14.84	9.66	38.44	36.50	Control group	16.70	7.35	48.88	28.88
Asperger group	7.89	3.08	23.59	9.77	Asperger group	11.28	3.25	32.14	9.73

Table 4. Y-axis intercepts for the control group and the Asperger's group, separately for the feature search and conjunction search task and for target-present and target-absent trials.

	Feature search					Conjunction search			
	present		absent			present		absent	
	M	SD	M	SD		M	SD	M	SD
Control group	709.76	161.95	744.00	186.33	Control group	700.77	135.64	677.42	169.09
Asperger group	638.49	80.94	638.80	88.10	Asperger group	625.36	106.01	582.35	89.55

5.2.3.3 Discussion

The aim of Experiments 1 and 2 was to examine feature and conjunction search performance in a group of people with Asperger's syndrome by comparing overall search reaction times, search rates and and y-axis intercepts to those of an age- and gender-matched group of controls. Visual search is well suited for the investigation of potential differences in cognitive processes between different groups as the task involves a series of hierarchical processes ranging from the structuring of a visual scene and feature extraction (both pre-selective processes), to the selection of individual items for processing and the decision whether the processed object corresponds to the target description or not (the search process proper), to the selection and execution of the appropriate response. Overall search reaction times reflect the entire chain of processes from the (observable) onset of the visual search display to the (observable) manual response indicating the observer's decision.

Search times per item (search rates) allow the deduction of how much time is required to process a single search object, that is, the time requirements of the search process proper. The y-axis intercept of the search function relating search reaction times to the number of search items (the set sizes) constitutes an estimate of the time taken to structure – i.e., prepare – the scene to be searched on the one hand, and for the response to be selected and executed on the other hand. Response selection and execution, in the feature and conjunction search tasks of Experiments 1 and 2, is assumed to take the same amount of time, in other words, in visual search tasks, response selection and execution is not affected by the processes occurring beforehand. Rather, as soon as a match is found between the object currently under the focus of attention and the target template, the target-present is triggered, alternatively, an absent-response is triggered after all display items were searched without there being a match. Consequently, since in both the feature and conjunction search task response selection involves two alternatives, it is safe to assume that any effects on the y-axis intercept arise at the level of structuring and initially representing the display. As these processes occur before the selection stage, they are referred to as pre-selective processes (in analogy, processes occurring following the selection stage are termed post-selective).

An important dependent variable in visual search tasks is performance accuracy. Accuracy analysis plays a key role in the interpretation of reaction time differences as accuracy data reveal observers trading speed for accuracy. In other words, in order to be able to interpret reaction time differences, faster reaction times must not be confounded by higher error rates. Therefore, the interpretation of reaction time data is preceded by an analysis of error rates.

The results of the present Experiments 1 and 2, in the following sections are discussed in terms of differences between the group of participants with Asperger's syndrome and the control group; the discussion of the findings is followed by an analysis of the difference between tasks.

Feature search. Error rates are very low overall in the feature search task of Experiment 1 suggesting that the task is either relatively easy to perform and/or that observers strive to avoid errors. In general, feature search tasks are considered as easy to do and consequently error rates are very low. Error analyses show that miss rates are higher than false alarm rates in both groups of observers. That is, if observers make errors, the cases in which they mistake a distractor for a target (false alarm) are rarer than the cases in which they ignore a target (miss). This bias seems to suggest that observers actively match the item currently under the focus of attention with the target template rather than responding to an activation signalling a difference (feature contrast) that is not further specified.

If the two groups are compared, the miss rate is lower in the Asperger's than in the controls, that is, faster reaction times in the Asperger's group are not due to a speed-accuracy trade off.

Importantly, there is no effect of set size on the error rates, but there is an interaction between set size and trial type in both groups. The interaction is due to the difference between misses and false alarms being significant for the set size of 25 items only. The finding that set size does not affect error rates is expected in a feature search task. Search in set size 25 displays seems to be more error-prone than in set size 5 and 15 displays, however.

Analyses of overall mean reaction times show slower reaction times in target-absent than in target-present trials in both groups of observers. This effect is not expected in a feature search task in which the target differs from distractors in a salient feature (shape), rather response times are expected to be more or less at the same level, with a slight disadvantage for target-absent RTs. However, the slower reaction times in target-absent trials are probably due to the difficult feature search task used in this study.

More importantly, however, participants with Asperger's syndrome are faster than participants of the control group in target-present trials and there is also a tendency for the Asperger's group to be faster than the controls in target-absent trials. That is, the decision that a target item is present is taken faster by people with Asperger's syndrome than by healthy controls. There is a tendency for faster responses of the Asperger's group in absent-trials also, rendering interpretation difficult. If there were a reaction time advantage only in target-present trials, an interpretation along the lines of the assumption that discrimination of the target item is expedited in people with Asperger's syndrome would be supported. This has been suggested in the literature (e.g., Plaisted, O'Riordan & Baron-Cohen, 1998a; Shah & Frith, 1993; Jolliffe & Baron-Cohen, 1997; O'Riordan & Plaisted, 2001) and could be likened to the target "popping out of the display" in people with Asperger's but not in participants of the control group. Instead of a pop-out effect, the fact that a reaction time advantage is observed in target-present and target-absent trials suggests that the process of matching the item currently under the focus of attention to the target description is achieved faster in people with Asperger's syndrome than in healthy controls.

The findings of a set size effect and interaction of set size and trial type (present, absent) supports the assumption that some sort of template matching is required to perform the variant of a feature search task used in Experiment 1.

In the comparison between the groups of participants, it is also important to analyze the non-significant interactions. The interaction between group and trial type (present, absent) was not statistically reliable, neither was the interaction with set size. Together, these non-findings suggest that the pattern of search performance in terms of target-absent and -present trials and set size is the same in both groups.

The previous interpretation of a faster search process in people with Asperger's syndrome is supported by the analysis of the search rates. In target-present trials, search times per item are significantly lower in people with Asperger's syndrome than in healthy controls. The same effect is observed in absent-trials, although only on the level of numerical comparisons, but not in terms of statistical reliability. Together, this suggests that in observers with Asperger's syndrome the search process is indeed expedited relative to the healthy controls. In addition, there might be a component of popout in target-present, but not target-absent trials (as suggested by the search time advantage in present- but not absent-trials).

The idea of a component of popout is supported by the finding that y-axis intercepts show a tendency of a difference between groups (lower intercept in the Asperger's group) in target-present trials only.

Conjunction search. Error rate analysis shows that participants with Asperger's syndrome make fewer errors in the conjunction search task than the controls. As in the feature search tasks, miss rates are higher than false alarm rates. The ratio of miss and false alarm rates suggests that participants base their decision on matching the currently scrutinized item (i.e., the item under the focus of attention) to a target template rather than responding to an activation coding feature difference. Such a strategy is, of course, expected in a conjunction search task.

Importantly, comparing the two groups, people with Asperger's syndrome miss fewer targets than the control group. This suggests that the template matching process is less error-prone in Asperger's than in controls.

Interestingly, there is an effect of set size on error rate in the observers of the control group, but not the Asperger's group. This again suggests that people with Asperger's syndrome scan search items for a match with the target template more efficiently than healthy observers.

Reaction time analyses show that people with Asperger's syndrome, in the conjunction search task, respond overall faster than the controls both in target-present and target-absent trials. Further, the response times of the two groups interact: the difference between target-present and target-absent reaction times is smaller in the group of Asperger's than in the controls; this is observed in all set sizes. These findings again speak for an advantage in the processing of individual search items in people with Asperger's compared to controls.

Observers of the control group show a set size effect, i.e., increasing reaction times with increasing set sizes both between set sizes of 5 and 15 and between 15 and 25 items. In contrast, in the Asperger's group a set size effect is observed only in target-absent trials (differences between all set sizes), a partial set size effect only is observed in Asperger's in target-present trials; reaction times increase only between set sizes of 5 and 15, but not between 15 and 25 items.

The overall reaction analyses, in summary, show that search is more efficient in participants with Asperger's than in controls. The pattern of set size effects for target-absent and target-present trials suggest that the process of scanning items and matching individual items to the target template is more efficient in Asperger's than in controls.

Search rates per item, proving support for the above stance, were significantly lower in people with Asperger's than in controls both in target-present and in target-absent trials. In terms of y-axis intercept, there is no significant difference between the control and Asperger's group, although there are tendencies of lower intercepts in Asperger's than in controls. Contrary to the feature search task, in the conjunction search task there seems to be no contribution of popout to target detection. It is likely that participants with Asperger's syndrome in the feature search task are able to reject the set of nontarget items that does not correspond to the target colour which, in turn generates a popoup on the form/shape dimension. Controls seem unable to adopt a similar strategy. In the conjunction search tasks, as the target is defined by a conjunction of colour and shape, items cannot be rejected as groups.

To summarize the findings of Experiments 1 and 2, a comparison of the two tasks shows that in terms of reaction times, there is an effect of task (feature, conjunction search) in the control group; further the control group also shows an interaction between tasks due to a larger difference between target-present and target-absent trials in the conjunction relative to the feature search task. Importantly, no effect of task is observed in the group of Asperger's. Trial type (target-present, target-absent) also affects performance in controls and trial type interacts with task; the interaction is due to a difference between tasks in target-absent but not target-present trials. In terms of search rates per item, there is an effect of search rate, trial type and an interaction between these factors in controls, but also in Asperger's.

That is, in terms of patterns, the two groups are highly similar, while in terms of overall search performance, there are significant differences. The differences between groups arise at the level of the processing of single items during the process of visual search.

Contrary to findings with autistic observers (e.g., Plaisted, O´Riordan & Baron-Cohen, 1998b), search rates of the Asperger's group were statistically reliably affected by the number of display items (set size). However, overall search rates of the Asperger's group did not differ significantly between conjunction and feature search tasks, whereas there is a significant task-dependent rate difference in the control group. The failure to replicate the set size effect repeatedly observed in conjunction search in autistic observers is interesting. As set size seems to affect search in Asperger's syndrome, the present results might contribute to a better differentiation between the various subtypes along the autistic spectrum with the Asperger's group being more similar to the normal observers than to the autistic group.

Since the present Experiments 1 and 2 showed that the Asperger's group seems to possess some different type of processing of visual stimuli relative to healthy controls, the question arises as to where in the visual processing stream this difference can be localized.

The differences might arise at early visual (pre-selective) or late (post-selective) processing steps. Experiments 1 and 2 probed the intervening search process, and the following experiments were designed to probe the pre- and post-selective stages, respectively.

5.2.4 Experiment 3 & 4: Early Processing Differences?

Experiment 3

In the feature and conjunction search experiments (Experiments 1 and 2) reported in the previous sections, people with Asperger's syndrome showed significantly faster search reaction times and a significantly more efficient search process (faster search times per item) compared to healthy controls. On the basis of these results, the question arises regarding the potential alternative stages of visual processing at which differences between the group of Asperger's and healthy controls can be identified. Potential alternative loci for the processing difference may be at early perceptual, pre-selective stages or at later, post-selective stages; i.e., before or after the selection process that has been shown to be expedited in the Asperger's group in feature and conjunction search.

In Guided Search – one of the most influential current models of visual search (see, e.g., Wolfe, 1994) – early, pre-selective processing stages include the extraction of visual features in a visual scene together with the generation of dimension-based (Müller, Heller & Ziegler, 1995; Found & Müller, 1996; Krummenacher & Müller, 2005) saliency signals. Saliency activation indicates, in a topographic representation, areas that contain information that is significantly different from the surrounding information. Dimension-based saliency signals are computed by contrasting visual features (e.g., colour: red, green, blue; orientation: horizontal, vertical, tilted; size: small, large) within dimension-based modules. If an area is characterized by high saliency activation, the location's informational content is high. Following computation of dimension-based saliency signals within a limited set of dimensional modules, the dimension-based saliency signals are integrated into an overall saliency (Wolfe, Cave & Franzel, 1989; Wolfe, 1994; Koch & Ullman, 1985; Itti & Koch, 2000, 2001; Crick, 1984) or priority representation (Fecteau & Munoz, 2006). The attentional focus samples high saliency areas with priority for making the information at this location available for higher order cognitive processes. In addition to feature extraction and the generation of dimension-based saliency representations, early processing stages include the saliency integration on the overall priority map and the allocation of focal attention. Higher order visual processes of object recognition and identification are referred to as late stages of processing. Krummenacher, Müller and Heller (2002), in a study investigating the mechanisms underlying the integration of dimension-based saliency signals, showed that, in search for a singleton feature target differing in one (singly defined) or two (redundantly defined) dimensions from distractor items, the dimension-based saliency signals are integrated before the response is triggered. Furthermore, Krummenacher et al. (2002) showed that reaction time benefits arising in search for redundantly defined targets compared to singly defined targets are explained on the level of an overall saliency signal based on *co-active* integration of dimension-based saliency activation. The target location of a redundantly defined target can be discerned earlier in time than the location of a singly defined target because the overall saliency activation, at a given point in time after onset of the search display, is higher for redundantly than for singly defined targets. Thus, the expedited search reaction times in redundant target trials (referred to as search redundancy gains) arise at an early level of processing (for recent further evidence for an early locus of the redundancy gain, see Zehetleitner, Krummenacher & Müller, 2009).

On the basis of the hypothesis that people with Asperger's syndrome have an advantage in discriminating visual information, it is expected that, in a group of participants with Asperger's syndrome, an advantage in the generation and integration of saliency activation is observed if the overall expedition of visual processing arises at early processing stages. Thereby, high-saliency locations, in participants with Asperger's syndrome, can be established faster and the information at these locations is made available for higher order object recognition processes at earlier points in time relative to healthy controls.

In order to test the hypothesis that the overall processing advantage in people with Asperger's syndrome arises at an early stage of processing, a singleton feature search experiment was conducted in which observers were presented, in target-present trials, with dimensionally singly defined targets or redundantly defined targets following the example of the study by Krummenacher, Müller and Heller (2002). In detail, observers were presented with targets defined on the colour (red or blue vertical bar), orientation (green left- or right-tilted bar) or both the colour and orientation (red or blue and left- or right-tilted bar) dimension; distractors were always green vertical bars (see Figure 5). Performance of a group of participants with Asperger's syndrome was compared to an age- and gender-matched sample of healthy controls.

5.2.4.1 Method Experiment 3

Participants. Thirteen observers with Asperger's syndrome and a control group of thirteen healthy subjects participated in Experiment 3 which was conducted online. The ages of the Asperger's group ranged between 17 and 57 years (M = 36.15 years; SD = 15.56 years) and the ages of the control group ranged between 18 and 57 years (M = 39.46 years; SD = 15.59 years). The Asperger's group consisted of six male and seven female participants and the control group of five male and eight female participants. The observers with Asperger's syndrome were all diagnosed by experts and additionally by an Autism-Spectrum Quotient (AQ, Baron-Cohen et al., 2001) of over 26 (cut-off for clinically significant levels of autistic traits, Woodbury-Smith et al., 2005). All observers had already participated in Experiments 1 and 2 and had normal or corrected to normal vision (including colour vision).

Apparatus. Because of the low prevalence of Asperger's syndrome, observers for the group with Asperger's syndrome were recruited in (German-speaking) Switzerland and Germany, and considering the fact that the internet removes the barriers of direct social interactions in persons with autistic spectrum disorders (Biever, 2007), the experiments were conducted online. The experiments were programmed with Adobe Macromedia Authorware 7.0 (Adobe Systems, 2009) in such a way as to make sure that the displays were always presented in the centre of the screen, irrespective of the diagonal and resolution at which individual monitors were run and independent of the internet browser used to run the experiments.

Search displays were presented on liquid crystal display (LCD) monitors ranging in screen diagonal between 14.1" to 24" (6 x 14.1", 14 x 17", 5 x 19", 1 x 24"), refresh rates varied between 60 Hz to 75 Hz (20 x 60 Hz, 6 x 75 Hz). Stimulus presentation and reaction time recording were controlled by the Adobe Macromedia Authorware Web Player on personal computers running the Windows operating system.

Observers were instructed to view the monitor from a distance of approximately 50 cm and to dimly illuminate their rooms. Distance was varied to adjust for screen size. Observers responded by pressing one of two alternative keys (left and right arrow keys on laptops or the C and M keys on desktops) with their left- and right-hand index fingers.

Stimuli and timing. The display consisted of a 7 x 7 matrix of bar stimuli (see Figure 5 for examples). Each bar subtended an area of approximately 1.34° of visual angle in height and of approximately .34° of visual angle in width. The bars in the matrix were slightly jittered with the horizontal distance between neighbouring bars varying between 1.7° and 3.56° of visual angle and the vertical distance between .98° and 2.33° of visual angle. Target bars were either defined by colour (red vertical or blue vertical) or by orientation (45° tilted to the left, 45° tilted to the right) or by a combination of colour and orientation (red or blue 45° left- or right-tilted bar). Distractor items were green vertical bars. Targets were presented at one randomly selected location of the inner 5 x 5 matrix to avoid edge effects (i.e., targets at the edges of the display are selected more slowly than targets at the centre of the display).

A trial started with the simultaneous presentation of all 49 bars. The display stayed on the screen until the observer entered the answer.

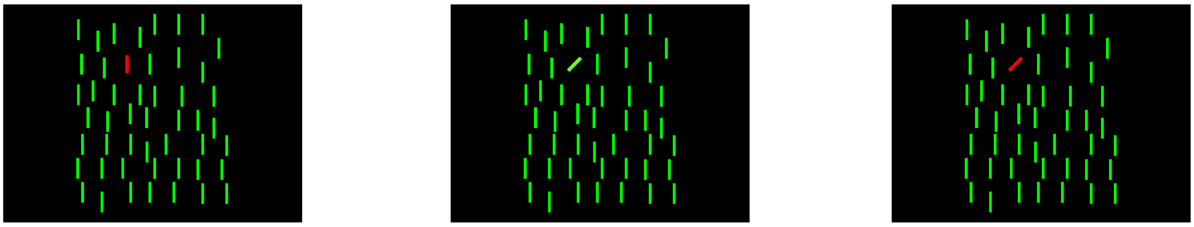


Figure 5. Examples of stimuli presented in the Experiment 3. The first and second panel illustrates singly defined targets (red and oriented to the right) and the third panel a target redundantly defined in two dimensions (colour and orientation).

Design and procedure. All observers performed the same target conditions: (a) single targets defined in one dimension (colour: red, blue; orientation: right-tilted, left-tilted) and (b) targets redundantly defined in two dimensions (colour and orientation: red & left-tilted, red & right-tilted, blue & left-tilted, blue & right-tilted). The three different target conditions were presented in randomized order within blocks of 48 trials comprising, over the entire experiment, 50 % target-present and 50 % target-absent trials. Observers responded by pressing one of two alternative keys (left and right arrow keys on laptops or the C and M keys on desktops) with their left- and right-hand index fingers.

Each trial started with a blank (500 ms) followed by a central fixation cross (1000 ms). After a second blank (unlike the Krummenacher et al. (2002) study varying between 800 and 1200 ms), the display remained visible until one of the response keys was depressed. To familiarize participants with the procedure, the experiment started with 24 practice trials, in which participants received feedback about whether they had responded correctly or incorrectly. A total of 384 trials, split into eight blocks of 48 experimental trials were presented. The number of repetitions for each of the eight alternative target definitions was 24, resulting in 192 target-present trials; another 192 target-absent trials were presented. The experiment, including practice trials, took approximately 30 minutes to complete.

5.2.4.2 Results Experiment 3

Errors. Error rates were very low in both groups (Asperger's: 0.74%; control: 1.34%) and did not differ significantly (*t*(24) = 1.86; *p* = .08). As in all of the observers there was at least one (single or redundant target) condition in which no error at all was made, error rates were not further analyzed.

Reaction times. The analysis of the reaction time (RT) data is subdivided into two sections with the first section examining mean RTs and reaction time redundancy gains and the second section testing the RT distributions for violations of Miller's (1982) race model inequality to identify the underlying processing architecture (parallel vs. parallel-coactive). Results of the reaction time and distribution analyses of the Asperger's group are compared to an age- and gender-matched control group.

Error trials (misses on target-present trials and false alarms in target-absent trials) were excluded from analysis (less than 1.04% of all trials). Further, in order to eliminate anticipatory or exceedingly slow reactions, RTs at the extreme ends of the RT distribution (smaller or bigger than 3 standard deviations from average RTs of each condition) for each participant and for each condition were excluded from the analysis.

Mean reaction times and RT redundancy gains. Table 5 presents the mean correct target-present RTs, and the associated error rates for single non-redundant targets and for single targets redundantly defined in two dimensions. Also given are the mean RT redundancy gains relative to the fastest singly defined target. Overall mean RTs in the Asperger's group were at 536.78 ms (SD = 56.83 ms) compared to 566.73 ms (SD = 88.22 ms) in the control group.

Table 5. Mean correct reaction times for the different target conditions of Experiment 3.

Condition	RT (ms)		Mean RT (ms) redundancy gains (Miller & Lopes, 1988)	
	Asperger	Controls	Asperger	Controls
Singly defined target				
Red	547.26	555.79		
Blue	550.64	581.25		
Left-tilted	582.87	616.64		
Right-tilted	562.11	616.80		
M	548.25	577.46		
Redundantly defined target				
red & left-tilted	511.56	551.23		
red & right-tilted	497.01	531.32		
blue & left-tilted	535.43	566.13		
blue & right-tilted	527.41	549.38		
M	506.33	538.80	26.81	15.67
Target absent	630.29	665.66		

Redundantly defined targets, in both groups, (Asperger's: 506.33 ms; control: 538.80 ms) were responded to faster than single colour (Asperger's: 536.67 ms; control: 552.65 ms) and orientation (Asperger's: 560.04 ms; control: 602.72 ms) targets.

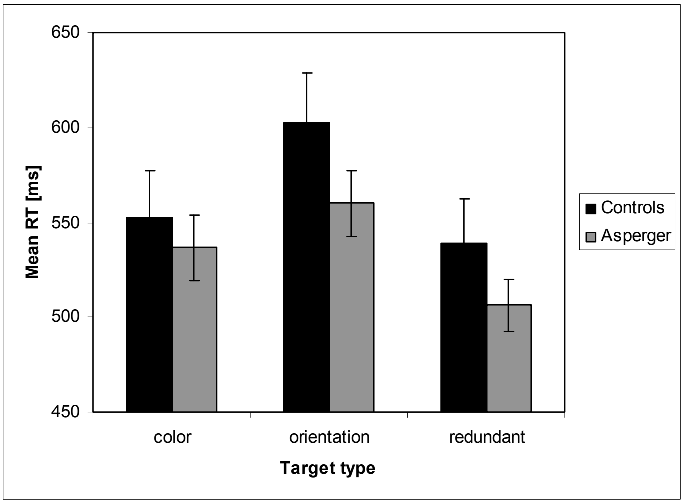


Figure 6. The mean RTs of the Asperger's group and the control group are plotted for targets defined by colour, by orientation or redundantly in colour and orientation.

More formally, the effects of target definition and group on reaction times were assessed in a mixed-factor ANOVA of target-present RTs with the within-subject factor target dimension (colour, orientation, redundant) and the between-subjects factor group (Asperger's, control). The ANOVA revealed the main effect of target dimension to be significant ($F(2,23) = 53.89$; $p < .001$), redundant targets were responded to fastest in both groups, followed by colour and orientation targets (see Figure 6). Planned contrasts revealed that, in both groups, RTs to singly defined targets (either defined by colour or by orientation) were significantly slower than RTs to redundantly defined targets (redundant vs. orientation: Asperger's $F(2,20) = 24.10$, $p < .001$; control $F(2,20) = 38.17$, $p < .001$; redundant vs. colour: Asperger's $F(2,20) = 24.10$, $p < .001$; control $F(2,20) = 38.17$, $p = .035$). Further, contrasts revealed reaction times to colour targets to be significantly faster than to orientation targets (Asperger's $F(2,20) = 24.10$, $p < .036$; control $F(2,20) = 38.17$, $p < .001$).

Thus, redundantly defined targets produced significant mean RT redundancy gains[12] in both the Asperger's and control groups.

Importantly, the interaction between the factors target dimension and group was not significant ($F(2,23) = 3.33$; $p = .054$). Planned comparisons showed that RTs of the Asperger's group did not differ from RTs, to singly or redundantly defined targets, of the control group (colour: $F(1,21) = 1.21$, orientation: $F(1,21) = 3.70$, redundant: $F(1,21) = 2.39$, $p > .07$).

The most conservative test compares RTs to redundant targets with RTs to the fastest of the single-target conditions. In this comparison, the redundancy gain in the Asperger's group was at 26.81 ms and at 15.67 ms in the control group. Gains in both groups were significantly different from zero (Asperger's group: $t(12) = 5.56$; $p < .001$; control group: $t(12) = 4.46$; $p = .001$). The redundancy gain in the Asperger's group did not differ significantly from the gain in the control group ($t(17.03) = -1.68$; $p = .112$).

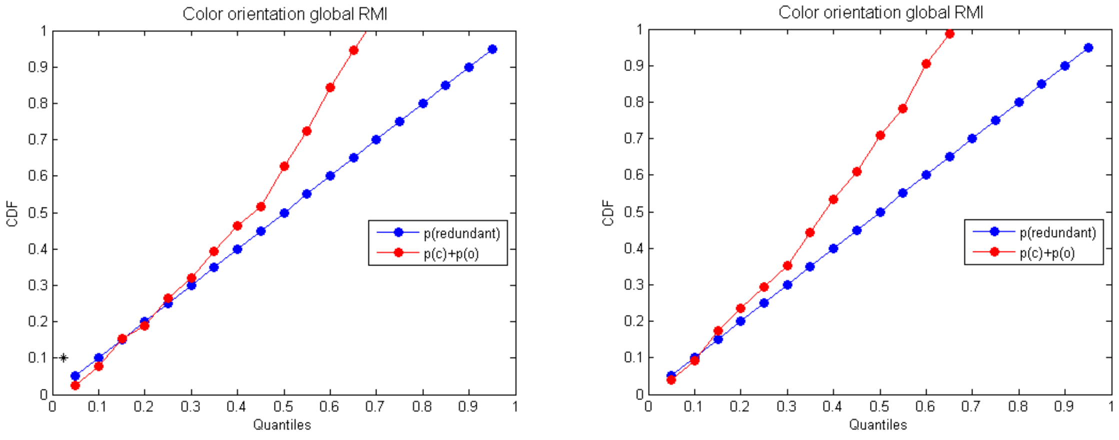
RT distribution analysis. Analysis of the RT distributions reveals a specific form of redundancy gain which is inconsistent with strict parallel models (claiming that a redundancy

---

[12] Note that mean RT redundancy gains were analysed according to a procedure proposed by Miller and Lopes (1988). Miller et al.'s test compares the two single-dimension conditions (i.e., colour and orientation) separately for each observer. In case the two dimensions differ significantly in terms of RT (on a liberal criterion of $\alpha = 10\%$), the faster of the two mean RTs is retained as a conservative estimate of single-dimension response times. If the RTs of the two target dimensions do not differ significantly, the overall mean of the two single-dimension conditions is used for comparison with redundant target trials. In any case, the resulting values are compared with the RTs of redundant-target trials. TIn Table 5 the mean RT redundancy gains, calculated according to the Miller and Lopes (1988) procedure, are presented in Table 5.

gain results simply from the fact that two targets have a higher chance of getting encountered early in the search than a single target). Miller (1982) showed that if each target produces separate and independent activation, reaction time distributions must satisfy the following race model inequality: $P(RT < t|T_1 \& T_2) \leq P(RT < t|T_1) + P(RT < t|T_2)$, where t is the time since display onset and T_1 and T_2 are target 1 and target 2. Violations of the inequality, the race model inequality (RMI), constitute evidence against parallel race and in favor of parallel-coactive processing.

By calculating $P(RT < t|T_1) + P(RT < t|T_2)$ for the set of response times t corresponding to 5%-quantiles (i.e., the 5th, 10th, 15th, etc. percentiles) of the redundant target RT distribution (T_1 and T_2 denote, in the present case, colour and orientation targets) the test for violations of the RMI was used to assess the underlying processing architecture, parallel vs. parallel co-active, in the Asperger's and the control group. The RMI is violated if $P(RT < t|T_1 \& T_2) > P(RT < t|T_1) + P(RT < t|T_2)$. The RMI analysis of the RT distributions revealed a significant violation of the RMI only in the Asperger's group, in the 5% quantile (see Figure 7).



a) b)

Figure 7. Test for violations of the RMI for redundant targets in the Asperger's (a) and control (b) group. The cumulative probability for the sum of the two singly defined targets, $P(RT < t|T_1) + P(RT < t|T_2)$, is plotted as a function of the vincentized (5% quantiles) redundant-target reaction time distribution, $P(RT < t|T_1 \& T_2)$. The diagonal line represents the baseline, $P(RT < t|T_1) + P(RT < t|T_2) = P(RT < t|T_1 \& T_2)$, reflecting the prediction of a parallel race model. Data points significantly below the diagonal represent violations of the RMI. Significant violations are indicated by * (paired-samples t-test $p < .05$). Violations were tested for significance with a paired-samples t-test comparing observed summed probabilities of single-target RTs (to a colour or orientation target) having occurred earlier than the baseline RT to a redundantly defined target (see Krummenacher et al. [2002] for details about the computation).

Therefore, the analysis of the RT distribution provides evidence for parallel-coactive processing of dimension-specific colour and orientation saliency signals when the target is defined redundantly in two dimensions in the Asperger’s group. No significant violation could be found in the control group.

5.2.4.3 Discussion Experiment 3

The pattern of error rates, mean search RTs and RT redundancy gains is very similar to the pattern found in unimpaired observers and replicates the previous results of Krummenacher, Müller and Heller (2002). RTs to redundantly defined targets were faster than to singly defined targets in both the Asperger’s and the control group with slightly larger gains in the Asperger’s group. RTs to colour targets were slightly faster than to orientation targets in both groups - a finding again replicating the results of Krummenacher, Müller and Heller (2002).

Inferring from the results of Experiment 3, the advantage found in the feature and conjunction search in observers with Asperger's syndrome seems not to be rooted in an additional advantage arising at early levels of feature encoding and representation. Rather the effects are highly likely limited to the level of processing concerned with matching the short-term memory representation of (integrated) features with a target representation.

The interpretation is supported by the fact that performance benefits in individuals with Asperger's seem to be found exclusively in search tasks where letters are used as search objects. Therefore, further experiments are required to specify the potential locus of the processes underlying the performance benefits in observers with autism spectrum disorders.

The violation of the race model assumption in the Asperger’s group provides evidence that integration of feature-based saliency activation is parallel-coactive in nature in individuals with the Asperger’s syndrome. The results of the distribution analysis, however, are difficult to interpret, as the findings of the control group differ from the findings of Krummenacher et al. (2002). Krummenacher et al. found co-active processing of features in redundant-target trials in healthy observers. In the present Experiment 3, though numerically lower than the predicted values, redundancy gains in controls were not statistically reliable. Overall, the results seem to suggest, however, that the same processing mechanisms are engaged in the processing of singly and redundantly defined singleton feature targets in both controls and people with Asperger's syndrome.

Altogether, the present findings provide further support for the interpretation that in people with Asperger's syndrome the search process is expedited.

Experiment 4

5.2.4.4 Method Experiment 4

To further investigate the possible locus of processing differences between a group of individuals with Asperger's syndrome and a healthy control group, in Experiment 4, a variant of the redundant target paradigm (Krummenacher, Müller & Heller, 2002) was used. In contrast to Experiment 3, in Experiment 4, redundant signals were presented at different rather than at one and the same location. That is, in redundant target trials, a colour and an orientation target were presented, with variable distance between the dual targets. Similar to Experiment 1 of Krummenacher, Müller and Heller (2002) and the present Experiment 3, targets singly defined in one dimension (colour or orientation) and dual targets defined in different dimensions (i.e., a colour-defined and an orientation-defined target) were presented. If dual (redundant) targets were presented in a trial, the distance between targets was varied in three steps; the dual targets were presented at neighbouring locations, with one distractor between targets or two distractors between targets. The location of one of the targets relative to the other target could be shifted on a horizontal, vertical or diagonal line. Mean reaction times and reaction time redundancy gains for redundant compared to single target conditions and the RT distributions were analyzed.

Participants. Eleven observers with the Asperger's syndrome and a control group of six healthy subjects participated in Experiment 4, again conducted online. The ages of the Asperger's group ranged between 23 and 52 years (M = 33.82 years; SD = 7.92 years) and the ages of the control group ranged between 24 and 36 years (M = 29.83; SD = 3.87 years). The Asperger's group consisted of six male and five female participants and the control group of two male and four female participants. The two groups did not differ in terms of age ($t(15)$ = -1.15; p = .269) or gender ($\chi^2(1)$ = .70; p = .620). The observers with Asperger's syndrome were all diagnosed by experts and additionally by having an Autism-Spectrum Quotient (AQ, Baron-Cohen et al., 2001) of over 26 (cut-off for clinically significant levels of autistic traits, Woodbury-Smith et al., 2005). All participants had no previous experience with visual search tasks and normal or corrected to normal vision (including colour vision).

Apparatus. The (online) experiments were programmed with Adobe Macromedia Authorware 7.0 (Adobe Systems, 2009) in such a way as to make sure that the displays were always presented in the centre of the screen, irrespective of the diagonal and resolution at which individual monitors were run and independent of the internet browser used to run the experiments.

Search displays were presented on liquid crystal display (LCD) monitors ranging in screen diagonal between 14.1" to 24", refresh rates varied between 60 Hz to 75 Hz. Stimulus presentation and reaction time recording were controlled by the Adobe Macromedia Authorware Web Player on personal computers running the Windows operating system.

Observers were instructed to view the monitor from a distance of approximately 50 cm and to dimly illuminate their rooms. Distance was varied to adjust for screen size. Observers responded by pressing one of two alternative keys (left and right arrow keys on laptops or the C and M keys on desktops) with their left- and right-hand index fingers.

Stimuli and timing. The display consisted of a 6 x 6 matrix of bar stimuli (see Figure 8 for examples). A bar subtended approximately 1.34° of visual angle in height and approximately 0.34° of visual angle in width. The bars in the matrix were slightly jittered with the horizontal distance between neighbouring bars varying between 1.70° and 3.56° of visual angle and the vertical distance between 0.98° and 2.33° of visual angle. Target bars were either defined by colour (red vertical or blue vertical) or by orientation (45° tilted to the left, 45° tilted to the right) or by a combination of colour and orientation (red or blue 45° left or right tilted bar). There were two different target conditions: (a) singly defined targets (i.e., red, blue, left-tilted, right-tilted) and (b) dual (redundant) targets each defined in a different dimension (i.e., one red and one left-tilted, one red and one right-tilted, one blue and one left-tilted or one blue and one right-tilted). Single targets were defined on the colour (red, blue) or the orientation (left-tilted, right-tilted) dimensions. Distractor items were green vertical bars.

Targets were presented at one (single-dimension targets) randomly selected location or two (dual redundant targets) random locations of the inner 4 x 4 matrix to avoid edge effects (targets at the edge of the display are selected more slowly than in the centre of the display). If two targets were presented together in one trial, they could be at neighbouring locations (separated by 1 unit of distance or distance 1: D1), with one distractor in between target locations (separated by two units of distance: D2) or with two distractors between target locations (D3).

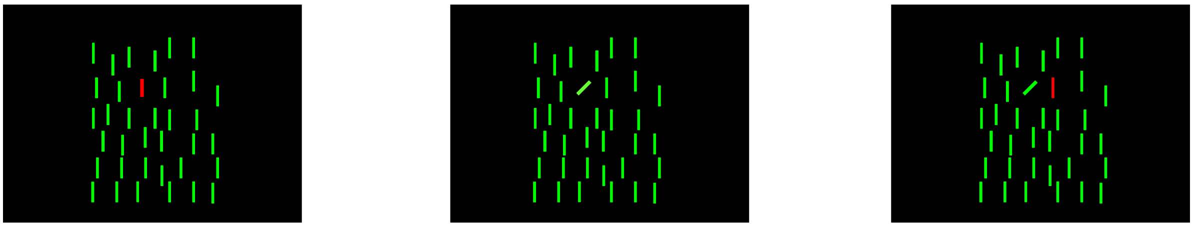


Figure 8. Examples of stimuli presented in the Experiment 4. The first and second panel illustrate singly defined targets (red and oriented to the right) and the third panel two (redundant) targets each defined in one dimension (colour and orientation).

A trial started with a blank (800 ms) followed by a central fixation cross (800 ms). After a second blank (varying between 400 and 600 ms) all 36 bars were presented simultaneously. The display remained visible until the observer responded.

Design and procedure. All observers performed the same target conditions: (a) single targets singly defined in one dimension (red, blue, right-tilted, left-tilted) and (b) dual (redundant) targets each defined in one dimension (i.e., one red and one left-tilted, one red and one right-tilted, one blue and one left-tilted or one blue and one right-tilted), presented either on neighbouring locations, or separated by one or two distractor items. In the first (672 trials) session the different target conditions were presented in randomized order within 14 blocks of 48 trials and in the second session (624 trials) and third session (624 trials) within 13 blocks of 48 trials containing on average 50 % target-present and 50 % target-absent trials. Participants had to indicate, by pressing a pre-designated key, if one or two target(s) was (were) present in the display and by pressing another pre-designated key if no target was present. The experiment was conducted in three separate sessions performed on different days. Each session started with 24 practice trials in which participants received feedback about whether their responses were correct or incorrect. The practice block was followed by 14 (day 1) or 13 (days 2 and 3), respectively, blocks of experimental trials, each block consisting of 48 experimental trials. Overall, the number of trials for each of the single target alternatives (red, blue, left-tilted, right-tilted) was 120 and for each redundant target alternatives (three different distances, red & right-tilted, red & left-tilted, blue & right-tilted, blue & left-tilted) 120 (for each distance overall 140 trials). The target-absent trials totalled 1920 trials. Each experimental session, including practice trials, took approximately 50 minutes to complete.

5.2.4.5 Results Experiment 4

The analysis of the reaction time (RT) data is divided into two sections examining the mean reaction times, RT redundancy gains, and the RT distributions, comparing probabilities of responses having occurred, at a given point in time after display onset, in redundant target trials (dual targets) compared to single target trials, separately for the Asperger's group and an age- and gender-matched control group.

Error trials (misses in target-present and false alarms in target-absent trials) were excluded from analysis. Further, to eliminate anticipatory or delayed reactions, RTs at the extreme ends of the RT distribution (below or above 3 standard deviations of average RTs of each condition) were excluded from the analysis for each participant and condition separately.

Mean reaction times and RT redundancy gains. Table 6 presents the mean correct target-present RTs, for targets differing from distractors on a single dimension (single targets) and for dual (redundant) targets differing from distractors on two dimensions, separately for the three distances (D1, D2, D3), for the Asperger's and the control group. Also given are the mean RT redundancy gains for the three different distances relative to the fastest single-feature target.

In both groups RTs were slower to singly defined targets (Asperger's group: M = 536.43 ms, SD = 86.04 ms; control group: M = 586.15 ms, SD = 161.50 ms) relative to (dual) redundant targets (Asperger's group: M = 486.98 ms, SD = 66.37 ms; control group: M = 536.65 ms, SD = 134.36 ms).

A mixed-factors analysis of variance (ANOVA) of the target-present RTs (with the within-subject factor target condition [single, dual D1, D2, D3] and the between-subject factor group [Asperger's, control]) revealed the main effect of target condition to be significant (*F*(2,30) = 15.80; *p* < .001). The groups did not differ significantly in terms of target conditions (*F*(1,15) = .81; *p* = .383). Planned contrasts revealed RTs to singly defined targets to be significantly slower than those to dual targets in the nearest distance D1 (Asperger's: *p* = .001; control group: *p* = .014), with one distractor between targets D2 (Asperger's: *p* < .001; control group: *p* = .002) and with two distractors between targets D3 (Asperger's: *p* < .001; control group: *p* = .008) (*F*(3,13) = 7.06; *p* = .005). That is, in all redundant target conditions, a similar pattern of significant mean RT redundancy gains relatively to the fastest of the two singly defined target alternatives was evident. Gains in the Asperger's group were at 30.16 ms, and at 27.98ms in the control group, if targets were presented at neighbouring locations. Redundancy gains in trials with targets with one distractor in between were at 27.61 ms in the Asperger's group and at 27.48 ms in the control group. Finally, redundancy gains in trials with two distractors between dual targets were at 28.46 ms in the Asperger's group and at 23.68 ms in the control group.

Table 6. Mean correct reaction times for the different target conditions of Experiment 4.

Condition	RT (ms)		Mean RT (ms) redundancy gains (Miller & Lopes, 1988)	
	Asperger	Controls	Asperger	Controls
Singly defined target				
Red	512.45	593.08		
Blue	518.28	544.59		
Left-tilted	553.39	615.42		
Right-tilted	561.59	591.05		
M	536.43	586.04		
Dual target (D1)				
red & left-tilted	488.14	547.42		
red & right-tilted	479.72	529.43		
blue & left-tilted	485.69	533.74		
blue & right-tilted	488.74	527.78		
M	485.57	534.59	30.16	27.98
Dual target (D2)				
red & left-tilted	487.85	544.18		
red & right-tilted	489.60	521.98		
blue & left-tilted	495.42	535.29		
blue & right-tilted	479.63	541.21		
M	488.13	535.67	27.61	27.48
Dual target (D3)				
red & left-tilted	491.32	542.75		
red & right-tilted	488.64	536.60		
blue & left-tilted	480.52	539.45		
blue & right-tilted	488.27	538.28		
M	487.19	539.27	28.46	23.68
Target absent	534.37	577.26		

Errors. Error analysis shows that RT redundancy gains are not due to observers trading accuracy for speed. Error rates, very low overall, were at 1.64% (SD = 1.29%) in the Asperger's group and at 1.40% (SD = 1.33%) in the control group. Error rates (see Table 7) did not differ significantly between groups (*t*(15) = -.34; *p* = .721). More importantly, error rates were lower for all redundant target conditions relative to singly defined target conditions. However, only in the Asperger's group was the difference between single and redundant target error rates of all three dual target conditions statistically reliable (*F*(3,12) = 6.83; *p* = .005; single target compared to D1 condition: *p* = .002; single target compared to D2 condition: *p* = .001; single target compared to D3 condition: *p* = .003).

Table 7. Mean error (miss) rates for singly defined targets and dual (redundant) targets for all three distances (D1-D3) for the Asperger’s group and the control group.

Error %				
	Single	D1	D2	D3
Asperger	5.40	1.42	1.02	1.02
Controls	4.31	1.25	0.94	1.67

RT redundancy gains are calculated by the procedure described in Experiment 3. Relative to the fastest singly defined target, the Miller-Lopes (1988) RT redundancy gains were at 27.98 ms, 27.48 ms, and 23.68 ms for the control group and at 30.15 ms, 27.61 ms, and 28.46 ms for the Asperger’s group (see Table 8) for the dual targets each defined in a different dimension at neighbouring locations, separated by one and two distractor items, respectively. All redundancy gains were greater than zero in all conditions (D1: *t*(16) = 3.95, *p* = .001; D2: *t*(16) = 4.13, *p* = .001 ; D3: *t*(16) = 3.44, *p* = .003).

Table 8. Mean correct RTs as a function of three different distances (D1, D2, D3) between the dual redundantly in two different dimensions defined targets in the Asperger’s group and the healthy control group.

		Rts (ms)	
Target	D1	D2	D3
Asperger			
Red & left	488.14	487.85	491.32
Red & right	479.72	489.60	488.64
Blue & left	485.69	495.42	480.52
Blue & right	488.74	479.62	488.27
M	485.57	488.12	487.19
Controls			
Red & left	547.42	544.18	542.75
Red & right	529.43	521.98	536.60
Blue & left	533.74	535.29	539.45
Blue & right	527.78	541.21	538.28
M	534.59	535.67	539.27

RT distribution analysis. In analogy to the procedure reported in Experiment 3 to test the predictions of parallel race vs. parallel-coactive models of dimensional processing, the entire

RT distributions of single and redundant targets were tested for violations of the RMI (Miller, 1982). By calculating $P(\mathrm{RT} < t|\mathrm{T}_1) + P(\mathrm{RT} < t|\mathrm{T}_2)$ for all response times t of singly defined targets and relating them to the corresponding quantiles (i.e., the 5th, 10th, 15th, etc. percentiles) of the redundant target RT distribution (T_1 and T_2 denote colour and orientation targets), the test for violations of the RMI was applied to the groups of Asperger's and controls, separately for the three dual (redundant) target distances. The RMI is violated if $P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1\ \&\ \mathrm{T}_2) \mathbf{>} P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1) + P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_2)$. Significance of the violation was assessed using t-tests. In the Asperger's group, significant violations of the RMI were revealed for the first (the 5%) quantile in the D2 and D3 conditions (see Figure 9). Thus, the analysis of the RT distributions provides evidence for parallel-coactive processing of dimension-specific colour and orientation saliency signals when the target is redundantly defined in two dimensions in patients with Asperger's syndrome. No significant violations were found in the control group for either distance between the dual (redundant) stimuli (see Figure 10).

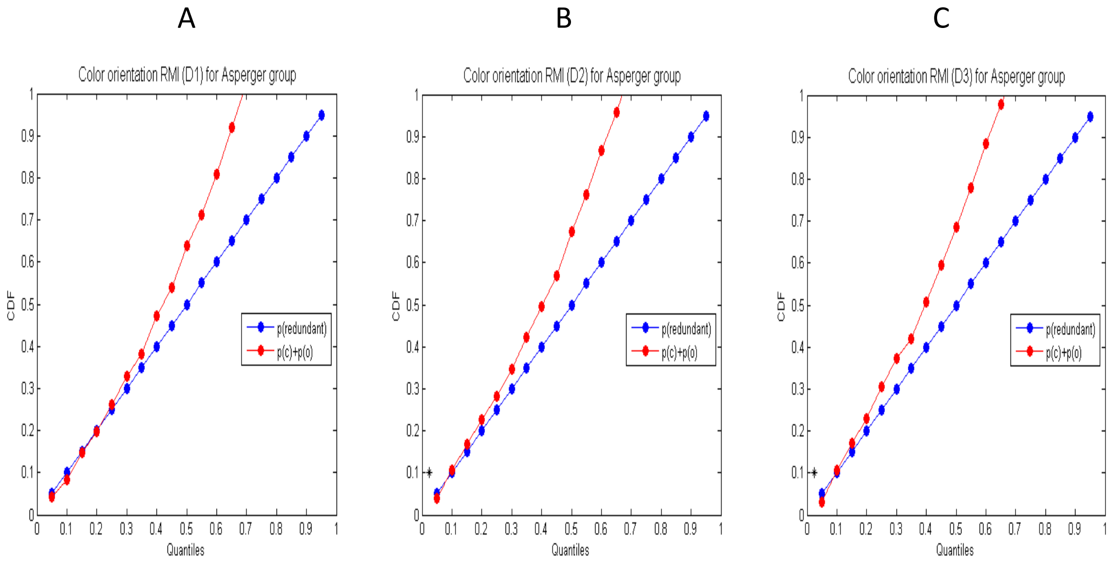


Figure 9. Test for violations of the RMI for redundant targets for (A) neighbouring targets (D1), targets separated by one (B; D2) or by two (C; D3) distractors in the Asperger's group. The cumulative probability for the sum of the two singly defined targets, $P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1) + P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_2)$, is plotted as a function of the vincentized (5% quantiles) redundant-target reaction time distribution, $P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1\ \&\ \mathrm{T}_2)$. The diagonal line represents the baseline, $P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1) + P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_2) = P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1\ \&\ \mathrm{T}_2)$. Data points below the diagonal represent violations of the RMI. Significant violations are indicated by * ($p < .05$).

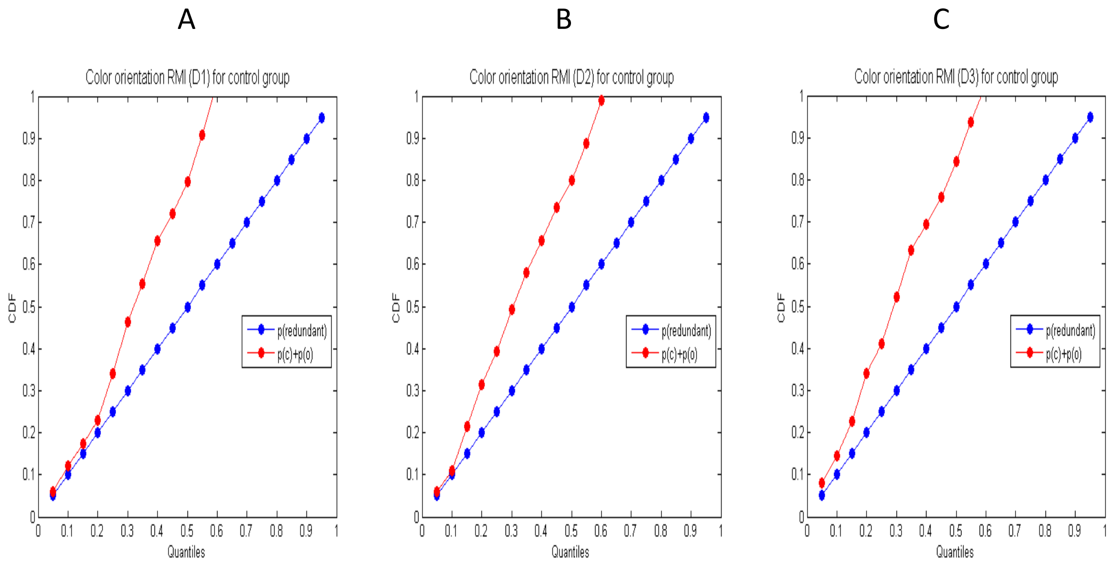


Figure 10. Test for violations of the RMI for redundant targets for (A) neighbouring targets (D1), targets separated by one (B; D2) or by two (C; D3) distractors in the control group. The cumulative probability for the sum of the two singly defined targets, $P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1) + P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_2)$, is plotted as a function of the vincentized (5% quantiles) redundant-target reaction time distribution, $P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1 \ \& \ \mathrm{T}_2)$. The diagonal line represents the baseline, $P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1) + P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_2) = P(\mathrm{RT} < \mathrm{t}|\mathrm{T}_1 \ \& \ \mathrm{T}_2)$. Data points below the diagonal represent violations of the RMI. Significant violations are indicated by * ($p < .05$).

5.2.4.6 Discussion Experiment 4

Overall, the reaction time analysis replicates previous findings of faster processing if targets were defined redundantly in two dimensions compared to targets singly defined in one dimension. However, a decrease in RT redundancy gains was not found with increasing distance between the dual (redundant) targets in either of the two groups. Thus, the present findings do not fully replicate the findings of Krummenacher, Müller and Heller (2002). Krummenacher et al. (2002) showed that RT redundancy gains decreased as a function of distance between dual target items. They explained their finding on the basis of the spatial nature of the dimension-based saliency signals. Dimension-based saliency signals are integrated into an overall saliency representation which controls the allocation of focal attention. In redundant target trials in which both dimensional signals differ from distractors at the same spatial location, one single peak of activation is generated on the overall saliency representation; that is, activation on the overall saliency representation is high and the attentional focus is directed to the location of the target relatively quickly. In contrast, if dimension-based activation is generated at different locations, integrated saliency activation is lower – in the case of nearby signals, or two independent peaks of activation are generated – in the case target items are separated by distractors that are presented in between targets. Thus, in dual target redundant trials, co-active integration is less efficient than in single target dual trials (as in Experiment 3). In the present Experiment 4, numerically, redundant target response times were lower than expected from the prediction of the race model inequality. However, as the differences are not statistically reliable, interpretation is difficult. Still, observers with Asperger's syndrome show a number of significant violations of Miller's (1982) RMI, suggesting that processing of visual features is more efficient in people with Asperger's syndrome than in healthy controls. As differences in significance are discussed here rather than significant differences, the scope of the interpretation is limited and further research is required.

5.2.5 Experiment 5: Early or Late Processing Differences?

Experiments 3 and 4 investigated whether improved performance in people with Asperger's syndrome arises at an early level of saliency generation and integration. The results suggest that, in the Asperger's group, processes of saliency generation might well be expedited relative to age-matched controls. RT redundancy gains also suggest that dimension-based saliency signals are integrated in a parallel-coactive fashion in people with Asperger's, while in healthy controls, dimension-based saliency signals engage in a parallel race.

The present Experiment 5 was designed to investigate whether semantic information affects search for singleton feature targets in people with Asperger's syndrome. In other words, Experiment 5 was aimed at testing if the processing difference between persons with Asperger's syndrome is located at a late stage of semantic processing. Note that the experimental paradigm used in Experiment 5 also allows testing for effects at an early stage of processing. In detail, immediately before each experimental trial of a singleton feature search experiment, observers were presented with a semantic cue (a word) indicating, with high probability, the dimension defining the target in the following search display. RTs were analyzed dependent on cue validity. Dimensionally, valid cues (e.g., indicating colour in a trial where the target is colour-defined) are expected to expedite RTs whereas invalid cues (e.g., indicating colour in a trial where the target is orientation-defined) are expected to incur a RT cost. In addition to the effects of the semantic cue, inter-trial transitions in terms of the target-defining dimension were analyzed. Targets were bars defined on the colour (red, blue) or the orientation (left-tilted, right-tilted) dimension and distractors were always green vertical bars. There are three types of inter-trial transitions: in same dimension, same feature (sDsF) trials, exactly the same target is shown in consecutive trials (e.g., trial N-1: red → trial N: red), in same dimension, different feature (sDdF) trials, the target feature, but not the target dimension changes (e.g., red → blue), and in different dimension (dD) trials, the target dimension changes (e.g., colour [red, blue] → orientation [left-tilt, right-tilt]).

The key issue of Experiment 5 is whether search performance of people with Asperger's syndrome is influenced by top-down knowledge, that is, by a high, semantic process, or by bottom-up (stimulus-driven) information only (Experiments 3 and 4).

Posner (1980) introduced a widely used experimental procedure referred to as the 'cueing paradigm'. In Posner's experimental procedure, observers were presented, at the beginning of a trial, with a central fixation cross that was followed by a symbolic cue, an arrow, presented at the location of the fixation cross, pointing to one of two possible target locations to the left or to the right of the centre. At one of the two locations, the upcoming target was presented. Posner assumed that the cue is able to direct the focus of attention to the indicated location, and that, if the cue validly indicates the target location, the response to the target is expedited relative to conditions in which the target appears at the non-indicated location. Usually, three different cue conditions are employed. In a neutral cue condition, the target equally likely appears at either of the two locations; in the valid cue condition, the target appears at the location indicated by the cue, and in the invalid cue condition, the target appears at the location opposite to the one indicated by the cue. The time it takes to detect the target item (simple RT), presented in one of two possible locations, is measured and compared between cue conditions. Results showed that, relatively to the neutral cue condition, RTs are expedited if the target is presented at the location indicated by the cue (valid cue condition) and RTs are slowed if the target is presented at the opposite location (invalid cue condition). Benefits in the valid cue condition are due to the fact that the attentional spotlight is already at the right location, and the costs in invalid cue condition are due to the necessity to shift the focus of attention from the (invalidly) cued location to the actual location of the target. The effect of a symbolic cue is generated endogenously and controlled by voluntary (high-level) processes. The engaged processes are therefore based on a person's internal goals, consequently, the symbolic cueing effect is referred to as an *endogenous cueing effect*.

Posner's (1980) cueing paradigm was used in combination with the visual search paradigm by Müller, Reimann and Krummenacher (2003). In a task involving visual search for singleton features, observers had to decide on the presence or absence of a singleton feature target, differing from distractors on either the colour or orientation dimension. Müller, Heller and Ziegler (1995; Found & Müller, 1996) showed that changing the target-defining dimension across trials (e.g., from colour to orientation), significantly increases search reaction times (RTs) compared to repetitions of the target-defining dimension. Müller et al. (1995; see also Found & Müller, 1996; Zehetleitner, Krummenacher & Müller, 2009) suggest that RT costs associated with dimension changes arise at the early level of feature extraction.

Müller, Reimann and Krummenacher (2003), at the beginning of each search trial, presented a semantic cue (i.e., the words "colour", "orientation" or "neutral") indicating the dimension of the upcoming target. Cue validity was 80%, that is, the cue validly indicated the target dimension in four out of every five trials. (In the neutral cue condition, the cue did not carry any information as to the target dimension.) Müller et al. (2003) found that RTs were affected by cue validity and therefore they proposed that early dimension-based bottom-up processes can be modulated by top-down semantic cues. Taking into account that, in addition to the semantic effect of the cue, RTs were also affected by dimension-based changes across consecutive trials, the authors concluded that RTs are determined by both bottom-up dimensional modulations and top-down information.

Since autistic observers (Plaisted, O'Riordan & Baron-Cohen, 1998b; O'Riordan et al., 2001; O'Riordan, 2004) and persons with Asperger's syndrome show considerably different patterns of performance relative to unimpaired controls in visual search tasks, using Müller, Reimann and Krummenacher's (2003) cueing paradigm, Experiment 5 investigated whether bottom-up and top-down dimension-based processes in participants with Asperger's syndrome are similar to those of normal observers. Müller et al. (2003) showed that normal observers' search RTs are significantly increased when the target-defining dimension changes across trials. However, RT costs were significantly reduced in validly and invalidly cued trials relative to trials with a neutral cue. The interaction between neutral and invalid cue conditions in healthy observers suggests that the processing system is 'reset' in the invalid cue condition if the dimension is changing. The cue and the target dimension of the previous trial cease to affect processing in the current trial. If there is no processing difference in late stages, the results of the Asperger's group are expected to show the same effects.

5.2.5.1 Method

Participants. Seven observers with Asperger's syndrome (four male, three female) ranging in age between 21 and 57 years (M = 41.57 years; SD = 13.49 years) participated in Experiment 5, which consisted of four sessions conducted online over several days. The observers with Asperger's syndrome were all diagnosed by experts and additionally by having an Autism-Spectrum Quotient (AQ, Baron-Cohen et al., 2001) of over 26 (cut-off for clinically significant levels of autistic traits, Woodbury-Smith et al., 2005). All of them had taken part in Experiments 1, 2 and 3. All observers had normal or corrected to normal vision (including colour vision).

Apparatus. The apparatus was the same as in Experiments 1, 2 and 3.

Stimuli and timing. The display consisted of a 7 x 7 cell matrix of bars. Each bar subtended an area of approximately 1.34° of visual angle in height and of approximately 0.34° of visual angle in width. The bars in the matrix were slightly jittered relative to cell centres with the horizontal distance between neighbouring bars varying between 1.7° and 3.6° of visual angle and the vertical distance between 0.98° and 2.3° of visual angle. Target bars were either defined by colour (red vertical, blue vertical) or by orientation (45° tilted to the left, 45° tilted to the right); distractors were always green vertical bars. All stimuli were presented against a dark grey background. Targets were presented at one or two randomly selected locations of the inner 5 x 5 matrix to avoid edge effects.

A trial started with the presentation of a symbolic dimensional cue (the words "*colour*", "*orientation*" or "*neutral*") at the centre of the display for 1600 ms. The offset of the cue was followed by a central fixation cross (850 ms) and replaced by the simultaneous onset of the 36 bar stimuli. The search display remained visible until a (target-present or target-absent) response was given.

Procedure. The independent variables were target (present, absent) and for target-present trials cue validity (valid, neutral, invalid), target dimension (colour, orientation), target feature (colour: red, blue; orientation: left-, right-tilted) and inter-trial transition, i.e., target in trial N relative to target on the preceding trial N-1 (same dimension, different dimension). Each of the 4 sessions was comprised of a total of 720 trials and took about 1 hour to complete. In total, 2880 trials were presented, split into 40 blocks. Neutral trials were presented in separate blocks of 72 trials. There were 8 neutral blocks, evenly distributed over the whole experiment, and 32 blocks with valid and invalid trials, presented in randomized order within the same blocks. The presentation of neutral and valid/invalid trials was separated to permit economical collection of the data required for the intertrial transition analysis (presenting neutral, valid and invalid trials in randomized orders within the same blocks would have required many more trials to achieve the necessary number of intertrial transitions separately for each trial type).

In neutral and valid/invalid blocks, the target-defining dimensions changed unpredictably from trial to trial. In all blocks, 60% target-present and 40% target-absent trials were presented. The number of target-present trials was higher, because they are of higher theoretical interest than absent trials in the present experiment. In target-present trials, half of the targets were defined in the colour, and half in the orientation dimension. Half of the colour targets were red, half blue; half of the orientation targets were 45° left-tilted, the other half 45° right-tilted. In neutral trial blocks, the symbolic cue (*neutral*) provided no information as to the dimension of the upcoming target. All targets were equally likely defined in either the colour or the orientation dimension. In valid as well as invalid trials, the cue contained information about the probability of the target-defining dimension (*colour* or *orientation*), i.e., any target in a search trial was defined with a probability of 80% in the cued dimension (valid trial) and a probability of 20% in the non-cued dimension (invalid trial).

Observers were instructed to set themselves for the actually cued dimension in the valid and invalid cue conditions and for both dimensions in the neutral cue condition. The observers' task was to respond *target present* to any of the possible targets and to respond *target absent* when there was no target presented. Both responses should be given as quickly and accurately as possible.

5.2.5.2 Results

Only target-present trials were analyzed. Error trials and outliers were excluded from further analysis. Target-present RTs in valid and invalid cue conditions were analyzed in terms of cueing costs and benefits relative to the neutral baseline.

RT cueing costs and benefits. Table 9 presents the group mean target-present RTs as a function of cue validity, separately for each target dimension. Individuals' mean RTs were examined in a repeated-measures analysis of variance (ANOVA) with the factors cue validity (neutral, valid, invalid) and target dimension (colour, orientation). The ANOVA revealed neither of the two main effects to be significant: cue validity, *F*(2,12) = 1.24; *p* = .324 and target dimension, *F*(1,6) = 3.64; *p* = .105). Planned comparisons showed that colour targets and orientation targets are responded to equally quickly (500.13 ms vs. 517.95 ms; *F*(1,6) = 3.64, *p* = .105).

Table 9. Group mean target-present RTs (ms) for valid, neutral and invalid cue conditions for each target defining dimension.

	Target dimension		
Cue	Color	Orientation	M
Valid	502.35 (80.86)	523.82 (80.44)	509.66 (80.21)
Neutral	498.44 (80.88)	513.07 (76.49)	505.75 (77.85)
Invalid	499.61 (80.07)	516.97 (82.32)	511.72 (78.97)

RT intertrial transition effects for neutral, valid and invalid cue trials. Figures 11 and 12 present the group mean RTs to a target on trial N dependent on the dimensional definition of the target on trial N-1, separately for valid, neutral and invalid cue conditions. As expected, in valid and neutral cue conditions the intertrial transition effects were dimension-specific. RTs to targets on trial N were slower, by 13.43ms overall, if the target on trial N-1 was defined in a different dimension (dD) compared to when it was defined on the same dimension (sD). The intertrial effects were very similar in the neutral and valid cue conditions in the Asperger's group. Although RTs were slightly slower in invalidly cued, relative to neutral, trials the difference between the two conditions was statistically not reliable (pair-wise comparisons: $p = .112$). RTs to validly cued trials were not different to RTs to neutrally cued trials (pair-wise comparisons: $p = .615$) ($F(2,5) = 2.96$; $p = .142$).

An ANOVA of the RTs with the factors cue validity (neutral, invalid, valid) and intertrial transition (sD, dD) revealed significant main effects of intertrial transition ($F(1,6) = 11.63$; $p = .014$) and cue validity ($F(2,12) = 5.82$; $p = .017$). In the valid and neutral cue condition, significantly higher RTs for dD compared to sD are found (valid dD-sD: 17.56 ms, $F(1,6) = 6.64$; $p = .042$; neutral: dD-sD: 15.99 ms, $F(1,6) = 6.06$, $p = .049$). However, in invalid-cue trials, no significant effect of dimension change (dD) relative to dimension repetition (sD) across consecutive trials on RTs is observed (invalid: dD-sD: 6.99 ms, $F(1,6) = 1.55$, $p = .260$).

In a comparison of invalid and neutral cue conditions, in invalid cue trials in which the dimension was repeated across consecutive trials (536.94 ms), RTs were significantly slower than in corresponding neutral cue (511.40 ms) trials ($F(2,5) = 5.65$; $p = .036$). In trials with dimension changes in consecutive trials, no significant difference between the invalid (543.93 ms), neutral (527.39ms) and valid (520.18 ms) cue conditions was found ($F(2,5) = 1.61$, *p*s > .299). The interaction between cue validity and intertrial transition was not significant ($F(2,12) = .87$; $p = .45$).

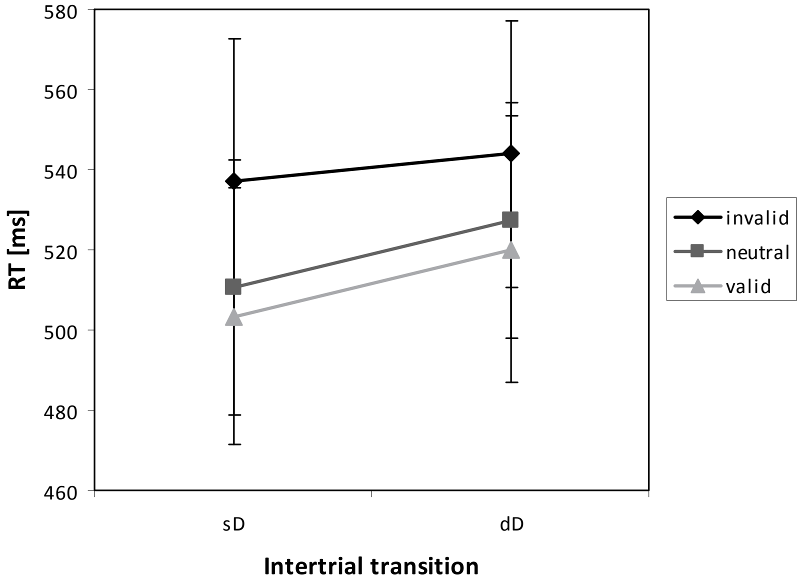


Figure 11. Group mean RTs to target on trial N dependent on the dimension of the target on trial N-1 are displayed for the Asperger's group. Targets in consecutive trials were either defined in the same dimension (sD) or in a different dimension (dD). RTs are plotted separately for the three different cue conditions (valid, invalid, neutral).

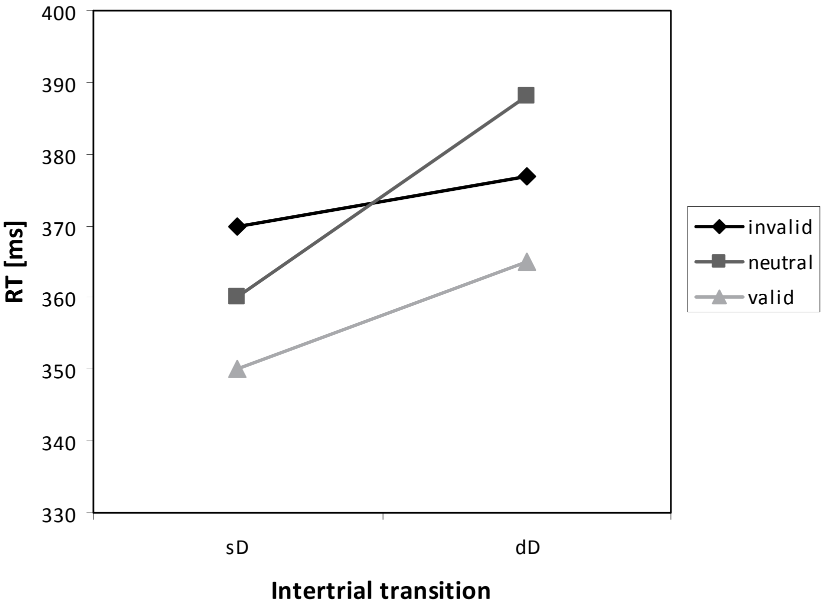


Figure 12. Group mean RTs to target on trial N dependent on the dimension of the target on trial N-1 are displayed for healthy observers (Müller et al., 2003). Targets in consecutive trials were either defined in the same dimension (sD) or in a different dimension (dD). RTs are plotted separately for the three different cue conditions (valid, invalid, neutral).

5.2.5.3 Discussion

The aim of Experiment 5 was to examine whether detection of singleton feature targets is affected by a semantic cue that is presented before each trial and whether inter-trial transition effects are modulated by the validity of the cue. Reaction time analysis shows that the semantic cue did not significantly affect search reaction times if search RTs are analyzed independent of their inter-trial history. This finding is in contrast to a finding by Müller et al. (2003) who showed cueing benefits and costs for valid- and invalid-cue trials, respectively (relative to the neutral cue condition.) Taken as such, the result seems to suggest that in the group of observers with Asperger's syndrome, RTs are not affected by pre-knowledge of the target defining dimension.

However, if inter-trial transitions are taken into account, a somewhat different interpretation is suggested.

The results of the bottom-up influences are consistent with the pattern seen in unimpaired observers (Müller, Reimann & Krummenacher, 2003), significantly faster RTs if the target-defining dimension is repeated across consecutive trials relative to dimension changes. Top-down influences exist, but in a different way than in healthy observers. The Asperger's group only benefits very little from valid cues. Valid cues seem to expedite RTs only slightly if at all compared to the neutral baseline condition. In contrast, invalid top-down information – that is, if the semantic cue differs from the visual information of the search display – disturbs the Asperger's group massively (as seen in the significantly higher RTs compared to the neutral cue condition), regardless of the inter-trial transition.

In contrast, the healthy observers (Müller, Reimann & Krummenacher, 2003) benefit from the valid cue and seem not to be much disturbed by the invalid cue. The interaction between the two factors of intertrial transition and cue validity found in the healthy observers of Müller, Reimann and Krummenacher (2003) could not be replicated in the Asperger's group. In invalid cue conditions, in which the target defining dimension is changing compared to the previous trial, RTs were significantly faster than the RTs in neutral cue conditions in the healthy observers. Müller, Reimann and Krummenacher (2003) argued that a resetting of the processing system in the invalid cue condition takes place if the dimension is changing. The cue and the target dimension of the previous trial cease to affect processing in the current trial. In the Asperger's group no 'resetting' of the processing system in dimension change trials with invalid cues occured. The results argue for a different kind of processing in individuals with Asperger's syndrome with different influences of top-down information on their search performance compared to healthy observers.

Since there was almost no difference in the bottom-up manipulation (only in the invalid cue conditions) but there was a difference in the top-down influences, the results of Experiment 5 argue for differences between the Asperger's and healthy controls at a late processing stage.

5.2.6 **Experiments 6 & 7: Stimulus Characteristics**

Experiments 1 and 2, as well as Experiments 3 and 4 showed that the pattern of performance in visual search in observers with Asperger's syndrome, although expedited overall, is quantitatively comparable to the pattern of healthy control observers. Experiment 5 has shown that semantic information also affects performance in participants with Asperger's syndrome; however, the pattern of effects is different from that observed in healthy observers.

Experiments 6 and 7 were designed to investigate whether highly efficient search in autism spectrum disorders is possibly due to the stimulus material employed in the studies in the literature (Plaisted, O'Riordan and Baron-Cohen, 1998b; O'Riordan et al., 2001; O'Riordan, 2004). In detail, Experiments 6 and 7 were designed to test if the performance benefit in visual search is due to the specific and complex features of the letter-stimuli employed in the cited studies. Letter stimuli differ from feature stimuli in singleton feature search tasks (Müller et al., 1995; Found & Müller, 1996; Krummenacher et al. 2002) in several respects. Feature targets are assumed to generate dimension-based saliency signals (Wolfe, 1994) which are able to trigger a response before or without identification of the target item. In contrast, letters are highly overlearned, but complex, stimuli. It was shown that letter processing occurs in a feature-based fashion (Neisser, 1964), that is, letter features (lines of different orientations and curvatures) are integrated into representations of individual letters that are used for letter identification.

Based on this argument and the evidence that persons with autism are better able to discriminate objects than normal observers (e.g., O'Riordan, & Plaisted, 2001), it can be hypothesized that the performance advantage observed in the Asperger's group relative to the control group is due to an ability, in people with Asperger's syndrome, to integrate features more efficiently into object (i.e., letter) representations. Consequently, letter (target) identification is expedited. In Experiments 6 (feature search) and 7 (conjunction search) the hypothesis of expedited feature extraction and/or integration was tested by employing pseudo-letters rather than letters as in the feature and conjunction searches of Experiments 1 and 2, respectively. Familiar letters were replaced with unfamiliar letter-like forms (i.e., pseudo-letters), similar to those used in a recent study by Burgund and Abernathy (2008) who investigated the degree of letter specificity in children and adults at the same reading level in comparing the advantage for letters over pseudo-letters in both groups. Results showed that adults are more sensitive to the visual form of letters than children are.

5.2.6.1 General Method

The two visual search tasks (singleton feature search and conjunction search) were conducted in separate sessions with the order of task counterbalanced within two groups of observers (Asperger's syndrome and control). All the experiments were conducted online.

Apparatus. The apparatus was exactly the same as for Experiments 1 and 2.

Stimuli and timing. Stimuli and timing were exactly the same as in Experiments 1 and 2, except that letters were replaced by pseudo-letters. In both feature and conjunction search tasks, displays consisted of 5, 15, or 25 pseudo-letter characters (distractors and, if present, a single target). Pseudo-letters were created with the Font Creator 5.6 software package (1997-2007 High-Logic). Creation of the non-letters was performed by moving one or two lines of the letters D, E, and P from the 'Arial' font of the Roman alphabet to a different relative location compared to the underlying letter (following the procedure proposed by Burgund and Abernathy, 2008). The resulting pseudo-letters are of the same complexity as the corresponding letters (see Figure 13).

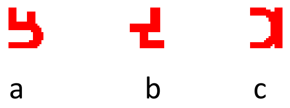


Figure 13. Pseudo-letters used in Experiments 6 and 7.

Display letters consisted of two dimensions: colour (red and green) and form (pseudo-letters of D, E, and P) and were presented on a dark grey background.

5.2.6.2 Method Experiment 6 – Feature Search Task

Participants. Nine observers with Asperger's syndrome (4 male, 5 female) ranging in age between 17 and 52 years (M = 34.00; SD = 11.46 years) and seven observers of the control group ranging in age between 19 and 53 years (3 male, 4 female; M = 32.22, SD = 10.16 years) participated in Experiment 6, which consisted of one session. The two groups did not differ in terms of age ($t(16)= -.38.$; $p = .71$) or gender ($\chi^2(1) = .05$; $p = .82$). The observers with Asperger's syndrome were all diagnosed by experts and clinicians who had extensive experience with diagnosing this disorder according to criteria specified in the ICD-10 (WHO, 1993) and additionally by having an Autism-Spectrum Quotient (AQ, Baron-Cohen et al., 2001) of over 26 (cut-off for clinically significant levels of autistic traits, Woodbury-Smith et al., 2005). The AQ functions as a measure for the degree to which an adult with normal intelligence has autistic traits. All participants had no previous experience with visual search tasks. They reported normal or corrected-to-normal vision (including colour-vision).

Procedure. The procedure was exactly the same as in Experiment 1, except for the replacement of the letters with pseudo-letters. The observers were instructed to search for a red target pseudo-letter (Figure 13 [a]) and to ignore the distractors (red or green distractor pseudo letters (Figure 13 [b] and [c]). The target was unique, i.e., differed from distractors in terms of form. An example display can be seen in Figure 14.

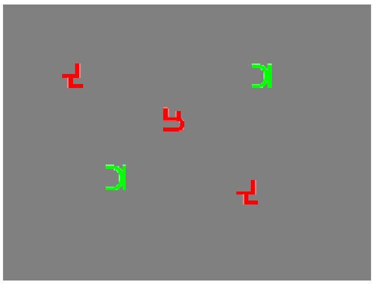


Figure 14. Example display of the feature search experiment.

5.2.6.3 Results Experiment 6

The performance of the Asperger's group in the feature search task was compared to a group of healthy age- and gender-matched controls. For each participant, RT data for correct trials and error data were averaged for all trials for each combination of set size (5, 15, 25) and trial type (target present, target absent). The mean RT data were initially analyzed in a mixed-factors ANOVA with the between-subject factor group (Asperger's, control) and the two within-subject factors trial type and set size. Figure 15 displays the mean RT data as a function of group, trial type and set size.

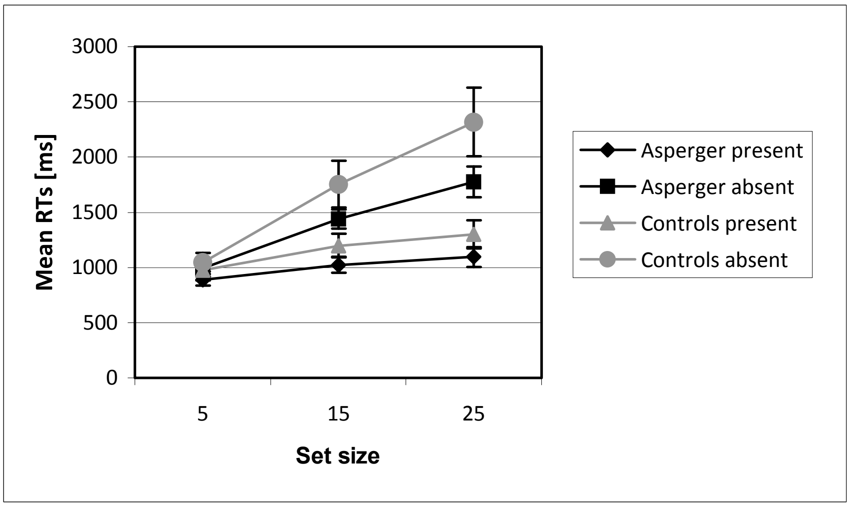


Figure 15. Mean RT data as a function of group (Asperger's, control), trial type (target-present, target-absent) and set size (5, 15, 25).

Errors. Error rates were low overall, 3.02% (SD = 1.69%) in the Asperger's group and 2.05% (SD = 1.80%) in the control group.

An analysis (ANOVA) of the error rates with the factors trial type (target-present, target-absent), set size (5, 15, 25), and group (Asperger's, control) revealed a significant main effect of trial type (*F*(1, 15) = 18.82; *p* = .001). The main effect of group was not significant (*F*(1,15) = 1.33; *p* = .267). There was no interaction between the two factors (*F*(1,15) = .05; *p* = .829). Both groups made significantly more errors in target-present (Asperger's: M = 5.06%, SD = 3.32%; control: 3.89%, SD = 3.66%) compared to target-absent trials (Asperger's: M = 0.99%, SD = 1.14%; control: 0.21%, SD = 0.29%); pair-wise comparisons: Asperger's: *F*(1,15)= 10.70, *p* = .012; control: *F*(1,15) = 8.21, *p* = .006).

The main effects of set size, the two-way interactions between set size and group, between set size and trial type and the three-way interaction between trial type, set size and group did not reach significance.

To sum up the results of the analysis of the error rates, accuracy in both groups was very similar (no significant main effect of group). Both groups made signifcantly more errors in targe-present trials (misses) compared to target-absent trials (false alarms).

Reaction time analysis. Mean RTs were subjected to an ANOVA with the within-subjects factors trial type (target-present, target-absent), set size (5, 15, 25) and the between-subjects factor group (Asperger's, control). The ANOVA revealed a significant main effect of trial type (*F*(1,15) = 97.69; *p* < .001), a non-significant main effect of group (*F*(1,15) = 1.36; *p* = .262), and a non-significant interaction between group and trial type (*F*(1,15) = 2.03; *p* = .175). Both groups responded significantly faster in target-present trials (Asperger's: M = 1002.40 ms; SD = 208.8 ms; control: M = 1155.78 ms; SD = 283.27 ms) compared to target-absent trials (Asperger's: M = 1402.92 ms; SD = 286.74 ms; control: M = 1705.71 ms; SD = 524.59 ms) (Asperger's: *F*(1,15) = 38.02, *p* < .001); control: *F*(1,15) = 60.38, *p* < .001). Despite the fact that the overall RTs in the Asperger's group were numerically faster in target-present (M = 1002.40 ms) as well as in target absent-trials (M = 1402.92 ms) compared to the control group (target-present: M = 1155.78 ms; target-absent: M = 1705.71 ms), this difference did not reach significance (pair-wise comparisons: present: *F*(1,14) = 1.56, *p* = .232; absent: *F*(1,14) = 2.19, *p* = .161).

Furthermore, a significant main effect of set size (*F*(2,30) = 88.43; *p* < .001) and a tendency of a significant interaction between set size and group (*F*(2,30) = 4.14; *p* = .053) was found. Pair-wise comparisons of RTs for each of the three set sizes showed that the two groups did not differ significantly in any of the set sizes (all *p*s > .174). The RTs of both groups (Table 10) for set size 25 were significantly higher than for set 15, furthermore the RTs for set size 15 displays were significantly higher than for set size 5 items (pair-wise comparisons: all *p*s < .012).

Table 10. Mean RTs for target-present and target-absent trials (M) for the three set sizes, separately for the Asperger's and control group (standard deviations in brackets) are displayed.

	Asperger's group			Control group		
Size	present	absent	*M*	present	absent	*M*
5	887.81 (152.50)	993.50 (222.14)	940.65 (184.99)	972.86 (242.40)	1045.04 (222.97)	1008.95 (225.22)
15	1023.86 (211.42)	1441.61 (260.37)	1232.73 (232.24)	1196.22 (283.55)	1754.21 (559.97)	1475.22 (413.56)
25	1095.54 (272.23)	1773.64 (417.67)	1434.59 (332.48)	1298.25 (335.55)	2317.87 (814.83)	1808.06 (565.60)

The significant interaction between the factors trial type and set size (*F*(2,30) = 54.68; *p* < .001) revealed a much less steep increase in RTs in target-present trials compared to target-absent trials. Pair-wise comparisons showed that, if both groups are analyzed together, in target-present as well as in target-absent trials, RTs are significantly higher for set size of 25 compared to the set size of 15 items and set size 5 trials; the RTs for 15 items were significantly higher than for 5 items (pair-wise comparisons: all *p*s < .002).

The three-way interaction of trial type, set size and group was not significant (*F*(2,30) = 2.98; *p* = .094).

Search times per item. The efficiency of the process of searching the display items for a target is reflected in the search times per item – represented by the slope of the RT function. Search times per item were analyzed in an ANOVA with the factors trial type (target-present, target-absent) and group (Asperger's, control). The ANOVA revealed a significant main effect of trial type (*F*(1, 15) = 58.30; *p* < .001), a tendency of a significant main effect of group (*F*(1, 15) = 4.23; *p* = .057) and a non-significant interaction between trial type and group (*F*(1, 15) = 3.14; *p* = .097). Although the mean search types per item seemed to be numerically different between the Asperger's group (target present: M = 10.39 ms; SD = 7.30 ms; target absent: M = 39.01 ms; SD = 14.64 ms) and the control group (target-present: M = 16.27 ms, SD = 7.24 ms; target-absent: M = 63.64 ms, SD = 31.21 ms), planned comparisons showed no significant differences between the Asperger's and control group in target-present trials (*F*(1,15) = 2.05, *p* = .173). However, in target-absent trials the difference between the two groups tended to be significant (*F*(1,15) = 4.03, *p* = .063). For each of the two groups of observers in target-present trials, RTs per item were significantly slower in target-absent than in target-present trials (Asperger's: *F*(1,15) = 18.26, *p* < .001; control: *F*(1,15) = 41.79, *p* = .001). (for values see Table 11).

Y-axis intercept. In order to complete the picture, the time required to complete processes that are not related to search process proper, that is, the time required to structure the display into a (primal) sketch providing the basis for the operation of the search process, as well as the time required to programme and execute the appropriate (present or absent) response, needs to be determined. The non-search time is reflected by the y-axis intercept of the search function, i.e., the location on the (y-) axis representing search RT, where the search function cuts the y-axis (values see Table 11).

Y-axis intercepts were subjected to a two-way ANOVA with the within-subject factor trial type (target-present, target-absent) and the between-subject factor group (Asperger's, control). The analysis revealed no main effect of trial type (*F*(1,15) = 4.38; *p* = .054) and group (*F*(1,15) = .47; *p* = .506). The interaction was not significant either (*F*(1,15) = 1.97; *p* = .181). Planned comparisons revealed no significant difference between the two groups in target-absent trials (*F*(1,15) = 1.67; *p* = .215) with y-axis intercepts in the Asperger's group at 817.81 ms compared to the control group with 704.73 ms as well as in target-present trials (*F*(1,15) = .002, *p* = .964; Asperger's: 846.61 ms; controls: 850.89 ms).

In the feature search task, non-search processes did not differ between the groups of participants with Asperger's syndrome and controls.

Table 11. Mean search times per item (left) and mean y-axis intercepts (right), separately for target-present and target-absent trials, and for participants with Asperger's syndrome and controls are displayed.

	Search times per item		Y-axis intercept	
	Asperger	Control	Asperger	Control
present	10.39	16.27	846.61	850.89
absent	39.01	63.64	817.81	704.73

5.2.6.4 Method Experiment 7 – Conjunction Search Task

Participants. Eight observers with Asperger's syndrome ranging in age between 25 and 52 (4 male, 4 female; M = 36.13, SD = 10.18 years) and nine observers of the control group ranging in age between 19 and 53 (4 male, 5 female; M = 31.56, SD = 9.59 years) participated in Experiment 7, which consisted of one session. The two groups did not differ in terms of age ($t(16) = -.95$; $p = .36$) or gender ($\chi^2(1) = .05$; $p = .82$). The observers with Asperger's syndrome were all diagnosed by experts and clinicians who had extensive experience with diagnosing this disorder according to criteria specified in the ICD-10 (WHO, 1993) and additionally by having an Autism-Spectrum Quotient (AQ, Baron-Cohen et al., 2001) of over 26 (cut-off for clinically significant levels of autistic traits, Woodbury-Smith et al., 2005). The AQ functions as a measure for the degree to which an adult with normal intelligence has autistic traits. All participants had no previous experience with visual search tasks. They reported normal or corrected-to-normal vision (including colour-vision).

Procedure. The procedure was exactly the same as in Experiment 2, except for the replacement of the letters with pseudo-letters. The observers were instructed to search for a red target pseudo-letter (Figure 13 [c]) and to ignore the green (Figure 13 [c]) and red distractor pseudo-letters (Figure 13 [b]). The target was unique in terms of a unique conjunction of features (form and colour). An example display can be seen in Figure 16.

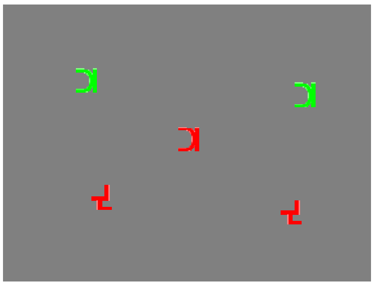


Figure 16. Example display of the conjunction search experiment.

5.2.6.5 Results Experiment 7

Search performance in the conjunction search task with pseudo-letters of the Asperger's group was compared to the search performance of a healthy control group. For each participant, RT data for correct trials and error data were averaged for all trials of each particular combination of set size (5, 15, 25) and trial type (target-present, target-absent). The mean RT data were initially analysed using a mixed-factors ANOVA with the between-subject factor group (Asperger's, control) and the two within-subject factors trial type (target-present, target-absent) and set size (5, 15, 25 items). Figure 17 displays the mean RT data as a function of group, trial type and set size.

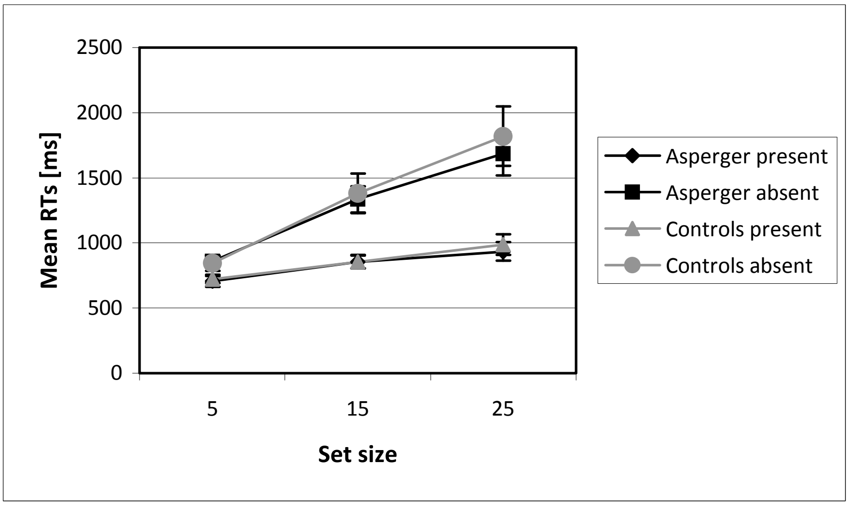


Figure 17. Mean RT data as a function of group (Asperger's, control), trial type (target-present, target-absent) and set size (5, 15, 25).

Errors. Error rates were very low overall, with 1.98% (SD = 2.15%) in the Asperger's group and 2.75% (SD = 3.01%) in the control group.

An ANOVA of the error rates of target-present and target-absent trials (factor trial type), set sizes 5, 15 and 25 items (factor set size) and the Asperger's and control group (factor group) revealed a non-significant main effect of group (*F*(1, 15) = .36; *p* = .559), a significant main effect of trial type (*F*(1, 15) = 11.58; *p* = .004), and a non-significant interaction between the factors group and trial type (*F*(1, 15) = .10; *p* = .759). Both groups made significantly more errors in target-present (Asperger's: M = 3.75%, SD = 4.27%; control: 4.88%, SD = 5.54%) compared to target-absent trials (Asperger's: M = .21%, SD = .41%; control group: .62%, SD = .59%) (planned comparisons: Asperger's: *F*(1,15) = 4.51, *p* = .016; control group: *F*(1,15) = 7.33, *p* = .051).

The main effect of set size, the two-way interactions between set size and group, and between set size and trial type and the three-way interaction between trial type, set size and group did not reach significance (all *p*s > .380).

In summary, accuracy in both groups was highly similar.

Reaction time analysis. Mean RTs were analyzed in an ANOVA of the RTs with the within-subjects factors trial type (target-present, target-absent), set size (5, 15, 25) and the between-subjects factor group (Asperger's group, control group). The mean reaction times for both groups and for target-present and target-absent trials can be extracted from Table 12. The ANOVA revealed a non-significant main effect of group ($F(1,15) = .10$; $p = .753$), a significant main effect of trial type ($F(1,15) = 60.93$; $p < .001$), and a non-significant interaction between group and trial type ($F(1,15) = .06$; $p = .812$). In both groups, RTs were significantly faster in target-present trials (Asperger's: M = 831.32 ms, SD = 148.09 ms; control group: M = 856.22 ms, SD = 160.06 ms) compared to target-absent trials (Asperger's: M = 1293.65 ms, SD = 274.85 ms; control: M = 1348.18 ms, SD = 437.51 ms; $p < .001$). Despite the fact that the overall RTs in the Asperger's group seemed to be numerically faster in target-present (M = 831.32 ms) as well as in target-absent trials (M = 1293.65 ms) compared to the control group (target-present: M = 856.22 ms; target-absent: M = 1348.18 ms), the differences were not statistically reliable (planned comparisons: present: $F(1,15) = .11$, $p = .745$; absent: $F(1,15) = .09$, $p = .766$).

Further, a significant main effect of set size ($F(2,30) = 60.73$; $p < .001$) was found. RTs of both groups to displays of set size 25 items were significantly higher for set size 15 items and RTs to set size 15 displays were significantly higher than for set size 5 display (pair-wise comparisons: all $p < .004$). The non-significant interaction between set size and group ($F(2,30) = .43$; $p = .543$) showed that the two groups did not differ significantly in their RTs for any of the three set sizes (all *p*s > .634).

Table 12. Mean RTs for target-present and target-absent trials (M) for the three set sizes, separately for the Asperger's and control group (standard deviations in brackets).

	Asperger's group			Control group		
Size	present	absent	*M*	present	absent	*M*
5	704.92 (121.01)	860.49 (118.54)	782.70 (113.06)	723.24 (98.25)	845.08 (179.67)	784.16 (133.29)
15	854.79 (137.78)	1335.25 (286.12)	1095.02 (200.10)	856.23 (156.02)	1381.27 (456.99)	1118.75 (302.94)
25	934.24 (203.03)	1685.21 (477.09)	1309.72 (315.08)	989.18 (236.42)	1818.17 (687.74)	1403.68 (456.34)

The interaction between the factors trial type and set size ($F(2,30) = 46.50$; $p < .001$) was significant, reflecting a much less steep increase in RTs in target-present compared to target-absent trials. Pair-wise comparison showed that in target-present as well as target-absent trials, RTs of the set size 25 trials were significantly higher than those of set size 15 and set size 5 trials, respectively; RTs of set size 15 trials were significantly higher than of set size 5 items (pair-wise comparisons: all *p*s < .002).

The three-way interaction of trial type, set size and group was not significant ($F(2,30) = .36$; $p = .588$)

Search times per item. The efficiency of the process of searching the display items for a target is reflected in the search times per item – represented by the slope of the RT function. Search times per item were analyzed in an ANOVA with the factors trial type (target-present, target-absent) and group (Asperger's, control). The ANOVA revealed a significant main effect of trial type ($F(1, 15) = 48.03$; $p < .001$), a non-significant main effect of group ($F(1, 15) = .40$; $p = .537$) and a non-significant interaction of trial type and group ($F(1, 15) = .35$; $p = .561$). As the mean search times per item were very similar for the Asperger's group (target-present: M = 11.47 ms; SD = 6.08 ms; target absent: M = 41.24 ms; SD = 21.82 ms) and the control group (target present: M = 13.30 ms; SD = 7.69 ms; target absent: M = 48.65 ms; SD = 26.31 ms), pair-wise comparisons, as expected, showed no significant differences between the Asperger's and control groups in target-present trials ($p = .597$) or target-absent trials ($p = .540$). In both groups however, target-present trial search times per item were significantly lower than target-absent search times (Asperger's: $F(1,15) = 18.96$, $p = .001$;control: $F(1,15) = 30.08$, $p < .001$). (Values see Table 13)

Y-axis intercept. In order to complete the picture, the time required to complete processes that are not related to search process proper, that is, the time required to structure the display into a (primal) sketch providing the basis for the operation of the search process, as well as the time required to program and execute the appropriate (present or absent) response, needs to be determined. The non-search time is reflected by the y-axis intercept of the search function, i.e., the location on the (y-) axis representing search RT, where the search function cuts the y-axis (values see Table 13).

Y-axis intercepts were subjected to a two-way ANOVA with the within-subject factor trial type (target-present, target-absent) and the between-subject factor group (Asperger's, control). The analysis revealed no main effect of trial type ($F(1,15) = .61$; $p = .450$) and group ($F(1,15) = .60$; $p = .452$). The interaction was not significant either ($F(1,15) = 1.42$; $p = .254$).

In the conjunction search task, non-search processes did not differ between the groups of participants with Asperger's syndrome and controls.

Table 13. Mean search times per item (left) and mean y-axis intercepts (right), separately for target-present and target-absent trials, and for participants with Asperger's syndrome and controls are displayed.

	Search times per item		Y-axis intercept	
	Asperger	Control	Asperger	Control
present	11.47	13.30	666.44	662.17
absent	41.24	48.65	677.73	608.30

Comparison of feature and conjunction search tasks

Accuracy analysis. The error rates for both groups were quite low and remarkable fewer errors were made in target-absent trials. Slightly more errors were made in the feature search compared to the conjunction search.

The ANOVA with the within-subjects factors experiment type, trial type and set size and the between-subjects factor group revealed only a significant main effect of trial type ($F(1,14) = 23.76$; $p < .001$). Subjects of both groups made significantly more errors in both experiments in target-present compared to target-absent trials (pair-wise comparisons: $p = .008$; $p = .002$). All other factors (including group) and all interactions were not significant. The error rates did not differ significantly between the two groups.

Mean RTs. The mean RTs of the pseudo-letter feature and conjunction search tasks of Experiments 6 and 7 were compared in a mixed-factors ANOVA with the within-subject factors task (feature, conjunction), trial type (target-present, target-absent) set size (5, 15, 25) and the between-subjects factor group (Asperger's, control).

Interestingly, the RTs of the conjunction search task, arguably the harder of the two tasks, because it requires feature integration, are remarkably faster, in both groups, than RTs of the feature search task. Furthermore, in the feature and conjunction search tasks, the Asperger's group responded slightly faster than the control group, both in target-present and target-absent trials.

The ANOVA revealed the main effect of group to be non-significant (*F*(1,14) = 1.56; *p* = .232); the main effect of task was significant (*F*(1,14) = 16.85; *p* = .001), but the interaction between task and group was not significant (*F*(1,14) = 3.22; *p* = .094). Planned comparisons revealed a significant difference between the feature and conjunction search tasks in the control group (*F*(1,14) = 17.40, *p* = .001), but not in the Asperger's group (*F*(1,14) = 2.67, *p* = 125).

There was a significant main effect of trial type (*F*(1,14) = 80.72; *p* < .001). Planned comparisons revealed significantly faster RTs, in both groups and in both experiments for target-present relative to target-absent trials (Asperger's: *F*(1,14) = 31.50, p < .001; controls: *F*(1,14) = 50.32, *p* < .001).

The main effect of set size was significant (*F*(2,28) = 91.55; *p* < .001). Pair-wise comparisons, for both groups and for both tasks, revealed significantly higher RTs for set size 25 displays compared to set size 15 and set size 5 displays (all *p*s < .002). There was a tendency of a significant interaction between group and set size (*F*(2,28) = 2.89; *p* = .072) revealing increasing RT differences between the Asperger's and the control group with increasing set size. The biggest difference in RTs between the groups is observed in set size 25 displays. (The values are given in Table 14.)

Further, a tendency of a significant interaction between trial type and set size was found (*F*(2,28) = 2.89; *p* = .072). The difference in RTs between target-present and target-absent trials increases with increasing set size in both experiments and in both groups of observers.

The two-way interactions between trial type and group, task and trial type, task, trial type and group, task and set size, the three-way interactions between task, set size and group, between trial type, set size and group, between task, trial type and set size, and four-way interaction between task, trial type, set size and group were not statistically reliable (all *p*s > .149).

Table 14. Mean RTs (M) and their standard deviations (SD) for the three different set sizes are shown for the Asperger's group and the control group for both experiment types together.

Asperger group			Control group	
Size	M	SD	M	SD
5	836.13	137.80	892.47	112.21
15	1140.21	207.94	1300.67	220.84
25	1344.07	302.23	1620.79	312.27

Search times per item (search slope). The analysis of the slope of the function showed only a significant main effect of trial type. All other main effects or interactions were non-significant including the non-significant main effect of group (*F*(1,14) = 2.93; *p* = .109). Concerning their search times per item, the two experiments were not significantly different. However, concerning their overall RTs the two experiments differed significantly (*F*(1,14) = 16.85; *p* = .001).

5.2.6.6 Discussion Experiments 6 & 7

The aim of Experiments 6 and 7 was to investigate the effects of using pseudo-letters instead of letter stimuli on search performance in a group of observers with Asperger's syndrome in comparison with a group of healthy observers. In Experiment 6, the target differed by a single feature from the non-targets, in Experiment 7 the target was defined by a conjunction of features.

In the feature search task (Experiment 6) participants with Asperger's syndrome were slightly more efficient than the controls. However, the RTs did not differ significantly between groups. Still, the RT values of the Asperger's group are lower in all conditions relative to the control group. Furthermore, y-axis intercepts (time required for structuring the display, e.g.) did not differ between the groups in both tasks. In terms of interpretation this means that it is difficult to decide whether the differences between Asperger's and controls are due to the letter stimuli or, alternatively, due to the requirements imposed by the processing of complex stimuli in general.

The present results suggest that there is no difference between people with Asperger's syndrome and healthy controls, if the task involves the processing of pseudo-letters. That is, overall search performance and thus performance differences, are modulated by the stimulus material used. If pseudo-letters are considered complex, and, importantly, not overlearned stimuli, it can be concluded that complex stimuli are processed no faster in people with Asperger's syndrome than in healthy observers. Stated differently, the difference in processing performance between observers with Asperger's and healthy controls observed in Experiments 1 and 2 are probably, at least partially, due to the fact that the stimuli are highly overlearned.

5.2.7 General Discussion

The aim of Experiments 1 and 2 was to examine feature and conjunction search performance in a group of people with Asperger's syndrome by comparing overall search reaction times, search rates and and y-axis intercepts to those of an age- and gender-matched group of controls. Visual search is well suited for the investigation of potential differences in cognitive processes between different groups, as the task involves a series of hierarchical processes ranging from the structuring of a visual scene and feature extraction (both pre-selective processes), to the selection of individual items for processing and the decision whether the processed object corresponds to the target description or not (the search process proper), to the selection and execution of the appropriate response. Overall search reaction times reflect the entire chain of processes from the (observable) onset of the visual search display to the (observable) manual response indicating the observer's decision.

Search times per item (search rates) allow the deduction of how much time is required to process a single search object, that is, the time requirements of the search process proper. The y-axis intercept of the search function relating search reaction times to the number of search items (the set sizes) constitutes an estimate of the time taken to structure – i.e., prepare – the scene to be searched on the one hand, and for the response to be selected and executed on the other hand. Response selection and execution, in the feature and conjunction search tasks of Experiments 1 and 2, is assumed to take the same amount of time, in other words, in visual search tasks, response selection and execution is not affected by the processes occurring beforehand. Rather, as soon as a match is found between the object currently under the focus of attention and the target template, the target-present is triggered, alternatively, an absent-response is triggered after all display items are searched without there being a match. Consequently, since in both the feature and conjunction search task response selection involves two alternatives, it is safe to assume that any effects on the y-axis intercept arise at the level of structuring and initially representing the display. As these processes occur before the selection stage, they are referred to as pre-selective processes (in analogy, processes occurring following the selection stage are termed post-selective).

An important dependent variable in visual search tasks is performance accuracy. In order to be able to interpret reaction time differences, faster reaction times must not be confounded by higher error rates. Therefore, the interpretation of reaction time data is preceded by an analysis of error rates.

Feature search. Error rates are very low overall in the feature search task of Experiment 1 suggesting that the task is either relatively easy to perform and/or that observers strive to avoid errors. In general, feature search tasks are considered easy to do and consequently error rates are very low. Error analyses show that miss rates are higher than false alarm rates in both groups of observers. That is, if observers make errors, the cases in which they mistake a distractor for a target (false alarm) are rarer than the cases in which they ignore a target (miss). This bias seems to suggest that observers actively match the item currently under the focus of attention with the target template rather than responding to an activation signalling a difference (featue contrast) that is not further specified.

If the two groups are compared, the miss rate is lower in the Asperger's than in the controls, that is, faster reaction times in the Asperger's group are not due to a speed-accuracy trade off.

Importantly, there is no effect of set size and error rates, but there is an interaction between set size and trial type in both groups. The interaction is due to the difference between misses and false alarms being significant for the set size of 25 items only. The finding that set size does not affect error rates is expected in a feature search task. Search in set size 25 displays seems to be more error-prone than in set size 5 and 15 displays, however.

Analyses of overall mean reaction times show slower reaction times in target-absent than in target-present trials in both groups of observers. This effect is not expected in a feature search task in which the target differs from distractors in a salient feature (shape), rather response times are expected to be more or less at the same level, with a slight disadvantage for target-absent RTs. However, the slower reaction times in target-absent trials are probably due to the difficult search task used in this study.

More importantly, however, participants with Asperger's syndrome are faster than participants of the control group in target-present trials and there is also a tendency for the Asperger's group to be faster than the controls in target-absent trials. That is, the decision that a target item is present is taken faster by people with Asperger's syndrome than by healthy controls. There is a tendency for faster responses of the Asperger's group in absent-trials also, rendering interpretation difficult. If there were a reaction time advantage only in target-present trials, an interpretation along the lines of the assumption that discrimination of the target item is expedited in people with Asperger's syndrome would be supported. This has been suggested in the literature (e.g., Plaisted, O'Riordan & Baron-Cohen, 1998a; Shah & Frith, 1993; Jolliffe & Baron-Cohen, 1997; O'Riordan & Plaisted, 2001) and could be likened to the target "popping out of the display" in people with Asperger's but not in participants of the control group. Instead of a pop-out effect, the fact that a reaction time advantage is observed in target-present and target-absent trials suggests that the process of matching the item currently under the focus of attention to the target description is achieved faster in people with Asperger's syndrome than in healthy controls.

The findings of a set size effect and interaction of set size and trial type (present, absent) supports the assumption that some sort of template matching is required to perform the variant of a feature search task used in Experiment 1.

In the comparison between the groups of participants, it is also important to analyze the non-significant interactions. The interaction between group and trial type (present, absent) was not statistically reliable, neither was the interaction with set size. Together, these non-findings suggest that the pattern of search performance in terms of target-absent and -present trials and set size is the same in both groups.

The previous interpretation of a faster search process in people with Asperger's syndrome is supported by the analysis of the search rates. In target-present trials, search times per item are significantly lower in people with Asperger's syndrome than in healthy controls. The same effect is observed in absent-trials, although only on the level of numerical comparisons, but not in terms of statistical reliability. Taken together, this suggests that in observers with Asperger's syndrome the search process is indeed expedited relative to the healthy controls. In addition, there might be a component of popout in target-present, but not target-absent trials (as suggested by the search time advantage in present- but not absent-trials).

The idea of a component of popout is supported by the finding that y-axis intercepts show a tendency of a difference between groups (lower intercept in the Asperger's group) in target-present trials only.

Conjunction search. Error rate analysis shows that particpants with Asperger's syndrome make fewer errors in the conjunction search task than the controls. As in the feature search tasks, miss rates are higher than false alarm rates. The ratio of miss and false alarm rates suggests that participants base their decision on matching the currently scrutinized item (i.e., the item under the focus of attention) to a target template rather than responding to an activation coding feature difference. Such a strategy is, of course, expected in a conjunction search task.

Importantly, comparing the two groups, people with Asperger's syndrome miss fewer targets than the control group. This suggests that the template matching process is less error-prone in Asperger's than in controls.

Interestingly, there is an effect of set size on error rate in the observers of the control group, but not the Asperger's group. This again suggests that people with Asperger's syndrome more efficiently scan search items for a match with the target template than healthy observers.

Reaction time analyses show that people with Asperger's syndrome, in the conjunction search task, respond overall faster than the controls both in target-present and target-absent trials. Furthermore, the response times of the two groups interact: the difference between target-present and target-absent reaction times is smaller in the group of Asperger's than in the controls; this is observed in all set sizes. These findings again speak for an advantage in the processing of individual search items in people with Asperger's compared to controls.

Observers of the control group show a set size effect, i.e., increasing reaction times with increasing set sizes both between set sizes of 5 and 15 and between 15 and 25 items. In contrast, in the Asperger's group a set size effect is observed only in target-absent trials (differences between all set sizes), a partial set size effect only is observed in Asperger's in target-present trials; reaction times increase only between set sizes of 5 and 15, but not between 15 and 25 items.

The overall reaction analyses, in summary, show that search is more efficient in participants with Asperger's than in controls. The pattern of set size effects for target-absent and target-present trials suggest that the process of scanning items and matching individual items to the target template is more efficient in Asperger's than in controls.

Search rates per item, proving support for the above stance, were significantly lower in people with Asperger's than in controls both in target-present and in target-absent trials. In terms of y-axis intercept, there is no significant difference between the control and Asperger's groups, although there are tendencies of lower intercepts in Asperger's than in controls. Contrary to the feature search task, in the conjunction search task there seems to be no contribution of popout to target detection. It is likely that participants with Asperger's syndrome in the feature search task are able to reject the set of nontarget items that does not correspond to the target colour which, in turn generates a popoup on the form/shape dimension. Controls seem unable to adopt a similar strategy. In the conjunction search tasks, as the target is defined by a conjunction of colour and shape, items cannot be rejected as groups.

To summarize the findings of Experiments 1 and 2, a comparison of the two tasks shows that in terms of reaction times, there is an effect of task (feature, conjunction search) in the control group; furthermore the control group also shows an interaction between tasks due to a larger difference between target-present and target-absent trials in the conjunction relative to the feature search task. Importantly, no effect of task is observed in the group of Asperger's. Trial type (target-present, target-absent) also affects performance in controls and trial type interacts with task; the interaction is due to a difference between tasks in target-absent but not target-present trials. In terms of search rates per item, there is an effect of search rate, trial type and an interaction between these factors in controls, but also in Asperger's.

That is, in terms of patterns, the two groups are highly similar, while in terms of overall search performance, there are significant differences. The differences between groups arise at the level of the processing of single items during the process of visual search.

Contrary to findings with autistic observers (e.g., Plaisted, O´Riordan & Baron-Cohen, 1998b), search rates of the Asperger's were statistically reliably affected by the number of display items (set size). However, overall search rates of the Asperger's group did not differ significantly between the conjunction and feature search task, whereas there is a significant task-dependent rate difference in the control group. The failure to replicate the set size effect repeatedly observed in conjunction search in autistic observers is interesting. As set size seems to affect search in Asperger's syndrome, the present results might contribute to a better differentiation between the various subtypes along the autistic spectrum with the Asperger's group being more similar to the normal observers than to the autistic group.

Since the present Experiments 1 and 2 showed that the Asperger's group seems to possess some different type of processing of visual stimuli relative to healthy controls, the question arises as to where in the visual processing stream this difference can be localized. The differences might arise at early visual (pre-selective) or late (post-selective) processing steps. Experiments 1 and 2 probed the intervening search process, and the following experiments were designed to probe the pre- and post-selective stages, respectively.

In **Experiment 3**, designed to probe the pre-selective stages, the pattern of error rates, mean search RTs and RT redundancy gains is very similar to the pattern found in unimpaired observers and replicates the previous results of Krummenacher, Müller and Heller (2002). RTs to redundantly defined targets were faster than to singly defined targets in both the Asperger's and the control group with slightly larger gains in the Asperger's group. RTs to colour targets were slightly faster than to orientation targets in both groups - a finding again replicating the results of Krummenacher, Müller and Heller (2002).

Inferring from the results of Experiment 3, the advantage found in the feature and conjunction search in observers with Asperger's syndrome seems not to be rooted in an additional advantage arising at early levels of feature encoding and representation. Rather the effects are highly likely limited to the level of processing concerned with matching the short-term memory representation of (integrated) features with a target representation.

This interpretation is supported by the fact that performance benefits in individuals with Asperger's seem to be found exclusively in search tasks where letters are used as search objects. Therefore, further experiments were required to specify the potential locus of the processes underlying the performance benefits in observers with autism spectrum disorders.

The violation of the race model assumption in the Asperger's group provides evidence that integration of feature-based saliency activation is parallel-coactive in nature in individuals with Asperger's syndrome. The results of the distribution analysis, however, are difficult to interpret, as the findings of the control group differ from the findings of Krummenacher et al. (2002). Krummenacher et al. found co-active processing of features in redundant-target trials. In Experiment 3, though numerically lower than the predicted values, redundancy gains in controls were not statistically reliable. Overall, the results seem to suggest, however, that the same processing mechanisms are engaged in the processing of singly and redundantly defined singleton feature targets in both controls and people with Asperger's syndrome.

Altogether, the present findings provide further support for the interpretation that in people with Asperger's syndrome the search process is expedited.

For further investigation of the possible locus of the processing differences between a group of individuals with Asperger's syndrome and a healthy control group, in **Experiment 4**, a variant of the redundant target paradigm (Krummenacher, Müller & Heller, 2002) was used, in which dual redundant targets were presented with variable distances between the dual targets. Again, pre-selective stages were tested.

Overall, the reaction time analysis replicates previous findings of faster processing if targets were defined redundantly in two dimensions compared to targets singly defined in one dimension. However, in a decrease in RT redundancy gains was not found with increasing distance between the dual (redundant) targets in either of the two groups. Thus, the present findings do not fully replicate the findings of Krummenacher, Müller and Heller (2002). Krummenacher et al. (2002) showed that RT redundancy gains decreased as a function of distance between dual target items. They explained their finding on the basis of the spatial nature of the dimension-based saliency signals. Dimension-based saliency signals are integrated into an overall saliency representation which controls the allocation of focal attention. In redundant target trials in which both dimensional signals differ from distractors at the same spatial location, one single peak of activation is generated on the overall saliency representation; that is, activation on the overall saliency representation is high and the attentional focus is directed to the location of the target relatively quickly. In contrast, if dimension-based activation is generated at different locations, integrated saliency activation is lower – in the case of nearby signals, or two independent peaks of activation are generated – in the case of target items separated by distractors that are presented in between targets. Thus, in dual target redundant trials, co-active integration is less efficient than in single target dual trials (as in Experiment 3). In Experiment 4, numerically, redundant target response times were lower than expected from the prediction of the race model inequality. However, as the differences are not statistically reliable, interpretation is difficult. Still, observers with Asperger's syndrome show a number of significant violations of Miller's (1982) RMI, suggesting that processing of visual features is more efficient in people with Asperger's syndrome than in healthy controls. As differences in significance are discussed here rather than significant differences, the scope of the interpretation is limited and further research is required.

Experiments 3 and 4 investigated whether improved performance in people with Asperger's syndrome arises at an early level of saliency generation and integration. The results suggest that, in the Asperger's group, processes of saliency generation might well be expedited relative to age-matched controls. RT redundancy gains also suggest that dimension-based saliency signals are integrated in a parallel-coactive fashion in people with Asperger's while in healthy controls, dimension-based saliency signals engage in a parallel race.

Experiment 5 was designed to investigate whether semantic information affects search for singleton feature targets in people with Asperger's syndrome. In other words, Experiment 5 was aimed at testing if the processing difference between persons with Asperger's syndrome is located at a late stage of semantic processing. Note that the experimental paradigm used in Experiment 5 also allows testing for effects at an early stage of processing. The aim of Experiment 5 was to examine whether detection of singleton feature targets is affected by a semantic cue that is presented before each trial and whether inter-trial transition effects are modulated by the validity of the cue. Reaction time analysis shows that the semantic cue did not significantly affect search reaction times, if search RTs are analyzed independent of their inter-trial history. This finding is in contrast to a finding by Müller et al. (2003) who showed cueing benefits and costs for valid- and invalid-cue trials, respectively (relative to the neutral cue condition). Taken as such, the result seems to suggest that, in the group of observers with Asperger's syndrome RTs are not affected by pre-knowledge of the target defining dimension.

However, if inter-trial transitions are taken into account, a somewhat different interpretation is suggested.

The results of the bottom-up influences are consistent with the pattern seen in unimpaired observers (Müller, Reimann & Krummenacher, 2003), significantly faster RTs if the target-defining dimension is repeated across consecutive trials relative to dimension changes. Top-down influences exist, but in a different way than in healthy observers. The Asperger's group only benefits very little from valid cues. Valid cues seem to expedite RTs only slightly, if at all, compared to the neutral baseline condition. In contrast, invalid top-down information – that is, if the semantic cue differs from the visual information of the search display – disturbs the Asperger's group massively (as seen in the significantly higher RTs compared to the neutral cue condition), regardless of the inter-trial transition.

In contrast, the healthy observers (Müller, Reimann & Krummenacher, 2003) benefit from the valid cue and seem not to be much disturbed by the invalid cue. The interaction between the two factors of intertrial transition and cue validity found in the healthy observers of Müller, Reimann and Krummenacher (2003) could not be replicated in the Asperger's group. In invalid cue conditions, in which the target defining dimension is changing, compared to the previous trial, RTs were significantly faster than the RTs in neutral cue conditions in the healthy observers. Müller, Reimann and Krummenacher (2003) argued that a resetting of the processing system in the invalid cue condition takes place if the dimension is changing. The cue and the target dimension of the previous trial cease to affect processing in the current trial. In the Asperger's group no 'resetting' of the processing system in dimension change trials with invalid cues occured. The results argue for a different kind of processing in individuals with Asperger's syndrome, with different influences of top-down information on their search performance compared to healthy observers.

Since there was almost no difference in the bottom-up manipulation (only in the invalid cue conditions) but there was difference in the top-down influences, the results of Experiment 5 argue for differences between the Asperger's and healthy controls at a late processing stage.

Experiments 1 and 2, as well as Experiments 3 and 4 showed that the pattern of performance in visual search in observers with Asperger's syndrome, although expedited overall, is quantitatively comparable to the pattern of healthy control observers. Experiment 5 has shown that semantic information also affects performance in participants with

Asperger’s syndrome; however, the pattern of effects is different from that observed in healthy observers.

Finally, **Experiments 6 and 7** were designed to investigate whether highly efficient search in autism spectrum disorders is possibly due to the stimulus material employed in the studies in the literature (Plaisted, O’Riordan and Baron-Cohen, 1998b; O’Riordan et al., 2001; O’Riordan, 2004). In detail, Experiments 6 and 7 were designed to test, if the performance benefit in visual search is due to the specific and complex features of the letter-stimuli employed in the cited studies.

The aim of Experiments 6 and 7 was to investigate the effects of using pseudo-letters instead of letter stimuli on search performance in a group of observers with Asperger’s syndrome in comparison with a group of healthy observers. In Experiment 6, the target differed by a single feature from the non-targets, in Experiment 7 the target was defined by a conjunction of features.

In the feature search task (Experiment 6) participants with Asperger’s syndrome were slightly more efficient than the controls. However, the RTs did not differ significantly between groups. Still, the RT values of the Asperger’s group are lower in all conditions relative to the control group. Furthermore, y-axis intercepts (time required for structuring the display, e.g.) did not differ between the groups in both tasks. In terms of interpretation this means that it is difficult to decide whether the differences between Asperger’s and controls are due to the letter stimuli or, alternatively, due to the requirements imposed by the processing of complex stimuli in general.

The present results suggest that there is no difference between people with Asperger’s syndrome and healthy controls, if the task involves processing pseudo-letters. That is, overall search performance and thus performance differences are modulated by the stimulus material used. If pseudo-letters are considered complex, and, importantly, not overlearned, stimuli, it can be concluded that complex stimuli are processed no faster in people with Asperger’s syndrome than in healthy observers. Stated differently, the difference in processing performance between observers with Asperger’s and healthy controls observed in Experiments 1 and 2 is probably, at least partially, due to the fact that the stimuli are highly overlearned.

Appendix I

Experiment 1: Correlation of search performance with the AQ

Baron-Cohen et al. (2001) propose the Autism Spectrum Quotient (AQ) as a measure reflecting the degree to which an adult has traits associated with the autistic spectrum. The AQ has widely been used in diagnosing Asperger's syndrome (e.g., Bishop, Maybery, Maley, Wong, Hill & Hallmayer, 2004; Austin, 2004; Kurita, Koyama, & Osada, 2005). In the sample of 13 participants with Asperger's syndrome of the present study, AQs ranged between 26 (the lower cut-off for a person being diagnosed with Asperger's syndrome) and 48 (M = 38.31; SD = 6.54). The AQ values of each participant can be extracted from Table 15.

Table 15. AQ values for each participant of the Asperger's and control group for Experiment 1 and 2.

Participant	Control	Asperger
1	19	45
2	14	48
3	12	39
4	15	45
5	10	35
6	7	36
7	10	34
8	7	30
9	12	46
10	22	35
11	15	40
12	13	39
13	7	26
14	24	
15	24	
M	14.07	38.31
SD	5.85	6.54

In order to examine whether expedited search RTs are related to individual AQ scores, mean individual RTs were correlated with AQ scores.

Nonparametric correlations (Spearman's rho [ρ]) were computed in consideration of the small sample size, and to avoid potential artificial effects of extreme values as a consequence of sample size.

The correlation of the individual overall RTs with AQ, separately for target-present and -absent search times, revealed for the control group (see Table 15 for AQ values) a positive but non-significant correlation between the AQ and overall RTs in target-present trials (ρ = .39; p = .192) and target-absent trials (ρ = .31; p = .303).

The correlation of the individual overall RTs with AQ, separately for target-present and -absent search times, revealed for the Asperger's group a positive but non-significant correlation between the AQ and overall RTs in target present trials (ρ = .18; p = .56) and target absent trials (ρ = .19; p = .542).

The correlation of the individual search times per item with AQ, separately for target-present and -absent search times, revealed for the control group a significant positive correlation between the AQ and search times per item in target-present trials and target-absent trials (both: ρs = .618; p = .014). This finding suggests that, in controls, the higher the AQ values, the higher are the search times per item (or vice versa). Note that individual AQ values were very low in all participants of the control group, ranging between 7 and 24 (M = 14.07; SD = 5.85).

For participants with Asperger's syndrome, the correlation between the AQ and search times per item was neither significant in target-present (ρ = .18; p = .551) nor in target-absent trials (ρ = .12; p = .686). This finding both qualifies the interpretation of the significant correlation in healthy observers and the very idea of individual search times per item being predictable by AQ scores.

Still, pursuing the possibility of correlations between search performance and AQ, the participants were split into gender subgroups. In the control group, male (N = 6) a tendency of a significant positive correlation for search times per item in target-present (ρ = .77; p = .072) and a positive, but not significant, correlation in target-absent trials (ρ = .71; p = .111) was found. In female participants of the control sample (N = 9), no significant correlation was found in target present (ρ = .55; p = .128) or target absent trials (ρ = .47; p = .201). Note that all the correlations were positive, indicating that the higher the AQ values, the higher are the search times per item (or vice versa).

In the group of observers with Asperger's syndrome, male participants (N = 6) showed a tendency of significant positive correlations between the AQ and search times per item in target-present trials (ρ = .77; p = .072); in target-absent trials (ρ = .49; p = .329), the correlation was not significant. Female participants (N = 7) of the Asperger's group revealed a near significant negative correlation between the AQ and the search times per item in target-present trials (*ρ* = -.74; *p* = .058) and a negative, but not significant, correlation in target-absent trials (*ρ* = -.14; *p* = .758). Male participants of the Asperger's group revealed a positive correlation between the AQ and the search times per item suggesting that the higher the AQ values are the higher are search times per item (or vice versa). The negative correlation in the female observers with the Asperger's syndrome indicates that the higher the AQ values were the lower the search times per item.

Overall, the correlation results are incoherent at best. With the exception of female observers in the group of participants with Asperger's syndrome, correlations between AQ and search times per item, reflecting efficiency of the search process, were positive. Under the assumption of an expedited search process, negative correlations were expected. A tendency of a negative correlation was observed in female observers of the Asperger's group, and in target-present trials only.

Thus, in contrast to studies in the literature in which performance correlated with AQ, the findings of the present study do not provide support for the assumption that AQ allows for prediction of relative performance benefits.

Appendix II

Experiment 2: Correlation of search performance with the AQ

Baron-Cohen et al. (2001) propose the Autism Spectrum Quotient (AQ) as a measure reflecting the degree to which an adult has traits associated with the autistic spectrum. The AQ has widely been used in diagnosing Asperger's syndrome (e.g., Bishop, Maybery, Maley, Wong, Hill & Hallmayer, 2004; Austin, 2004; Kurita, Koyama, & Osada, 2005). In the sample of 13 participants with Asperger's syndrome of the present study, AQs ranged between 26 (the lower cut-off for a person being diagnosed with Asperger's syndrome) and 48 (M = 38.31; SD = 6.54).

In order to examine whether expedited search RTs are related to individual AQ scores, mean individual RTs were correlated with AQ scores.

Spearman's rho (*ρ*) non-parametric correlations of the overall RTs with the AQ revealed, for the control group, a non-significant correlation between the AQ and overall RTs in target-present (*ρ* = .05; *p* = .861) and a significant positive correlation in target-absent trials (*ρ* = .11; *p* = .722).

Spearman's rho (*ρ*) non-parametric correlations of the overall RTs with the AQ revealed, for the Asperger's group, a tendency for a positive correlation between the AQ and overall RTs in target-present (*ρ* = .53; *p* = .064) and a significant positive target-absent trials (*ρ* = .56; *p* = .048). Thus, the higher the AQ values are, the higher are the overall RTs.

Spearman's rho (*ρ*) non-parametric correlations of the search times per item with the AQ revealed, for the control group, a significant positive correlation between the AQ and search times per item in target-present (*ρ* = .63; *p* = .012) and target-absent trials (*ρ* = .58; *p* = .023). Thus, the higher the AQ values are, the higher are the search times per item.

For the Asperger's group, a positive but non-significant correlation between the AQ and the search times per item in target-present trials (*ρ* = .23; *p* = .446) and a tendency of a significant positive correlation in target-absent trials (*ρ* = .51; *p* = .078) were revealed.

In follow-up analyses, correlations between search times per item and the AQ were computed dependent on participants' gender (and group). In the control group, male participants were found to have significant positive correlations for search times per item in target-present and in target-absent trials (both: *ρ*s = .83; *p*s = .042). Non-significant, but also positive, correlations were found in female participants of the control group in target-present (*ρ* = .42; *p* = .260) and target-absent trials (*ρ* = .345; *p* = .364). All correlations were positive indicating that the higher the AQ values were, the higher the search times per item.

In the group of observers with Asperger's syndrome, in male observers, there was a non-significant positive correlation between AQ and search times per item in target-present trials (*ρ* = .60; *p* = .208) and a tendency of a significant positive correlation in target absent trials (*ρ* = .77; *p* = .072). The female participants of the Asperger's group showed a non-significant negative correlation between the AQ and the search times per item in target-present trials (*ρ* = -.36; *p* = .427) and a non-significant positive correlation in target-absent trials (*ρ* = .18; *p* = .699).

Overall, the correlation results are incoherent at best. With the exception of female observers in the group of participants with Asperger's syndrome, correlations between AQ and search times per item, reflecting efficiency of the search process, were positive. Under the assumption of an expedited search process, negative correlations were expected. A tendency of a negative correlation was observed in female observers of the Asperger's group, and in target-present trials only.

Thus, in contrast to studies in the literature in which performance correlated with AQ, the findings of the present study do not provide support for the assumption that AQ allows for prediction of relative performance benefits.

5.3 Project III: Development of Component Functions of Selective Attention in Children

5.3.1 Summary

Using whole- and partial-report tasks, the component functions of attention proposed in Bundesen's (1990) Theory of Visual Attention (TVA) were estimated in children aged 6 to 10 years of age attending first, second, and third grade of primary school, respectively. TVA assumes that visual selective attention is reflected in parameters of processing speed in items processed per unit time, the capacity of visual short-term memory, the ability to top-down control the allocation of attentional resources to relevant information, and the spatial distribution of attentional weights in the visual field.

Results show significant increases in processing speed and visual short-term memory capacity with increasing age. Further, top-down control capability is significantly more developed in third-graders compared to first-graders while first and second-graders' top-down control did not differ significantly. In summary, the present findings provide evidence for the global trend hypothesis assuming that all components of information processing develop mostly in concert.

5.3.2 Introduction

Intact attentional functions are key prerequisites for everyday activities and successful academic performance, as well as social and family life. The importance of attentional functions can best be seen if they are disturbed in any way. As an example, between 2% and 10% of children are affected by attention deficit hyperactivity/hypoactivity (ADHD) disorders resulting in problems at school, and/or in their interactions with their friends or family. Children suffering from attention disorders are often not able to perceive details of information in attempts to acquire knowledge, or execute practical actions in a defective or delayed fashion. Because of the obvious negative consequences associated with these impairments in academic and social life it is crucial that attentional deficits are diagnosed as early as possible in childhood. Up to now, many diagnoses of attention disorders in children have been primarily based on questionnaires directed at parents and/or teachers. If tests are applied, many of them are not optimally suited for testing children. Almost all of the tests require children to execute an additional motor task, generating sources for confounds of selective and executive processes. As an example, in the 'Continuous Attention Performance Test' (CAPT; Nubel, Starzacher & Grohmann, 2006), children are required to press a pushbutton if they detect a certain sequence of animal sounds.

Several tests were not suitable for children younger than seven, although according to ICD-10 or DSM-IV, ADHD, for example, needs to be diagnosed before the age of seven. Examples of such tests are the 'Frankfurter Aufmerksamkeitsinventar' (FAIR; Moosbrugger & Oehlschlägel, 1996) or the 'Dortmunder Aufmerksamkeitstest' (DAT; Lauth, 1993), applicable only to children older than seven or nine years of age, respectively. Another problem with attention tests is that they lack adequate, i.e., state-of-the-art, theoretical foundation. Thus, there is a necessity to develop a test of selective attention that can be applied to children of a young age and that does not have the practical and theoretical constraints described above.

The present study was aimed at testing healthy children of various ages with a new test of attention based on Bundesen's (1990) 'Theory of Visual Attention' (TVA).

Bundesen's (1990) TVA is based on the assumption that visual selective processing occurs in a two-stage process: an initial unselective stage, in which the localization of the most interesting components of a visual scene and a parallel comparison of the currently seen information with templates stored in visual long-term memory (vLTM) take place. Processing on the first stage is assumed to be automatic in nature, i.e., there are no limitations to processing capacity. TVA assumes that features and categories are selected in order to categorize visual items. In a second, selective processing stage, items engage in a competitive race for entrance into visual short-term memory (vSTM). Entering vSTM corresponds to being categorized and being categorized corresponds to being in vSTM. Only items represented in vSTM are represented consciously and are thus able to affect behaviour. Importantly, the capacity of vSTM is limited to a maximum of n elements that can be processed in parallel. Only the first n winners of the race can be stored and processed in vSTM. VSTM is assumed to constitute a memory component, in which information is kept active as long as it is needed; information is either stored in long-term memory, or, if it exceeds short-term memory capacity, it is lost. According to TVA, the vSTM is comprised of the activated representations of vLTM.

The second, selective processing stage, according to TVA, is constrained by four components that can be described as theoretically and empirically independent (Finke et al., 2005) : capacity of visual short-term memory (vSTM), processing speed, top-down control and the spatial distribution of attentional weights in a visual scene.

Short-term memory capacity is reflected by the number of elements that are processed simultaneously in vSTM. Processing speed refers to the number of elements processed per unit time (i.e., number of items per second). Both components are indicators of the general information processing efficiency of the visual system. Top-down control refers to the ability to voluntarily bias selection in favour of items characterized by specific (pre-known) features (e.g., prioritize red items and ignore green items because it is known that the target item is red). Top-down control is defined as the ratio of weight attributed to target and non-target objects $\alpha = w_N / w_T$, that is, the lower the value of α the more weight is attributed to targets, i.e., the more efficient top-down control of the selection process is. The lateralized weight parameter w_λ indicates whether attentional weight attributed to objects is distributed evenly across the visual field (lateralized weights are space-based, i.e., averaged across target and non-target objects). Lateralized weights are calculated according to $w_\lambda = w_L / (w_L + w_R)$. Even distribution of weights is reflected by $w_\lambda = .5$; values below and above .5 reflect greater weight (attentional bias) in the right and left hemifields, respectively.

A great number of studies in the literature dedicated to the investigation of the development of the components of attention are discussed in the next section. Studies examining the 'processing speed' component coherently report a consistent increase of processing speed throughout the entire childhood and into adolescence across a wide variety of tasks such as simple (Elliot, 1970; Guttentag, 1985) or choice reaction time (Kerr, Blanchard, & Miller (1980); Kerr, Davidson, Nelson, & Haley, 1982) as well as more complex tasks like mental rotation (e.g., Wickens, 1974; Hale, 1990; Kail & Salthouse, 1994). Young (age 7) childrens' responses (as measured in reaction times) are substantially slower, by a constant factor, than those of young (age 19) adults (Wickens, 1974; Kail, 1991a). Speed is changing substantially in early and middle childhood and more slowly afterwards (Kail, 1991a). Responses of 4-year-olds were 3.0 times, of 5 to 7 year-olds were 1.9 times, of 10-year olds 1.8 times and of 12-year-olds 1.5 times slower than responses of adults. With increasing age, children gradually approximate the adults' speeds (Hale, 1990; Kail, 1991a; Kail & Hall, 1994); and at the age of 15, processing times reach the level of adults (Kail, 1991a). Importantly, the changes in processing speed are nonlinear with respect to age and - in most of the tasks employed to examine the development of processing speed - can best be described by an exponential function (Kail, 1991a; Kail, 1991b, Kail, 1986). In other words, the increase of processing speed during childhood is linear as a function of adults' processing speed and the slope of the function relating children's processing speed to adults' speed decreases (becomes shallower) with age (Kail, 1991a).

In visual search tasks, in which participants have to indicate if a pre-defined target item is present or absent in an array of distractor items, age-related improvements in search speed, as measured by reaction times (RTs) were also found (e.g., Day, 1978; Lobaugh, Cole & Rovet, 1998).

Furthermore, an increase in processing speed was related to increasing short-term memory capacity (Kail, 1992; Kail & Park, 1994). An age-related increase in short-term memory capacity was found in a longitudinal study of a sample of children aged 5, 7, and 12 months (Rose, Feldman, & Jankowski, 2001). In Rose et al.'s study in 2001, children were presented with up to four items in succession and then tested for recognition by successively pairing each item with a novel one. Results showed significant capacity increases in the first year of life.

Studies by Chuah and Maybery (1999), Dempster (1981) and Gathercole (1999) revealed a dramatic increase of short-term memory storage capacity during childhood years. Chuah and Maybery (1999) showed in a spatial span paradigm (illuminating squares on the screen with recall by touch) similar results as in verbal span paradigms (auditorily presented letter sequences) and assumed that an ordered search process common to verbal and spatial short-term memory plays a critical role in the span development (increasing span with increasing age). Dempster (1981) examined possible sources of developmental differences in memory span by drawing on existing research. He concluded that identification speed is a major source of developmental differences in memory span. Finally, Gathercole (1999) discussed the dramatic increases in capacity of short-term memory during the childhood years by assuming that the increase reflects changes in many different component processes (e.g., perceptual analysis). She furthermore highlights the crucial role of the short-term memory in the acquisition of knowledge and skills during childhood.

Capacity of short-term memory in older children and adults is often assessed in span tasks such as ‘digit span’, ‘Corsi block span’ or pattern recall (Rose, Feldman & Jankowski, 2001; Gathercole, 1999). In Dempster’s (1981) study the digit span between 2 and 7 years of age increased from around 2 to 5 digits. Wilson, Scott and Power (1987) found increasing visual spans in a visual pattern task between 5 and 11 years. A steep increase is observed between 3 and 8 years of age, followed by shallower increases and an asymptotic level at about 11 years (Gathercole, 1999). In a whole report task, Cowan et al. (1999) presented lists of spoken digits; the participants’ task was to recall as many digits as possible. To prevent mnemonic strategies, participants played a computer game preventing them from attending to most of the list items. The resulting unattended span - corresponding to the short-term memory capacity - increases significantly between children in first grade with 2.5 items, fourth-grade students with 3.0 items and adults with 3.5 items correctly recalled on average.

A large number of studies report a considerable improvement in the ability of selecting (instructed) relevant information and ignoring irrelevant information during the age span between 3 to 14 years (e.g., Davidson, Amso, Anderson & Diamond, 2006; Dempster, 1992;

Dempster & Corkill, 1999; Harnishfeger, 1995; Johnstone et al., 2007; Kail, 2002; Pritchard & Neumann, 2009; Zelazo, Craik & Booth, 2004). The findings reporting improvements of top-down control were obtained using a number of different tasks including go/no-go, stop-signal, visual search (e.g., conjunction search; Hommel, Li & Li, 2004) and Stroop tasks (Comalli, Wapner & Werner, 1962).

It is generally accepted that selective attention is mediated by a set of component mechanisms. Bundesen's (1990) TVA is one of the must successful recent attempts at a theoretical description and mathematical model of component processes of attention. TVA is built entirely on previous findings and theoretical concepts, notably limited memory capacity (Miller, 1956), biased competition (Desimone & Duncan, 1995; Duncan, Humphreys & Ward, 1997), it uses the methods of whole and partial report (Sperling, 1960) and psychophysical methods of data analysis.

As the methods used in the studies discussed above included a wide variety of different tasks such as visual search, tapping, span tasks, go/nogo tasks, stroop tasks or mental rotation tasks, it is quite difficult to compare the findings of the different approaches. The advantage of a TVA-based test is obvious: The method (whole report, partial report) is very simple, performance is expressed in parameters reflecting independent component processes of attention, interpretation of the findings is supported by a coherent theoretical framework, and, importantly, findings can be compared across different ages.

The usability of the whole and partial report methods as diagnostic tools was examined in healthy adult subjects (Finke et al., 2005). Whole and partial report were also employed successfully in patient studies (e.g. Duncan et al., 1999; Finke et al., 2006; Habekost & Bundesen, 2003; Peers et al., 2005) demonstrating the specificity and usefulness of a TVA-based assessment.

In the present study, an adaptation of the whole and partial report procedure, using simple pictograms instead of letters, is employed to test visual selective attention in children. Children had to verbally report (no motor response was involved) the identity of briefly presented pictograms. The identities of the named pictograms were recorded (entered into the computer) by the experimenter for later analysis.

The aim of this study was to examine the usability of the whole and partial report task in children and to assess the development of component processes of selective attention (based on Bundesen's TVA) in children of different ages attending the first, second or third grade of primary school. In accord with the results reviewed above, increasing performance in the component functions visual short-term memory capacity, speed of processing and top-down control (selection effectiveness) was expected to emerge with increasing age. Lateralization of attentional weight distribution was used as a control measure. 63 healthy children ranging in age from 5 to 10 years completed the whole and partial report task.

A test of visual attention for children based on Bundesen's (1990) Theory of Visual Attention (TVA)

The test of visual attention for children uses the variants of the whole and partial report procedures introduced by Duncan et al. (1999). Line drawings of objects were used instead of letters (see Figure 1). Recognition of line drawings was assessed in pretests. 30 children named the 25 pictograms to be used in the test. Objects that were prone to mis-identification or confusion with other objects were removed before testing.

In the whole report part of the test, five red or green drawings were presented either to the left or to the right of a central fixation cross and the children were instructed to report as many objects as possible irrespective of colour. In the partial report part, objects were drawn in red or green and children were instructed to report only the red objects and to ignore any green object.

Figure 1. The pictures used in the whole and partial report tasks of the present study.

5.3.3 Method

The test of visual attention for children involves two tasks, the partial report and whole report task (Sperling, 1960). All 63 children completed both procedures in counterbalanced order. Based on the results of the partial report task, the components of attentional weights and top-down control were estimated. The results of the whole report task underlie the estimation of the component functions of visual short-term memory (vSTM) capacity and processing speed. Children attending the first, second or third grade of primary school were tested and performance was compared between grades.

Participants. Overall, 63 healthy children participated in the partial and whole report conditions. The 20 first-graders (12 girls, 8 boys) had a mean age of 6.4 years and ranged in age from 5/11 (years/months) to 7/9; 20 second-graders (9 girls, 11 boys) had a mean age of 7.8 years and ranged from 7/3 to 9/3, and 23 third-graders (13 girls, 10 boys) had a mean age of 8.9 years ranging from 8/9 to 10/2. The children were recruited from three different Swiss primary schools. Informed consent was obtained from the headmaster, teachers and parents for all children participating in the study. The children received small rewards for their participation. All observers had normal or a corrected-to-normal vision, including normal colour vision. They had no previous experience with the whole or partial report methods.

Apparatus. Presentation software for the partial report and whole report procedures was programmed under Microsoft Visual Studio, using the Microsoft DirectX libraries for millisecond timing and run on Microsoft Windows XP. Testing was conducted in dimly lit rooms, made available during the time required for testing by the school.

Stimuli were displayed on an IBM T40 notebook with a display diagonal of 14.1” with a resolution of 1024 × 768 pixels and a refresh rate of 60 Hz. Viewing distance was approximately 50 cm, maintained by seating children in a comfortable chair and positioning the computer (vertically oriented) monitor in front of the child.

Participants’ responses were entered into the computer for storage and offline analysis via an external keyboard by the examiner. Symbols printed on adhesive film were placed next to the letter labels on the keyboard for response recording. The keyboard was placed out of the field of view of the children in order to avoid any effects from children seeing the key labels while reporting the objects.

General procedure and stimuli for partial and whole report. Each participant completed the entire test (partial and whole report) in either two or three sessions, each lasting about 30 or 45 minutes, respectively. Great care was taken not to put strain on the children, thus sessions were adjusted to the children's age. The order of partial report and whole report was counterbalanced across participants.

Previous to each of the two conditions, participants were presented the entire set of stimuli (see Figure 1) and they were asked to name each of the objects individually. This pre-experiment routine served two purposes. First, it was used to determine whether the stimulus set contained drawings that were unfamiliar to the participant, and, second, the differences in naming particular objects were recorded by the experimenter in order to avoid potential confusion by names not expected by the experimenter. A further purpose of the pre-test routine was to familiarize observers with the stimuli.

During the testing proper, children were instructed to fixate a central white fixation cross (subtending 0.3° × 0.3° of visual angle), presented for 300 ms in the center of the display. Fixation was followed by a blank screen of 100 ms; then the pictures, painted in red or green ink, appeared on a black background, for short exposure durations, individually determined before the experiment. Pictures subtended an area of 0.8° × 0.7° of visual angle in height and width, respectively.

The pictures were randomly picked from a set of 25 pictures (see Figure 1) without replacement, i.e., each picture was presented only once in a given trial. The presentation of the pictures was terminated either by a blank (black) screen or by white masks (presented for 500 ms) replacing each of the pictures. Masks consisted of a square of 1.4° of visual angle in height and width, the two diagonals connecting the corners and an additional smaller square with line length of 0.7° of visual angle. After the masks (or the stimuli) had disappeared the screen remained blank until the participants' responses were recorded and the participant had indicated that he/she was ready for the next trial. Each trial was initiated by the experimenter pressing a key.

Participants were instructed to report the identity of the pictures they were quite sure to have recognized. There were no restrictions regarding the time required to produce the names and picture names could be reproduced in any order. Responses were entered into the computer via the keyboard by the examiner for storage and offline analysis.

5.3.3.1 Partial Report

Procedure and stimuli. Following the central fixation cross either one or two pictures were presented in the corners of an imaginary square with an edge length of 6° of visual angle centred on the middle of the monitor. Participants were presented with either one red (target) picture, two red (target) pictures or one red (target) picture accompanied by one green (non-target) picture (see Figure 3). If two pictures were presented in a trial, they were either in the upper or lower or the left or right hemi-field, but not on diagonally opposite locations (i.e., not upper left [right] and lower right [left] corner). The task in the partial report condition was to report only the identity of the red target pictures and to ignore the green non-target pictures. That is, the colour (red) served as a cue (presented with stimulus onset asynchrony (SOA) = 0 ms) indicating the to-be-reported items (see example in Figure 2).

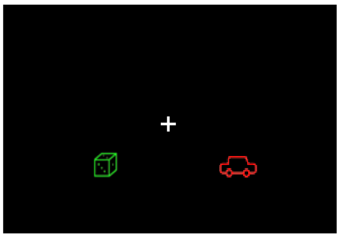


Figure 3. Example for one partial report trial with one target and one non-target. In partial report one red and one green picture was presented at four possible locations of an imaginary square to the left or/and to the right of a central fixation cross.

Previous to the partial report task, participants completed a pre-test comprised of a total of 32 trials: 12 trials with a single target; 12 trials with two targets, and 8 trials with one target and one non-target item. The aim of the pre-test was to determine the criterion presentation time, at which each individual participant performs at a level of an average of 70-80% correctly recognized pictures in trials with one single target picture. If a participant's performance level was above or below the criterion level, the presentation times in the partial report procedure were reduced or increased accordingly.[13]

The following partial report experiment involved 16 different conditions (4 single target [top left, right; bottom left, right], 4 dual target [top, left – top, right; bottom, left – bottom right; top, left – bottom, left; top, right – bottom, right], and 8 target and non-target conditions [target top, left – non-target top, right; top, right – top, left; bottom, left – bottom right; bottom, right – bottom, left; top, left – bottom, left; top, right – bottom, right; bottom, left – top, left; bottom, right – top, right]). Each of the conditions was repeated 18 times. A total of 288 trials was presented, split into 6 blocks of 48 trials each. All picture presentations were followed by masks at each stimulus location.

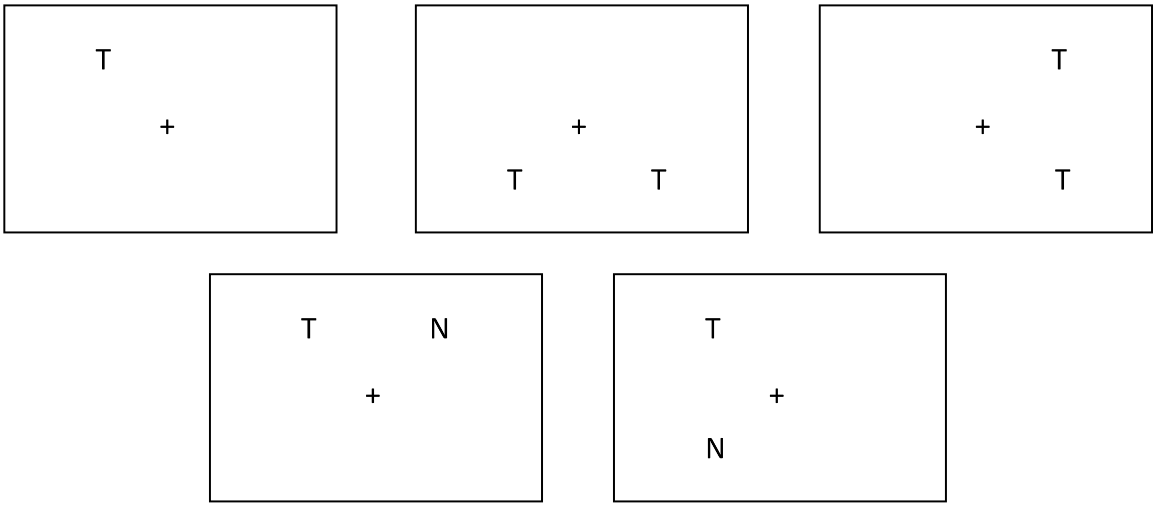


Figure 2. Examples for different trials in the partial report. One single target picture (top, left-hand panel), two target pictures arranged horizontally (top, middle panel) or vertically (top, right-hand panel) or a target picture accompanied by one non-target picture arranged horizontally (bottom, left-hand panel) or vertically (bottom, right-hand panel) could be presented at the four possible display locations.

---

[13] Based on preliminary studies, the initial presentation time was set at 200 ms for each child. If a child performed above the criterion of 70-80% for single target report, presentation times in the partial report were shortened to 150 ms if 80-90% and to 100ms if > 90%. Presentation times were extended to 300 ms if < 60% and to 250 ms if 60-70% if a child performed below the criterion level.

5.3.3.2 Whole Report

Procedure and stimuli. Following a central fixation cross, a column of five red or green pictures, spaced equidistantly, was presented 2.5° of visual angle to the left or right of the fixation cross (see Figure 4). Participants were asked to report the identity of as many pictures as possible that they were sure they had identified.

Before the main experiment, participants completed a pre-test of 24 trials with the search pictures masked after presentation. The aim of the pre-test was to determine the presentation time, for each participant, yielding a criterion performance level of an average of between 20 and 30% correctly identified pictures. If a participant's performance level was above or below criterion, the presentation times of the whole report proper experiment were decreased or increased accordingly.[14] As the whole-report procedure is employed to estimate processing speed and visual short-term memory capacity, both of which are based on a psychometric function, (at least) three different exposure durations are required. The pre-determined presentation time represents the medium-length presentation time for masked trials, short and long display presentation durations are obtained by halving and doubling, respectively, medium presentation duration. In each of the three presentation durations, in half of the trials, the pictures were followed by a blank (black) screen, in the other half of the trials, pictures were masked. The resulting six presentation times were expected to cover a broad range of performance by trying to cover the lower and upper part of the individual performance level (Finke et al., 2005).

The whole report experiment consisted of 12 different conditions (3 presentation times [short, medium, long] × 2 masking conditions [unmasked, masked] × 2 hemi-fields [left, right]); each of the conditions was repeated in 16 trials (with pictures randomly drawn in each trial). A total of 192 trials were presented, split into 4 blocks of 48 trials each.

---

[14] Based on preliminary studies, the initial presentation time was set at 200 ms for each child. If a child performed above the criterion of 20-30% for target report, presentation times in the whole report were shortened to 150 ms if 30-40% and to 100 ms if > 40%. Presentation times were extended to 300 ms if < 20% and to 250 ms if 20-30% if a child performed below the criterion level.

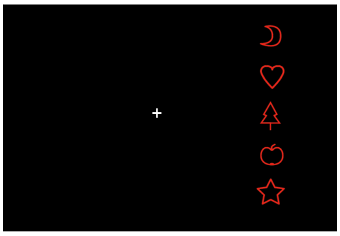


Figure 4. Example of a whole report trial. Five red or green pictures were presented in vertical columns to the left or to the right (shown) of a central fixation cross. The pictures were shown at equidistant locations with regard to the pictures' centres of gravity.

5.3.4 Results

The results section comprises two parts. In the first part, proportions of correctly reported pictures of the partial report condition will be reported, followed by the model estimates of the component functions of the sensory effectiveness, spatial distribution of attentional weights, and top-down control. In the second part, proportions of correctly reported pictures in the whole report condition are presented, followed by estimates of the capacity of vSTM and processing speed. Parameter estimates of the partial report and whole report conditions were obtained with the use of the analysis software by Kyllingsbæk (2006).

Performance of first-, second- and third-graders is compared as to the proportion of correctly identified pictures in the partial and whole report conditions and the estimates of the different attentional components.

5.3.4.1 Partial Report

First, percentages of correctly reported items, reflecting accuracy of performance, are reported and compared across grades. The report follows the pattern established by Duncan et al. (1999; see also Finke et al., 2005).

Accuracy in all three age groups (first, second and third grade) was highest (78.48%) for the conditions, in which a single target was presented (see Figure 5 a, b, and c, left-most columns). If two stimuli were presented, the performance decrease was more marked if the secondary stimulus was a target (decrease of 54.30% to 24.18%) than when the secondary stimulus was a non-target (decrease of 14.44% to 64.04%). This pattern is as predicted by TVA: performance is affected if multiple stimuli are presented, and presenting a secondary target affects performance more than presenting an additional non-target.

To compare performance across age groups, percentage correct data were subject to a repeated-measures analysis of variance (ANOVA) with the between-subject factor age group (first, second, third grade) and the within-subject factor condition (single target, dual target same hemi-field, dual target different hemi-fields, target and non-target same hemi-field, target and non-target different hemi-fields). The ANOVA revealed significant main effects of condition (*F*(4,240) = 642.73; *p* < .001) and age group (*F*(1,2) = 7.82; *p* < .001). The interaction between condition and age group was not significant (*F*(8,240) = 1.66; *p* = .109). Planned comparisons revealed that, compared to the single target conditions, performance was worse in conditions in which the target was accompanied by a non-target in the same (60.23% correct, [SD = 9.27]; *F*(1,60) = 267.11; *p* < .001) or opposite (67.86% correct, [SD = 10.41]; *F*(1,60) = 100.97; *p* < .001) hemi-field and in conditions in which the target was accompanied by another target in the same (17.68% correct, [SD = 11.21]; *F*(1,60) = 1417.65, *p* < .001) or different hemi-field (30.69% correct, [SD = 15.13]; *F*(1,60) = 624.41, *p* < .001).

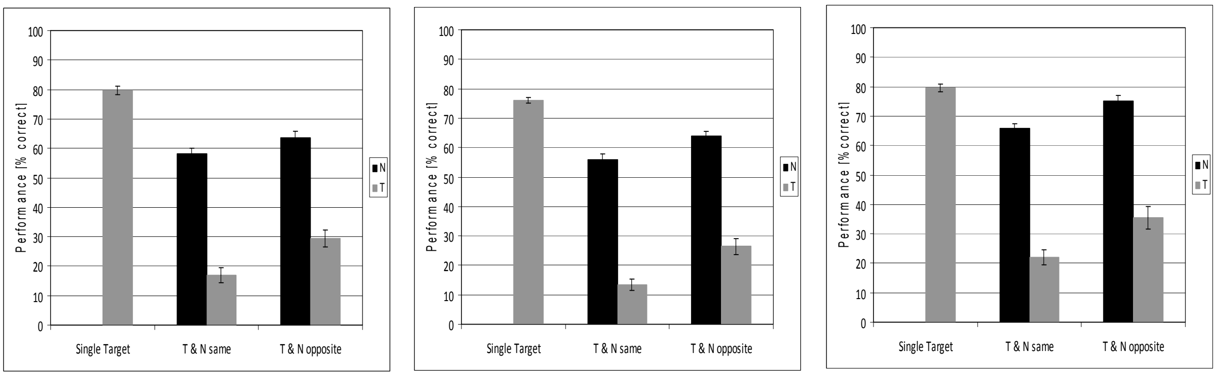
Planned comparisons did not reveal a performance difference in single target trials between age groups (first grade: M = 79.65, SD = 6.53; second grade: M = 76.11, SD = 4.14; third grade: M = 79.53, SD = 6.26; *F*(2,60) = 2.48; *p* = .09).

Planned comparisons further revealed significantly better performance (% correct) in third-graders (mean = 65.76, SD = 8.55) compared to both first- (mean = 58.13; SD = 8.21; *p* = .012) and second-graders (mean = 55.97; SD = 8.22; *p* = .001) in conditions in which a target was accompanied by a non-target in the same hemi-field (*F*(2,60) = 8.30; *p* = .001). The same result was found for conditions in which the target was accompanied by a non-target in the other hemi-field: Comparison third (M = 75.12; SD = 9.06) vs. first grade (M = 63.47; SD = 9.97; *p* < .001) and third vs. second grade (M = 63.89; SD = 7.67; p < .001) (*F*(2,60) = 11.93, *p* < .001).

Finally, planned comparisons showed that, if the target was accompanied by a second target in the same hemi-field the third- graders (M = 21.98; SD = 11.93) showed significantly better performance than the second- graders (M = 13.47; SD = 8.56; *p* = .038), but not than first-graders (M = 16.94, SD = 11.43, *p* = .398) (*F*(2,60) = 3.38; *p* = .041). If the target was accompanied by a second target in the opposite hemi-field there was no difference between the third-graders (M = 35.51; SD = 18.10) and the second-graders (M = 26.39; SD = 12.34; *p* = .148) or the first-graders (M = 29.44, SD = 12.88, *p* = .562) (*F*(2,60) = 2.12; *p* = .129). The differing conditions are plotted in Figure 6.

Overall, performance in terms of accuracy of reported items (percentage correct) appears to be very similar, if first- and second-graders are compared. Performance, however, is significantly improved in third- compared to first- and second-graders.

A striking result is that children, independent of their age, perform very badly in conditions with two target items present in the display.



a) b) c)

Figure 5. Mean percentage of correct responses for first- (a), second- (b), and third-graders (c). The left-most bar of each panel represents the (four) single target conditions corresponding to the quadrants of the visual field. The second and third bars from the left show performance in conditions in which two targets were presented in the same hemi-field and in which a target was accompanied by a non-target in the same hemi-field, respectively. The fourth and fifth bars show performance in conditions in which two targets were presented in opposite hemi-fields and conditions in which a target was accompanied by a non-target in the opposite hemi-field, respectively.
Grey bars represent displays containing target items only (left-most bars: single target; third and fifth bars from left: dual targets); black bars represent targets accompanied by non-targets (second from left: same hemi-field; fourth: different hemi-field).

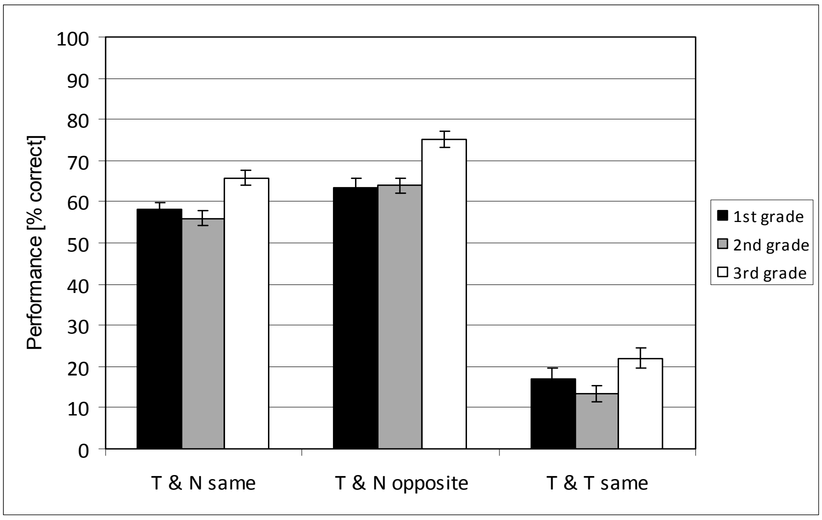


Figure 6. Significant differences between the three age groups in their performance (percent correct) are plotted for the conditions, in which a target was accompanied by a non-target in either the same or the opposite hemi-field or two targets in the same hemi-field. The third-graders were significantly better than the other two groups.

More importantly, Bundesen's (1990) TVA allows estimating participants' partial report performance in terms of component processes underlying attention, namely, the spatial distribution of attentional weight (w_λ), lateralized sensory effectiveness (A_λ) and top-down control (α).

The spatial distribution of attentional weight, i.e., the question whether attentional weight attributed to display objects is distributed evenly across the visual field, or, put differently, whether an observer favours objects presented in a particular area of the visual field (such as the left or right hemi-field) is computed on the basis of estimates of the attentional weights attributed to objects presented at each (of the four) stimulus locations. Attentional weight distributions were compared between age groups in a one-way ANOVA with the factor group. The ANOVA revealed no significant difference between the three age groups ($F(2,60) = .51$, $p = .604$). As expected for normal observers, the values of w_λ were around .5 for all three grades (1st grade: M= .47, SD = .13; 2nd grade: M = .50, SD = .14; 3rd grade: M = .51, SD = .10; see Figure 7) and not significantly different from .5 (all *p*s > .29). This finding indicates that equal weight is attributed to objects in both hemi-fields - a finding expected for healthy observers.

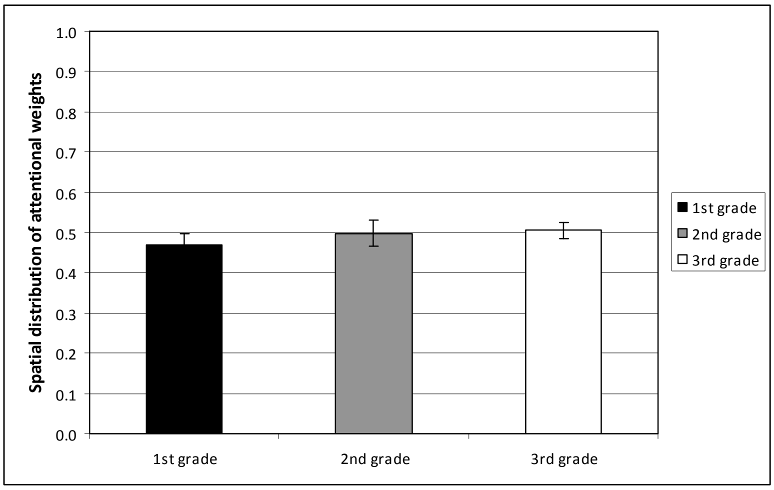


Figure 7. Values of the spatial distribution of attentional weights are plotted separately for all three grades.

The estimation of lateralized sensory effectiveness (A_{λ}) is based on perception accuracy at each stimulus location and is computed by weighting accuracy values of targets presented in the left hemi-field to the accuracy of left and right hemi-field targets. Equal distributions of sensory effectiveness over the left and right hemi-fields yields a value of .5, values larger or smaller than .5 indicate improved effectiveness in the left or right hemi-fields, respectively. Lateralized sensory effectiveness was compared between the different age groups in a one-way ANOVA with the factor group. The ANOVA did not show any significant difference between the three groups ($F(2,60) = 1.73$, $p = .185$): First-graders' values, on average, were at .50 (SD = .05), second-graders' at .46 (SD = .11) and third-graders' at .49 (SD = .05) (see Figure 8). Values were not significantly different from .5 in any of the groups (all *p*s > .15), indicative of equal sensory effectiveness in both visual hemi-fields in all the age groups. This result is as predicted.

It is of more importance in the present context of cognitive development, if the groups differ in the attentional weight allocated to target compared to non-target objects reflected in the value of the top-down control (α). Values of top-down control show the effectiveness of selecting targets and ignoring non-targets. By way of computation - top-down control equals the attentional weights of non-targets divided by the attentional weights of targets - estimates of top-down control range between 0 and 1. The closer the value to 0 the better the selection effectiveness, and the closer to 1, the worse the effectiveness is.

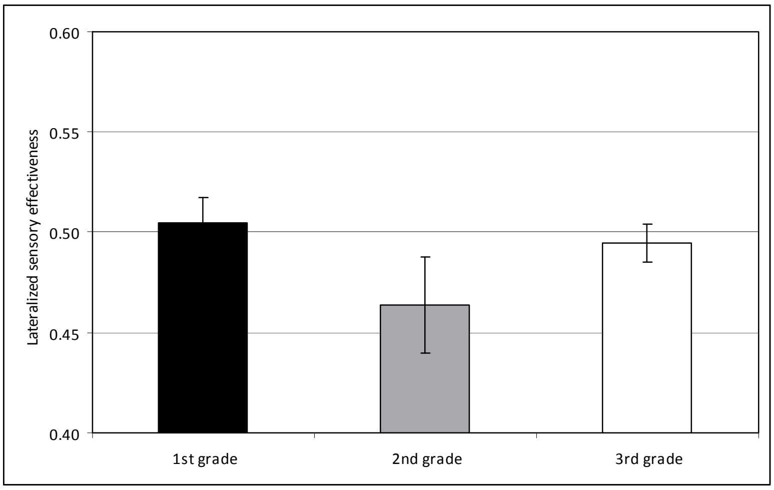


Figure 8. Values of the spatial distribution of the sensory effectiveness are plotted separately for all three grades.

In a first analysis step, it was determined, for all groups, whether values of selection effectiveness were significantly different from 1, the value corresponding to weight attributed in equal measures to target and non-target items (no selection of targets takes place). Estimates of top-down control were subject to a one-way ANOVA with the factor group (first, second, third grade) and revealed a significant main effect of group (*F*(2, 60) = 3.46; *p* = .04). Planned comparisons showed significantly better top-down control in the third-graders (M = .37; SD = .24) compared to the first-graders (M = .60; SD = .39; *p* = .050). Interestingly, no significant difference could be found between third- and second-graders (M = .55; SD = .29; *p* = .162) or second- and first-graders (M = .60; SD = .39; *p* = 1.000).

The data reveal two important findings. First, the ability to voluntarily (top-down) allocate processing weight to targets preferentially rather than equally to targets and non-targets, exists in participants of all three grades (*α* values are significantly different from 1). Second, there is a significant increase in selection effectiveness in the third grade compared to the first grade (Figure 9). Although the values seem to decrease (recall that lower values correspond to better selection) also between the first and second grades, this difference is not statistically reliable.

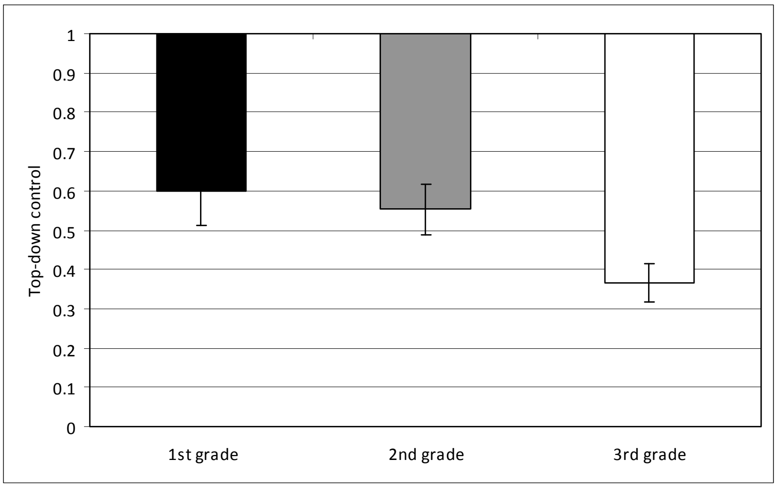


Figure 9. Values of the top-down control are plotted separately for all three grades.

In a last analysis step parameters of the partial report were correlated with the age of the children.

As expected, there was no significant correlation between age and lateralized sensory effectiveness (r = -.12; *p* = .170) or the spatial distribution of attention weight (r = .09; *p* = .251). The equal weighting of both hemi-fields is not changing with increasing age. Age and the top-down control values correlated negatively (r = - .28; *p* = .016). With increasing age top-down control values decrease and therefore children become better in selecting targets and ignoring non-targets. Figure 10 depicts the reported correlations.

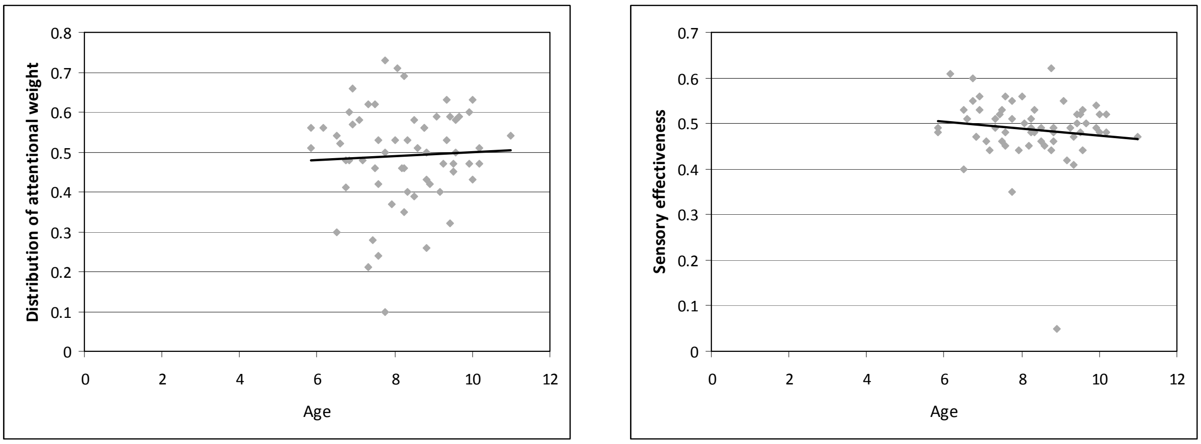


Figure 10. Correlations between age and distribution of attentional weight, sensory effectiveness, and top-down control are depicted.

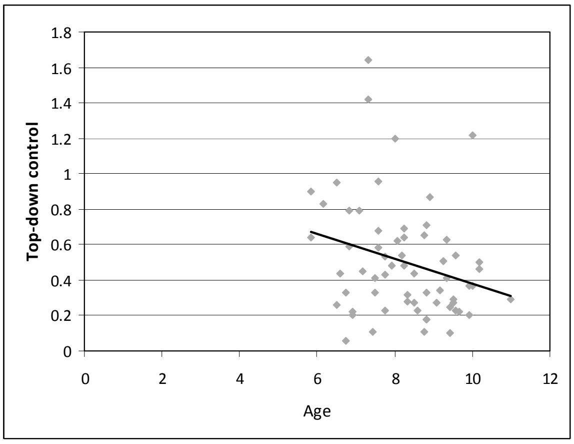


Figure 10. continued.

Table 1. Values of the partial report components for the first (a), second (b) and third (c) grade

a)

Participant	Aλ	wλ	α
1	0.51	0.52	0.44
2	0.53	0.30	0.95
3	0.61	0.56	0.83
4	0.56	0.57	0.20
5	0.44	0.37	0.48
6	0.56	0.53	1.20
7	0.48	0.51	0.64
8	0.51	0.50	0.43
9	0.51	0.21	1.64
10	0.55	0.41	0.33
11	0.49	0.56	0.90
12	0.47	0.60	0.59
13	0.40	0.54	0.26
14	0.44	0.48	0.45
15	0.45	0.24	0.68
16	0.60	0.48	0.06
17	0.52	0.28	0.11
18	0.53	0.66	0.22
19	0.47	0.48	0.79
20	0.46	0.58	0.79

b)

Participant	Aλ	wλ	α
1	0.48	0.42	0.96
2	0.05	0.42	0.87
3	0.45	0.51	0.23
4	0.49	0.62	1.42
5	0.55	0.73	0.53
6	0.49	0.47	0.51
7	0.56	0.53	0.58
8	0.53	0.53	0.28
9	0.45	0.46	0.54
10	0.48	0.35	0.69
11	0.46	0.50	0.71
12	0.50	0.71	0.62
13	0.35	0.10	0.23
14	0.48	0.40	0.32
15	0.51	0.69	0.64
16	0.46	0.62	0.41
17	0.49	0.58	0.27
18	0.46	0.39	0.44
19	0.49	0.46	0.48
20	0.53	0.46	0.33

c)

Participant	Aλ	wλ	α
1	0.54	0.60	0.20
2	0.42	0.40	0.34
3	0.52	0.51	0.46
4	0.47	0.53	0.63
5	0.55	0.59	0.27
6	0.49	0.26	0.18
7	0.49	0.47	0.37
8	0.50	0.59	0.22
9	0.48	0.50	0.18
10	0.48	0.47	0.50
11	0.47	0.54	0.29
12	0.49	0.43	0.33
13	0.48	0.45	0.29
14	0.44	0.58	0.54
15	0.53	0.50	0.23
16	0.44	0.56	0.11
17	0.50	0.32	0.25
18	0.48	0.43	0.37
19	0.52	0.59	0.10
20	0.52	0.63	1.22
21	0.41	0.63	0.41
22	0.52	0.47	0.27
23	0.62	0.56	0.65

5.3.4.2 Whole Report

First, percentage of correctly identified items (identification accuracy) is reported separately for each condition, and accuracy is then compared across grades. Percentages of correctly identified items were subjected to repeated-measures ANOVA with the within-subject factors display (unmasked, masked), exposure duration (short, medium, long) and the between-subject factor grade (first, second, third). The ANOVA revealed that, regardless of the presentation time, accuracy was always higher in conditions in which the pictures were presented unmasked compared to trials in which the presentation was followed by a mask (main effect of display; unmasked: 32.97%, masked: 24.48%; *F*(1,60) = 632.18; *p* < .001). Accuracy increased with increasing presentation times (main effect of exposure duration; short: M = 19.62 (SD = 4.75), middle: M = 29.93 (SD = 5.02), long: M = 36.62 (SD = 5.40); *F*(2,120) = 563.02; *p* < 001). Comparing percentage correct of the three age groups, the main effect of grade was significant (*F*(2,60) = 27.75, *p* < .001). Detailed analyses revealed significant differences in all six conditions (masked: short, middle, long presentation times; unmasked: short, middle, long presentation times; see Table 2). Planned comparisons revealed, in all conditions, significantly better performance for the third compared to the second and to the first grade (all *p*s < .03).

Table 2. Performance in percent correct for all three grades are displayed for all masked or unmasked conditions for short, middle or long presentation times (standard deviations are in brackets). Levels of significance for the ANOVA are shown in the last row.

	masked short	 middle	 long	unmasked short	 middle	 long
1st grade	11.73 (2.81)	21.98 (4.39)	31.46 (6.07)	22.25 (3.44)	30.50 (4.72)	35.50 (6.78)
2nd grade	13.00 (3.71)	24.10 (2.70)	32.68 (4.63)	22.47 (3.74)	33.05 (5.42)	38.50 (5.36)
3rd grade	16.85 (4.86)	29.35 (3.92)	37.58 (2.91)	30.24 (5.32)	39.27 (3.53)	42.88 (3.80)
ANOVA	F(2,60) = 9.97; *p* < .001	F(2,60) = 22.68; *p* < .001	F(2,60) = 10.62; *p* < .001	F(2,60) = 24.47; *p* < .001	F(2,60) = 21.11; *p* < .001	F(2,60) = 10.26; *p* < .001

Participants' performance in the whole report task allows the estimation of parameters reflecting the capacity of visual short-term memory (vSTM; *K*) and processing speed (*C*).

The number of items processed simultaneously in visual short-term memory, i.e. vSTM capacity, is estimated on the basis of the performance in the whole report task. In adult observers, processing is limited to about 3 to 4 items (letters). As the whole report task (as used in the present context) has not been performed by children yet, and as pictograms were used instead of the letters used in studies that could be consulted for comparison, the expected performance range is difficult to predict. In analogy to the findings of the partial report and the literature cited in the Introduction, an increase in vSTM capacity is expected to be observed with increasing age and children's capacity is assumed to be lower than the capacity of adult observers.

Estimates of visual short-term memory (obtained by applying Kyllingsbaek's 2006 analysis program) were analyzed in a one-way ANOVA with the factor age group (first, second, third grade). The ANOVA revealed a significant main effect ($F(2,60) = 9.11$; $p < .001$), i.e., vSTM capacity significantly differs between grades. Planned comparisons showed that third-graders' capacity (M = 2.41, SD = .31) was significantly higher than second-graders' (M = 2.09, SD = .42; $t(41) = -2.82$; $p = .021$) and first-graders' (M = 1.94, SD = .38; $t(41) = -4.50$; $p < .001$). Further, vSTM capacity of second-graders was (although numerically slightly higher) not significantly different from the capacity of first-graders ($t(38) = -1.22$; $p = .566$). (See Figure 11)

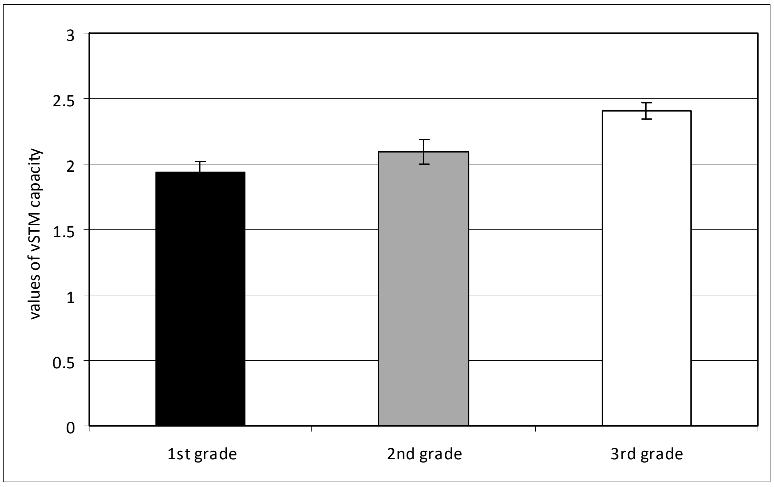


Figure 11. Estimates of visual short-term memory capacity (average number of items) for first-, second-, and third-graders.

A second important measure which is estimated on the basis of performance in the whole report task is the processing rate, i.e., the number of items processed per unit time (items per second). Similarly to vSTM capacity, it is difficult to make predictions about the expected range of processing speeds. In analogy to the findings of the partial report task and the findings reported in the literature (see Introduction), an increase in processing speed is expected to be observed with increasing age and children's processing speed is assumed to be lower than the speed of adult observers.

Estimates of processing speed (obtained using Kyllingsbaek's 2006 estimation procedure) were subjected to a one-way ANOVA with the factor age group. The ANOVA revealed the main effect of group to be significant (*F*(2,60) = 7.02; *p* = .002). Planned comparisons showed that the third-graders' average processing rate (13.33 items/sec, SD = 4.61) is significantly faster than the second-graders' (9.73 items/sec, SD = 3.39) and the first-graders' (8.43 items/sec, SD = 5.19) (*t*(41) = -2.89; *p* = 032; *t*(41) = -3.27; *p* = .002, respectively). Although numerically faster, second-graders' processing speed was not significantly different from first-graders' (*t*(38) = -.932, *p* = 1.000) (See Figure 12). Mean values of the capacity of vSTM and the processing speed can be seen in Table 3.

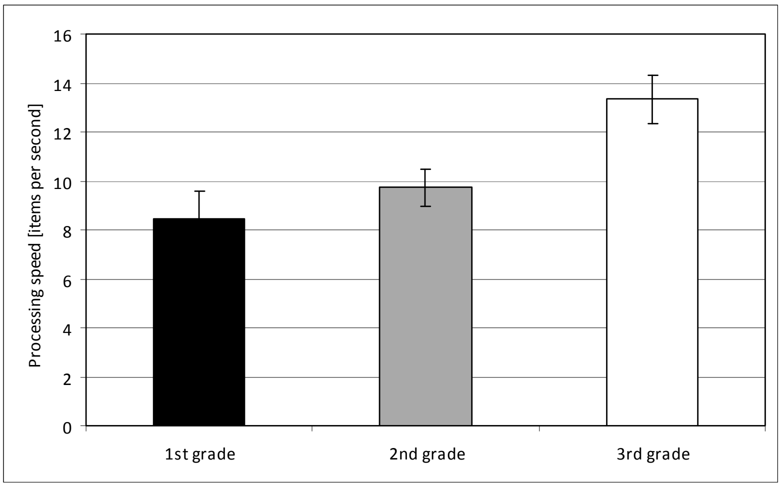


Figure 12. Values of the processing speed are plotted separately for all three grades.

In a last analysis step parameters of the whole report were correlated with the age of the children.

Age and the values of the capacity of vSTM correlated positively (r = .36; *p* = .002). With increasing age capacity increases and more items can be processed simultaneously. The processing speed correlates positively with age as well (r = .40; *p* < .001). Both correlations can be extracted from Figure 13.

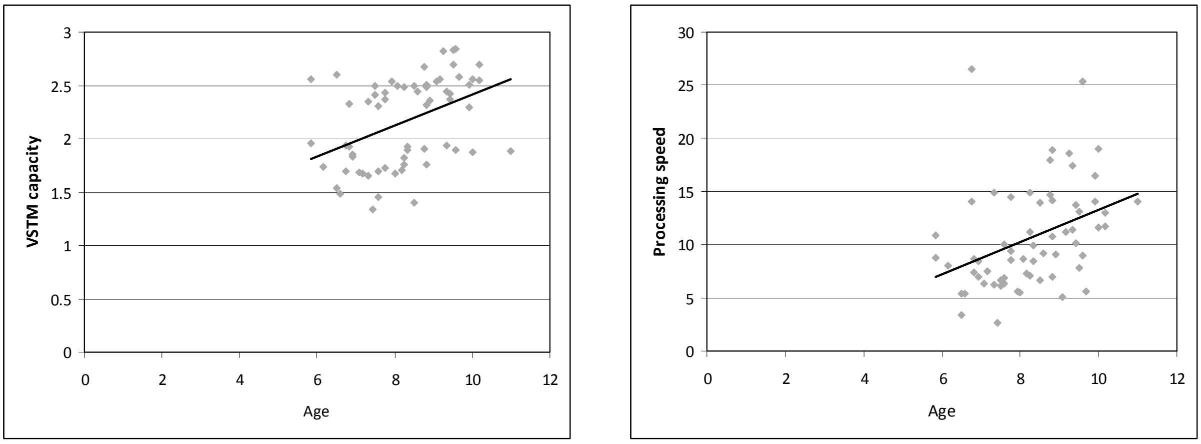


Figure 13. Correlations between age and vSTM capacity as well as processing speed are depicted.

Table 3. Parameters visual short-term memory capacity (*K*) and processing speed (*C*) for first- (a), second- (b) and third- (c) graders.

a)

Participant	K	C
1	1.48	5.37
2	2.60	3.39
3	1.74	7.98
4	1.85	7.02
5	2.54	5.64
6	1.67	5.49
7	2.56	8.73
8	1.73	14.51
9	2.35	6.22
10	1.69	14.05
11	1.96	10.86
12	2.33	7.44
13	1.54	5.44
14	1.67	7.50
15	2.31	6.39
16	1.94	26.50
17	1.34	2.59
18	1.83	8.47
19	1.93	8.67
20	1.68	6.39

b)

Participant	K	C
1	1.69	6.86
2	2.36	9.11
3	2.44	9.16
4	1.65	14.92
5	2.37	8.54
6	2.82	18.58
7	1.45	10.00
8	1.89	9.89
9	1.71	7.30
10	1.76	14.88
11	1.76	6.98
12	2.49	8.66
13	2.43	9.42
14	1.93	8.50
15	1.82	11.24
16	2.50	6.68
17	2.50	6.62
18	1.40	13.99
19	2.48	7.03
20	2.41	6.15

c)

Participant	K	C
1	2.51	14.09
2	2.56	11.22
3	2.69	13.01
4	1.94	11.37
5	2.54	5.11
6	2.51	10.73
7	2.29	16.46
8	2.58	5.65
9	2.48	18.95
10	2.55	11.75
11	1.88	14.05
12	2.32	14.14
13	2.69	7.85
14	2.84	25.34
15	1.89	9.00
16	2.67	14.71
17	2.37	10.15
18	2.56	11.58
19	2.42	13.77
20	1.87	19.03
21	2.44	17.47
22	2.83	13.05
23	1.91	18.01

5.3.5 General Discussion

The aim of the present study was to investigate the development of component processes of selective visual attention in children employing Bundesen's (1990) Theory of Visual Attention (TVA). TVA proposes that selective attention is modulated by a set of component processes – visual short-term memory, processing speed, attentional weight, and top-down control – yielding independent estimates of parameters describing individual performance. Performance is assessed using the whole report and partial report tasks. Percentage of correctly identified items (pictograms) is used to derive psychometric functions underlying estimates of short-term memory capacity and processing speed as well as an index of the efficiency of top-down control.

63 children, aged between 5 and 10 years, attending the first, second or third grade of primary school were tested. Overall, children show not only significant increases in recognition performance as measured in the proportion of correctly recognized items, but also significant increases in their processing speed and visual short-term memory capacity with increasing age. Importantly, the efficiency of top-down control, that is, the ability to prioritize target relative to non-target items by voluntarily allocating processing resources to targets is more developed with increasing age.

Proportions of correctly recognized items in the partial report task show an interesting pattern. Performance does not differ between grades if isolated items are considered, that is, sensory processing of single items is equally developed in first- as in second- and third-graders. However, there is an overall performance difference between grades in conditions, in which multiple items are presented.

In particular, if the target was accompanied by a second target in the same hemi-field, third-graders recognized a higher proportion of items than second-graders, (but not first-graders, although a higher proportion of targets was recognized by third-graders). Similarly, third-graders' percentage of correctly reported items is higher than both second- and first-graders' if a target is accompanied by a non-target item (in the same or different hemi-field).

A target item accompanied by a second target in the opposite hemi-field did not entail performance differences. Taken together, this pattern suggests that interference by secondary target or non-target affects performance differently in different grades.

According to TVA, the presentation of a secondary target entails a drop in recognition rates as processing resources need to be allocated to two rather than a single item; the drop is smaller if the secondary item is a non-target, because weight allocation is biased top-down. A dramatic drop in performance is indeed seen if a secondary target is presented in the same hemi-field. The drop is most severe in second- (and first-) relative to third-graders; this suggests that third-graders either have a larger pool of processing resources available for allocation to multiple targets, or they distribute available processing resources more efficiently (evenly) to multiple targets. The finding that presentation of non-targets affects performance to a larger degree in first- and second-graders than in third-graders together with the finding that top-down control of resource allocation (α) is more efficient in third-graders than in first-graders provides evidence for the latter interpretation. Furthermore, it is interesting to note that – even with processing weights evenly distributed across the left and right hemi-field – recognition performance is lower only in second relative to third-graders, if the secondary target is presented in the same hemi-field. These findings suggest some sort of intra-hemifield competition in the two younger compared to the relatively eldest grade under investigation in the present study.

The proportion of correctly recognized items was also higher in third- relative to second- and first-graders in the whole report. Given that recognition of single items (partial report) did not differ between age groups, the rate in correctly recognized items is likely due to higher processing speed and/or vSTM capacity.

Estimates of short-term memory capacity revealed that this is indeed the case. Capacity of third-graders is higher than capacity of second- and first-graders. Importantly, first- and second-graders’ capacities did not differ significantly. Taken together, this suggests that the significant increase in short-term memory capacity occurs at around age 9.

Interestingly, the same pattern was revealed in the processing speed analysis: Third-graders’ processing speed was different from second- and first-graders, but there is no difference between second- and first-graders in terms of processing speed, suggesting an increase in processing speed taking place at around age 9.

Importantly, as suggested by the present pattern of results, processing speed and visual short-term memory capacity seem to develop simultaneously (see below).

How does the performance of children compare to performance in adult observers? Presenting adult observers with the picture recognition partial report and whole report tasks provides a standard for performance comparison. Ten adult observers (4 male, 6 female) aged between 20 and 43 years took part in a comparison study with exactly the same method as the children. Short-term memory capacity in adult observers was 2.56 items on average (SD = .08), that is, adults' memory capacity in the picture recognition task is only slightly higher than third-graders' capacity (2.41 items). Similarly, processing speed is increased only by a relatively small amount in adults (16.33 items/sec, SD = 4.23) compared to third-graders (13.33 items/sec, SD = 4.61).

Interestingly, proportion of correctly reported items in the partial-report task is in about the same range as that of the children in single-target presentation conditions. Performance is better overall in multiple item conditions, probably due to better top-down control capabilities in adults.

Top-down control shows a significant development in third- compared to first-graders, but no difference was found between third- and second-graders (and between second- and first-graders). This finding might suggest that top-down control develops more slowly and more steadily over a longer period of time than, for example, visual short-term memory capacity and processing speed.

Importantly, it also suggests that there is dissociation in development between processes associated with encoding and representing visual information and processes of biasing these visual representations (see below).

Top-down control value is, on average, at α = .28 (SD = .21) in the sample of adult observers compared to α = .37 (SD = .24) in the sample of third-graders (recall that lower values indicate better top-down control).

Parameters of lateralized attentional weights (w_λ), used as a control measure, show values of around .50 for all age groups of children (as well as for the sample adult observers).

With regard to the findings on development in short-term memory capacity and processing speed reported in the literature, the present partial report and whole report procedure used to test visual attention in children shows that the present results are in accordance with previous results. The age-dependent differences observed in the present study replicate previous findings. Several papers report increases in visual short-term memory capacity in children as their ages increase (e.g., Gathercole, 1999) and faster processing speed with increasing age (e.g., Kail, 1991a). Furthermore, more developed top-down control capabilities in older relative to younger children were also reported (Dempster, 1992). There is one important difference, however, between the present approach and previous studies: using the framework of Bundesen's (1990) TVA and the whole report and partial report allows the assessment of all the different component processes in one comparably highly time-efficient approach.

In terms of theories of development, the present findings regarding the development of the three attentional components – visual short-term memory capacity, processing speed and top-down control – during the age span between 5 and 10 years provide evidence for theories of development. The global trend hypothesis proposed by Hale (1990) suggests that the cognitive components develop in relative synchrony. A precursor for the global trend hypothesis (Kail, 1986) assumed that the absolute quantity of all processing resources increases with maturing. Kail (1986) distinguished between automatic and controlled processes. Since automatic processes have no demand on limited processing resources, theses processes should not be affected by age. Controlled processes, on the other hand, compete for the limited processing resources and, therefore, their efficiency is sensitive to the quantity of these resources. In conclusion, Kail (1986) suggests that all controlled processes are similarly affected by age. With growing capacity and increasing resources, children can process information more efficiently. The global trend hypothesis proposed by Hale (1990) does not differentiate between automatic and controlled processes. It assumes that all components of information processing develop simultaneously and development occurs with similar rates in all components. However, the global trend hypothesis of Hale (1990) was restricted to cognitive processing speed. With the data of this study, this hypothesis can be expanded by assuming that not only the components of the processing speed, but also the capacity of vSTM increase with age. The case is somewhat more difficult for top-down control. The present data suggest that top-down control develops at a slower pace and over a longer period of time than processing speed and short-term memory capacity. Clearly, more research is required to decide whether top-down control develops in synchrony with other cognitive mechanisms or independently of them.

One potential fruitful application of the procedure developed in the present study is in examining the causes of attention disorders; in particular attention deficit hyperactivity disorders (ADHD). Preliminary results of a limited small sample of children diagnosed with ADHD suggest that their selection effectiveness is impaired relative to children of the same age. While short-term memory capacity and processing speed did not differ from a sample of same-age controls, their top-down selection efficiency was significantly worse: on average, top-down control was α = .69 (SD = .27); as compared to the control group's α = .37 (SD = .24). Clearly, these data are preliminary in nature, but they might be instructive in identifying the causes of ADHD.

6. Synopsis and General Discussion

Since in almost every theory of visual selective attention categories (e.g., colour, letter, or size) play a crucial role, I investigated these categorical processes in more detail. More precisely, the studies focused on the foundations, certain disturbances and the development of the categorization process.

In the first project the focus was on the foundations of the categorization process. The major question was, if the categorization process, assumed to be automatic in the TVA (Bundesen, 1990), is actually automatic and therefore not able to be influenced by simple bottom-up changes in simple or multiple features of the to-be-reported items (in the two TVA-based experimental procedures of whole and partial report) in pairs of consecutive trials. Experiments 1 and 2 focused on the influences of feature changes or repetitions on the components of the TVA and revealed specific changes in the components reflecting selection behaviour in the TVA (Bundesen, 1990). If the target-defining feature was repeated across trials, there was a significant advantage of the top-down control efficiency in the second relative to the first of two consecutive trials. Repetition of features therefore improves the ability to top-down set weight on target items and to ignore non-target items. If features change, the selective system has to attribute weights to the changed feature resulting in costs impeding the selection effectiveness. Furthermore, vSTM showed a significant increase in capacity in the second of two consecutive trials if the feature was repeated. In accordance with recent findings in the literature, vSTM capacity is not as stable as assumed (Bundesen, 1990), but rather variable, and changes in capacity occur according to specific situations and influences (e.g., Alvarez and Cavanagh, 2004). The variability seems furthermore to change in a very short temporal frame.

Results are in line with Maljkovic and Nakayama's (1994) 'priming of pop-out' idea. They found – as in the present study – performance enhancement if target defining features were repeated. The current results reveal further evidence for the DW account (Müller, Heller & Ziegler, 1995), which assumes that processing in the early processing steps such as feature-based saliency computation is dependent on limited processing resources.

In Experiments 3 (target positions repeated across trials, randomly changing target positions, and predictable changing target positions) and 4, the influences of multiple feature changes were investigated. The findings in the top-down control were that predictability, i.e., the (implicit) knowledge of the target location in the upcoming trial, does not improve top-down control effectiveness, rather, if anything, it worsens top-down performance compared to conditions in which target location varies randomly, which argues in favour of results reported by Maljkovic and Nakayama (1994, 1996), who also showed that the ability to predict target characteristics does not improve the search performance. This result could reflect a difficulty in shifting the location where a target is expected to appear to the location where the target appeared in the actual trial. To sum up the results of the three different variations of Experiment 3 (target positions repeated across trials, randomly changing target positions, and predictable changing target positions), the effectiveness of top-down control is massively affected by the a repetition or change in target location. Repetitions of target locations improve top-down control; predictable changes in target location cause a total breakdown, possibly due to interference between spatial and feature-based components of resource allocation.

The bottom-up influences on the different components of the TVA can support the concept that changes in features entail a requirement to adjust processing ressources at the early processing level (findings in the top-down control) (e.g., Müller, Heller & Ziegler, 1995). Models of fixed short-term memory capacity should be changed and include the ability to adjust the capacity in a fine-grained temporal frame to certain situations.

The top-down influences on the components of the TVA were investigated by using trial-by-trial cueing. Processing speed could not be speeded up or slowed down by top-down influences. Again, the vSTM capacity (assumed to be stable) was remarkably influenced and enhanced by validly cueing the target defining feature in the upcoming trial. The system is set for the dimension of the upcoming targets resulting in a facilitated storing of more items in vSTM. Another issue to be discussed is the higher vSTM capacity value in the whole report Experiments 2 and 6 compared to values normally observed in whole report experiments. Since stimuli were presented in both hemifields the interpretation stands to reason that two independent capacities – one in the right and one in the left hemisphere – contribute to the overall high vSTM capacity in Experiments 2 and 6. This interpretation is in line with several recent studies by Alvarez and Cavanagh (2005), Kraft et al. (2005), and Chakravarthi and Cavanagh (2009). If in further research the assumption of two independent capacities can be maintained, the computing of the mean capacity of vSTM in TVA by averaging the capacity values in the left and right hemifield has to be corrected.

Overall, the bottom-up and top-down influences on the selection performance and on the categorization process argue against the automatic and relatively independent categorical processing proposed by TVA (Bundesen, 1990). Instead they speak in favour of an ability to be influenced of the categorization process and therefore of the attentional components – repeatedly of the vSTM capacity. Thus, the idea of a stable vSTM component has to be changed into a variable and modifiable vSTM component with a capacity determined by basic visual features. If the capacity of vSTM can be modulated by such simple changes in features, theories of visual selection neglecting vSTM influences have to be updated to incorporate the possibility of capacity changes according to certain top-down influences or bottom-up changes. Since vSTM is a very important component for everyday normal functioning and the experiments presented here revealed vSTM capacity's susceptibility to influence, it is highly probable that it can be increased by training. It is very important to train children's brains while they are still developing and this furthermore opens up the possibility to train and improve short-term memory capacity in people suffering from short-term memory problems (Gathercole & Alloway, 2006).

Investigating specific characteristics of the TVA revealed interesting results. The processing of stimulus repetitions (the same letter was presented twice) in one and the same trial decreased the capacity of vSTM. The result was unexpected since it was assumed that it should be easier for the vSTM system to store two same items than multiple different items. It seems that all available slots in vSTM are occupied by target items; however, the total amount of information was reduced by the doubled letter. Alternatively, the neighbouring doubled letters could mask themselves and therefore prevent themselves from being processed. The same stimulus in the same trial could increase the demands on vSTM and therefore performance drops. Interestingly, processing speed was increased if two same targets were presented in one trial. Processing was therefore facilitated by repeating the stimulus in the same trial. Although there was a higher processing speed, vSTM capacity was decreased. The two same stimuli seem to remove a huge amount of capacity which is then not available any more for the remaining targets. The differing results favour the assumption of the independence of processing speed and vSTM capacity (e.g., Bundesen, 1990; Finke et al., 2005).

Different spatial positions of the target items cannot influence the spatial parameters of the TVA. However, again, vSTM capacity and the processing speed were significantly affected. According to Carrasco, Evert, Chang and Katz (1995) detection of targets in feature or conjunction search tasks becomes increasingly less efficient as the target is presented at more distant field eccentricities. However, if the stimuli are cortically magnified this effect could be flattened out (Carrasco & Frieder, 1997). Using the same computation of the cortical magnification factors as Carrasco and Frieder (1997) the size of letters on the three different spatial positions increased. Following the paper of Carrasco and Frieder (1997) no effects on the performance reflected in percent correct values and the different attentional components should be found. However, the general information processing components of the TVA were affected by different spatial positions, although corrected by cortical magnification. More precisely, the processing speed was significantly higher in the nearest position to the fixation cross compared to the farthest spatial position. Therefore, it seems that the spatial position of targets has a remarkable influence on performance in the attentional components of the TVA (Bundesen, 1990) and that the components are not as independent from spatial variations as assumed. This detoriation effect with increasing distance from fixation cross should be even more pronounced if the stimuli are not magnified. To confirm these findings the same experiments must be made without the magnification correction.

In the last experiment, the effects on the components of the TVA of exactly the same letters in exactly the same positions presented in pairs of consecutive trials were tested. For controlling if these possible effects are due to only the same letters or to the exactly same positions, same letters were presented at different positions in two consecutive trials. Furthermore, another question the experiments dealt with was whether the size of the used (letter-)stimuli (uppercase or lowercase) influences the effects of presenting same letters in same positions or same letters in different positions in pairs of consecutive trials. The general information processing components can be enhanced through the repetition of exactly the same letters. The system seems to be able to maintain the activation for the stimuli and their position on the actual trial facilitating the selection performance in the following trial. Since neither size nor position changes did affect the performance reflected in the different attentional components of the TVA (Bundesen, 1990), the results argue for processing of the experimental stimuli in the high conceptual processing stages. The concept of a certain letter is enough for recognizing the letter regardless of it being in upper or lower case.

Concluding the findings of the last three experiments, the repetition of the same target in one trial, the spatial position of the stimuli and the repetition of exactly the same letters in exactly the same location could affect the components of the TVA. Components of the TVA are therefore not really completely independent of basic visual influences. Testing with TVA based methods therefore requires care in the selection of the stimuli, their arrangement, their features and in the interpretation of the results in relation to other TVA based studies.

In investigating certain disturbances of the categorization process, participants with Asperger's syndrome were investigated with a series of different visual search tasks. People with autism spectrum disorders were repeatedly tested with various visual tasks and they consistently outperformed healthy control groups. In the present study the group of people with Asperger's syndrome revealed significantly faster reaction times and a more efficient search process. Their search process seems indeed to be expedited relative to healthy controls. In the feature search task, there might be a popout component in target-present trials but not in target-absent trials in the Asperger's group. The idea of a component of popout is supported by the finding that y-axis intercepts (i.e., time required to structure the display) show a tendency to differ between the two groups. Despite the popout explanation, the RT advantage in target-present and target-absent trials could also suggest that the process of matching the item currently under the focus of attention to the target description is achieved faster in the Asperger's group compared to healthy controls.

In the conjunction search task, again, the search was more efficient in participants with Asperger's syndrome than in controls. The process of scanning items and matching with the target template is more efficient in Asperger's than in controls. Support to this assumption comes from the significantly lower search rates per item in the Asperger's group in target-present as well as target-absent trials. In the conjunction search task popout does not contribute to target detection. The Asperger's group seems to be able to reject the set of non-target items not corresponding to the target colour which in turn generates a popout on the form/shape dimension. Controls can not adopt this strategy in the conjunction search task when the target is defined in a combination of colour and shape, and cannot reject non-targets as groups. For testing the hypothesis of rejecting non-targets as groups, a visual marking (e.g., Watson & Humphreys, 1997; Watson, Humphreys & Olivers, 2003) experiment could be conducted. Visual marking stands for prioritized selection for new objects by top-down attentional inhibition of old objects. Watson et al. introduced in a visual search experiment a time interval (gap) between the distractors from the one set and presented the target (if present) with the second set of distractors. Thus, the two distractor groups were presented successively, rather than at the same time as in a standard search task. The aim of the experiment was to examine if observers could use the gap to separate the old from the new distractors and thus select the target as a single-feature relatively to the second set of distractors. Comparing the performance of normal subjects to the performance of subjects with Asperger's syndrome, a performance benefit for the Asperger's group should arise if they are able to better reject non-targets as groups.

Since the Asperger's group seems to possess a different method of processing visual stimuli relative to healthy controls, the question should be examined whether the difference can be localized at early visual (pre-selective) or late (post-selective) processing stages. The first follow-up experiments suggest - since using redundant target paradigms for testing potential early processing differences showed no difference between a group of people with Asperger's syndrome compared to healthy controls - that the advantage found in the feature and conjunction search tasks is not rooted in an additional advantage arising at early levels of feature encoding or representation. In testing a potential late processing difference, the Asperger group showed interesting results patterns. Using trial-by-trial cueing of the target-defining dimension in visual search tasks combined with inter-trial changes or repetitions of target-defining dimensions showed that the Asperger's were massively disturbed by the invalid information, irrespective of a dimension change or not. In controls, if the cue was invalid and the target-defining dimension changed across trials, there was a system reset, resulting in faster RTs compared to neutral conditions. Since the Asperger's pattern was different in this experiment, I assumed that the performance difference can be located in late processing stages such as object identification or object recognition. However, since the control group was depicted from the paper of Müller, Reimann and Krummenacher (2003) the results should be considered as preliminary. In order to validate the assumptions based on the differences between the Asperger's group and the control group investigated by Müller, Reimann and Krummenacher (2003) it is absolutely necessary to collect data from an age- and gender-matched healthy control group.

The conducted experiments showed that the pattern of performance of the Asperger's group – although expedited overall – is quantitatively comparable to the pattern of healthy observers. Semantic performance (cue) affects the performance of the Asperger's group; however, the pattern of effects is remarkably different from that observed in healthy controls.

Since in the present search experiments no significant differences were found in search tasks using simple bar items the question arises whether the better performance of the Asperger's group might be due to the stimulus material used. Therefore, the influences of the highly overlearned letter targets on search performance were investigated by using different complex objects, namely pseudo-letters. In these two experiments (a feature and a conjunction search task) no performance difference could be found. Overall search performance and thus performance differences are modulated by the stimulus material used. If pseudo-letters are considered complex, and, importantly, not overlearned stimuli, it can be concluded that complex stimuli are processed no faster in people with Asperger's syndrome than in healthy observers. The difference in processing between the two groups is probably, at least partially, due to the fact that the letter stimuli are highly overlearned.

Summing up, the processing difference in Asperger's can be located in late processing steps of object identification or object recognition (influences of the cues) and performance difference might be partially due to the letters used in the studies. Furthermore to argue for the hypothesis that better performance in Asperger's is due to the highly-overlearned letters the researcher attempted to test this group with the TVA-based methods 'whole report' and 'partial report'. Testing the Asperger's group with whole and partial report was almost impossible. No exposure duration could be found, at which the participants could not report every letter presented in the display. In a next step, the Asperger's group should be tested with a whole report experiment including more than the five standard letters. Probably, the vSTM capacity for the overlearned letter stimuli might be remarkably increased in observers with Asperger's syndrome, eventually partially explaining their enhanced performance in visual search tasks with letters.

Further research is required to test all the mentioned assumptions. Eye movement (EM) patterns and electroencephalographic (EEG) data could help in further determining processing differences. The Asperger's group might probably show a different eye movement pattern or different activations in EEG compared to healthy observers. For locating the cortical areas of the processing differences, EEG might be useful. The EM and EEG results together with the above mentioned additional behavioural experiments could contribute to a clarification and explanation of the processing differences between the two groups.

The last project investigated the development of the categorization process and therefore the development in the component processes of selective visual attention proposed by Bundesen (1990) in three different age groups (first-, second- and third-graders) with TVA-based testing procedures. Children showed not only significant increases in their processing speed, but also in their vSTM capacity with increasing age. Capacity and processing speed in third-graders were significantly higher than in second- and first-graders. Interestingly, first- and second-graders' capacities and processing speeds did not differ significantly, suggesting a significant increase in these two components at around age 9. Both general information processing components seem to develop simultaneously. Processing speed and capacity values are only slightly worse than in adults doing the same whole and partial report task. However, in a next step, fourth- and fifth-graders need to be investigated for identifying the age at which the performance of children approximates the performance of adults.

The efficiency of top-down control, that is, the ability to prioritize target relative to non-target items by voluntarily allocating processing resources to targets, is also more developed with increasing age. However, there was only a significant difference between the third- and first-graders, not between third- and second-graders as in the development of processing speed or capacity of vSTM. Top-down control seems to develop more slowly and more steadily over a longer period of time. Importantly, it also implies that there is dissociation in development between general information processing components associated with encoding and representing visual information and spatial processing components biasing visual representations.

The age-dependent differences observed in this study are in accordance with previous results reported in the literature (e.g., Gathercole, 1999; Kail, 1991a; Dempster, 1992). The important difference lies in the advantage of using the framework of Bundesen's (1990) TVA and the whole and partial report methods: All of the different component processes can be assessed in one comparably highly time-efficient approach.

The global trend hypothesis proposed by Hale (1990), claiming that all components of information processing develop simultaneously and development occurs with similar rates in all components, can be broadened. The global trend hypothesis was restricted to cognitive processing speed. In this study, not only processing speed components, but also the capacity of vSTM and the selection effectiveness were shown as developing over childhood. Therefore, the hypothesis can be expanded by assuming that not only the components of the processing speed but also the capacity of vSTM increase with increasing age. However, they are not developing at a similar rate. Top-down control develops at a slower pace and over a longer period of time. Clearly, more research is required to decide whether top-down control develops in synchrony with other cognitive components or independently.

Interestingly, recognition rate drops dramatically if a secondary target stimulus in the partial report is presented. Performance is then only at around 20%. The drop was most severe in first- and second-graders compared to third-graders. Third-graders have either a larger pool of processing resources available for allocating to multiple targets or they are better able to distribute the processing resources more efficiently to multiple targets. Since top-down control is also more efficient in third-graders compared to the other age groups, the second interpretation is more probable. Since adults have almost no problem with a secondary target, the question arises, at which point in their development does the performance of children approximate the performance of adults. Therefore, the next age groups should be investigated.

One potential fruitful application of the procedure is in examining the causes of attention disorders. Preliminary results of a limited small sample of children diagnosed with attention deficit hyperactivity disorder (ADHD) suggest that their selection effectiveness is impaired relative to healthy age-matched children. Clearly, further subjects with ADHD need to be investigated to test the preliminary assumption of a worse top-down control compared to healthy control children and to identify possible causes for ADHD. It would furthermore be very instructive to additionally record the eye movements of the children and compare them to the eye movements of healthy age-matched children.

With this thesis I wanted to contribute to the understanding of the complex categorization process, discussed in almost every theory of visual selective attention. The foundations, disturbances in a particular neuropsychological group and the development of this process could clearly reveal the importance for visual selective attention.

7. References

Allport, D.A. (1971). Parallel encoding within and between elementary stimulus dimensions. *Perception & Psychophysics, 10,* 104–108.

Allport, D.A. (1980). Patterns and actions: cognitive mechanisms are content-specific. In G. Claxton (Ed.), *Cognitive Psychology: new directions*. London: Routledge & Kegan Paul.

Alvarez, G.A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science*, *15* (2), 106-111.

Alvarez, G.A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual hemifields. *Psychological Science, 16* (8), 637-643.

American Psychiatric Association. (1994). *Diagnostic and Statistical Manual of Mental Disorders*. Washington, DC: American Psychiatric Association.

Austin, E. (2004). Personality correlates of the broader autism phenotype as assessed by the Autism Spectrum Quotient (AQ). *Personality and Individual Differences, 38* (2), 451-460.

Baddeley, A.D., & Hitch, G. (1974). Working memory. In G.H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47-89). New York: Academic Press.

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The Autism-Spectrum Quotient (AQ): evidence from Asperger syndrome/high functioning autism, males and females, scientists and mathematicians. *Journal of Autism and Developmental Disorders, 31,* 5-17.

Bertone, A., Mottron, L., Jelenic, P., & Faubert, J. (2005). Enhanced and diminished visuo-spatial information processing in autism depends on stimulus complexity. *Brain, 128*, 2430-2441.

Biever, C. (2007). Web removes social barriers for those with autism. *New Scientist, 2610*, 26-27.

Bishop, D.V.M., Maybery, M., Maley, A., Wong, D., Hill, W., & Hallmayer, J. (2004). Using self-report to identify broad phenotype in parents of children with autistic spectrum disorders: a study using the Autism-Spectrum Quotient. *Journal of Child Psychology and Psychiatry, 45* (8), 1431-1436.

Broadbent, D.E. (1958). *Perception and communication.* London: Pergamon.

Broadbent, D.E. (1971). *Decision and stress*. Oxford, UK: Academic Press.

Broadbent, D.E. (1982). Failures of attention in selective listening. *Journal of Experimental Psychology, 44*, 428-433.

Bundesen, C. (1987). Visual attention: Race models for selection from multielement displays. *Psychological Research, 49,* 113-121.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97* (4), 523-547.

Bundesen, C., & Habekost, T. (2008). *Principles of Visual Attention: Linking Mind and Brain*. Oxford: Oxford University Press.

Bundesen, C., Habekost, T., & Kyllingsbæk, S. (2005). A neural theory of visual attention: Bridging Cognition and Neurophysiology. *Psychological Review, 112* (2), 291-328.

Bundesen, C., Pedersen, L.F., & Larsen, A. (1984). Measuring efficiency of selection from briefly exposed visual displays: a model for partial report. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 329-339.

Bundesen, C., Shibuya, H., & Larsen, A. (1985). Visual selection from multielement displays: A model for partial report. In M.I. Posner & O.S.M. Matin (Eds.), *Attention and Performance XI* (pp. 631-649). Hillsdale, NJ: Erlbaum.

Burgund, E.D., & Abernathy, A.E. (2008). Letter-specific processing in children and adults matched for reading level. *Acta Psychologica, 129*, 66-71.

Carrasco, M., Evert, D.L., Chang, I., & Katz, S.M. (1995). The eccentricity effect: Target eccentricity affects performance on conjunction searches. *Perception and Psychophysics, 57* (8), 1241-1261.

Carrasco, M., & Frieder, K.S. (1997). Cortical magnification neutralizes the eccentricity effect in visual search. *Vision Review, 37* (1), 63-82.

Cave, K.R., & Wolfe, J.M. (1990). Modelling the role of parallel processing in visual search. *Cognitive Psychology, 22* (2), 225-271.

Chakravarthi, R., & Cavanagh, P. (2009). Bilateral field advantage in visual crowding. *Vision Research, 49*, 1638-1646.

Cherry, E.C. (1953). Some experiments on the recognition of speech, with one and with two ears. *Journal of the Acoustical Society of America, 25*, 975-979.

Chuah, Y.M.L., & Maybery, M.T. (1999). Verbal and spatial short-term memory: common sources of developmental change? *Journal of Experimental Child Psychology, 73*, 7-44.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*, 87-185.

Crick, F. (1984). Function of the thalamic reticular complex: the searchlight hypothesis. *Proceedings of the National Academy of Sciences, 81* (14), 4586-4590.

Comalli, P.E., Wapner, S., & Werner, H. (1962). Interference effects of the Stroop color-word test in children, adulthood, and aging. *Journal of Genetic Psychology, 100*, 47-53.

Cowan, N., Nugent, L.D., Elliott, E.M., Ponomarev, I., & Saults, J.S. (1999). The role of attention in the development of short-term memory: age differences in the verbal span of apprehension. *Child Development, 70* (5), 1082-1097.

Davidson, M.C., Amso, D., Anderson, L.C., & Diamond, A. (2006). Developments of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia, 44*, 2037-2078.

Davis, G., & Driver, J. (1998). Kanizsa subjective figures can act as occluding surfaces at parallel stages of visual search. *Journal of Experimental Psychology: Human Perception and Performance, 24* (1), 169-184.

Day, M.C. (1978). Visual search by children: The effect of background variation and the use of visual cues. *Journal of Experimental Child Psychology, 25*, 1-10.

Dempster, F.N. (1981). Memory span: Sources of individual and developmental differences. *Psychological Bulletin, 89* (1), 63-100.

Dempster, F.N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review, 12*, 45-75.

Dempster, F.N., & Corkill, A. (1999). Individual differences in susceptibility to interferences and general cognitive ability. *Acta Psychologica, 101*, 395-416.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18*, 193-222.

Deutsch, J.A., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review, 70*, 80-90.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General, 113*, 501–517.

Duncan, J., Bundesen, C., Olson, A., Humphreys, G., Chavada, S., & Shibuya, H. (1999). Systematic analysis of deficits in visual attention. *Journal of Experimental Psychology: General, 128* (4), 450-478.

Duncan, J., Bundesen, C., Olson, A., Humphreys, G., Ward, R., Kyllingsbæk, S., von Raamsdonk, M., Rorden, C., & Chavda, S. (2003). Dorsal and ventral simultanagnosia. *Cognitive Neuropsychology, 20*, 675-701.

Duncan J., & Humphreys, G.W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*, 433-458.

Duncan, J., & Humphreys, G.W. (1992). Beyond the search surface: Visual search and attentional engagement. *Journal of Experimental Psychology: Human Perception and Performance, 18* (2), 578-588.

Duncan, J., Bundesen, C., Olson, A., Humphreys, G., Chavada, S., & Shibuya, H. (1999). Systematic analysis of deficits in visual attention. *Journal of Experimental Psychology: General, 128* (4), 450-478.

Duncan, J., Humphreys, G., & Ward, R. (1997). Competitive brain activity in visual attention. *Current Opinion in Neurobiology, 7* (2), 255-261.

Egeth, H., & Lamy, D. (2003). Attention. In I. B. Weiner (Ed.), *Handbook of Psychology*, Vol. 12. Hoboken, New Jersey: Wiley & Sons, Inc.

Ehlers, S., Nydén, A., Gillberg, C., Dahlgren, S.-O., Hjelmquist, E., & Odén, A. (1997). Asperger Syndrome, Autism and attention disorders: A comparative study of the cognitive profiles of 120 children. *Journal of Child Psychiatry, 38* (2), 207-217.

Elliott, R. (1970). Simple reaction time: Effects associated with age, preparatory interval, incentive-shift and mode of presentation. *Journal of Experimental Child Psychology, 9* (1), 86-107.

Fecteau, J.H., & Munoz, D.P. (2006). Salience, relevance, and firing: a priority map for target selection. *Trends in Cognitive Sciences, 10* (8), 382-390.

Finke, K., Bublak, P., Dose, M., Müller, H.J., & Schneider, W.X. (2006). Parameter-based assessment of spatial and non-spatial attentional deficits in Huntington's disease. *Brain, 129*, 1137-1151.

Finke, K., Bublak, P., Krummenacher, J., Kyllingsbæk, S., Müller, H.J., & Schneider, W.X. (2005). Usability of a theory of visual attention (TVA) for parameter-based measurement of attention I: evidence from normal subjects. *Journal of the International Neuropsychological Society, 11*, 832-842.

Finke, K., Schneider, W.X., Redel, P., Dose, M., Kerkhoff, G., Müller, H.J., & Bublak, P. (2007). The capacity of attention and simultaneous perception of objects: a group study of Huntington's disease patients. *Neuropsychologia, 45*, 3272-3284.

Found, A., & Müller, H.J. (1996). Searching for unknown feature targets on more then one dimension: Further evidence for a dimension weighting account. *Perception and Psychophysics, 58* (1), 88-101.

Frith, C. (1989). *Autism: Explaining the enigma*. Oxford: Blackwell.

Gathercole, S.E., & Alloway, T.P. (2006). Practitioner Review: Short-term and working memory impairments in neurodevelopmental disorders: diagnosis and remedial support. *Journal of Child Psychology and Psychiatry, 47* (1), 4-15.

Guttentag, R.E. (1985). A developmental study of attention to auditory and visual signals. *Journal of Experimental Child Psychology, 35*, 56-80.

Habekost, T., & Rostrup, E. (2007). Visual attention capacity after right hemisphere lesions. *Neuropsychologia, 44*, 876-895.

Hale, S. (1990). A global developmental trend in cognitive processing speed. *Child Development, 61* (3), 653-663.

Happé, F.G.E. (1994). Wechsler IQ profile and theory of mind in autism: a research note. *Journal of Child Psychology and Psychiatry, 35*, 1461-1471.

Happé, F.G.E., & Frith, U. (2006). The weak coherence account: detailed-focused cognitive style in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 36* (1), 5-25.

Harnishfeger, K.K. (1995). The development of cognitive inhibition: Theories, definitions, and research evidence. In F.N. Dempster (Ed.), *Interference and inhibition in cognition* (pp. 175-204). London: Academic Press.

Hollingworth, A., Richard, A.M., & Luck, S.J. (2008). Understanding the function of visual short-term memory: Transsaccadic memory, object correspondence, and gaze correction. *Journal of Experimental Psychology: General, 137* (1), 163–181.

Hommel, B., Li, K.Z.H., & Li, S.-C. (2004). Visual search across life span. *Developmental Psychology, 40* (4), 545-558.

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research, 40* (10-12), 1489-1506.

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience, 2*, 1-11.

Johnston, W.A., & Heinz, S.P. (1978). Flexibility and capacity demands of attention. *Journal of Experimental Psychology: General, 107*, 420-435.

Johnstone, S.J., Dimoska, A., Smith, J.L., Barry, R.J., Pleffer, C.B., Chiswick, D., & Clarke, A.R. (2007). The development of stop-signal and go/no-go response inhibition in children aged 7-12 years: Performance and event-related potential indices. *International Journal of Psychophysiology, 63*, 25-38.

Jolliffe, T., & Baron-Cohen, S. (1997). Are people with autism and Asperger syndrome faster than normals on the Embedded Figures Test? *Journal of Child Psychology & Psychiatry & Allied Disciplines, 38* (5), 527-534.

Kail, R. (1986). Sources of age differences in speed of processing. *Child Development, 57* (4), 969-987.

Kail, R. (1991a). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin, 109* (3), 490-501.

Kail, R. (1991b). Processing time declines exponentially during childhood and adolescence. *Developmental Psychology, 27* (2), 259-266.

Kail, R. (1992). Processing speed, speech rate, and memory. *Developmental Psychology, 28*, 899-904.

Kail, R. (2002). Developmental change in proactive interference. *Child Development, 73* (6), 1703-1714.

Kail, R., & Hall, L.K. (1994). Processing speed, naming speed, and reading. *Developmental Psychology, 30* (6), 949-954.

Kail, R., & Park, Y.-S. (1994). Processing time, articulation time, and memory span. *Journal of Experimental Child Psychology, 57*, 281-291.

Kail, R., & Salthouse, T.A. (1994). Processing speed as a mental capacity. *Acta Psychologica, 86*, 199-225.

Kerr, B., Blanchard, C., & Miller, K. (1980). Children's use of sequence information in partially predictable reaction-time sequences. *Journal of Experimental Child Psychology, 29*, 529-549.

Kerr, B., Davidson, J., Nelson, J., & Haley, S. (1982). Stimulus and response contributions to the children's reaction-time repetition effect. *Journal of Experimental Child Psychology, 34*, 526-541.

Klin, A. (2003). Asperger Syndrome: an update. *Revista Brasileira de Psiquatria, 25* (2), 103-109.

Klin, A. (2006). Autism and Asperger Syndrome: an overview. *Revista Brasileira de Psiquiatria*, *28* (supl I), 3-11.

Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: towards the underlying neural circuitry. *Human Neurobiology, 4* (4), 219-227.

Kraft, A., Müller, N.G., Hagendorf, H., Schira, M.M., Dick, S., Fendrich, R.M., Brandt, S.A. (2005). Interactions between task difficulty and hemispheric distribution of attended locations: implications fort he splitting attention debate. *Cognitive Brain Research, 24*, 19-32.

Krummenacher, J., Müller, H.J., & Heller, D. (2001). Visual search for dimensionally redundant pop-out targets: Evidence for parallel-coactive processing of dimensions. *Perception & Psychophysics, 63*, 907-917.

Krummenacher, J., Müller, H.J., & Heller, D. (2002). Visual search for dimensionally redundant pop-out targets: Parallel-coactive processing of dimensions is location-specific. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 1303-1322.

Kurita, H., Koyama, T., & Osada, H. (2005). Autism-Spectrum Quotient-Japanese version and its short forms for screening normally intelligent persons with pervasive developmental disorders. *Psychiatry and Clinical Neurosciences, 59*, 490-496.

Kuhn, G., & Land, M.F. (2006). There's more to magic than meets the eye. *Current Biology, 16* (22), 950-951.

Kyllingsbæk, S. (2006). Modeling visual attention. *Behavior Research Methods, 38* (1), 123-133.

Lauth, G.W. (1993). DAT. Dortmunder Aufmerksamkeitstest. Göttingen: Hogrefe.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 21* (3), 451-468.

Lobaugh, N.J., Cole, S., & Rovet, J.F. (1998). Visual search features and conjunctions in development. *Canadian Journal of Experimental Psychology, 52* (4), 201-211.

Logan, G. (1996). The CODE theory of visual attention: An integration of space-based and object-based attention. *Psychological Review, 103* (4), 603-649.

Luce, R.D. (1959). *Individual choice behavior*. New York: Wiley.

Luce, R.D. (1963). Detection and recognition. In R.D. Luce, R.R. Bush, & E. Galanter (Eds.), *Interaction: Perception, development and cognition* (pp. 203-230). Hillsdale, NJ: Erlbaum.

Makovski, T., & Jiang, Y.V. (2007). Distributing versus focusing attention in visual short-term memory. *Psychonomic Bulletin & Review, 14* (6), 1072–1078.

Maljkovic, V., & Nakayama, K. (1994). Priming of popout: I. Role of features. Memory and *Cognition, 2* (6), 657-672.

Maljkovic, V., & Nakayama, K (1996). Priming of pop-out: II. The role of position. *Perception & Psychophysics, 58,* 977-991.

Maljkovic, V., & Nakayama, K. (2000). Priming of pop-out: III. A short-term implicit memory system beneficial for rapid target selection*. Visual Cognition, 7,* 571-595.

Marois, R., & Ivanoff, J. (2005). Capacity limits of information processing in the brain. *Trends in Cognitive Science, 9* (6), 296-305.

Marr, D. (1982). *Vision. A Computational Investigation into the Human Representation and Processing of Visual Information*. New York: Freeman.

Matsukura, M., Luck, S.J., & Vecera, S.P. (2007). Attention effects during visual short-term memory maintenance: Protection or prioritization? *Perception and Psychophysics, 69* (8), 1422-1434.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*, 81-97.

Miller, J. (1982). Divided attention: Evidence for co-activation with redundant signals. *Cognitive Psychology, 14*, 247-279.

Miller, J., & Lopes, A. (1988). Testing race models by estimating the smaller of two true mean reaction times: An analysis of estimation bias. *Perception and Psychophysics, 44*, 513-524.

Moosbrugger, H., & Oehlschlägel, J. (1996). Frankfurter Aufmerksamkeitsinventar. Bern, Göttingen: Huber.

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology, 11*, 56-60.

Mottron, L., & Belleville, S. (1993). A study of perceptual analysis in a high-level autistic subject with exceptional graphic abilities. *Brain and Cognition, 23*, 279-309.

Mottron, L., Burack, J.A., Iarocci, G., Belleville, S., & Enns, J.T. (2003). Locally oriented perception with intact global processing among adolescents with high-functioning autism: evidence from multiple paradigms. *Journal of Child Psychology and Psychiatry, 44* (6), 904-913.

Mottron, L., Drawson, M., Soulieres, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: an update, and eight principles of autistic perception. *Journal of Autism and Developmental Disorders, 36* (1), 27-43.

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature discriminations. *Perception & Psychophysics, 57*, 1-17.

Müller, H.J., & O'Grady, R.B. (2000). Dimension-based visual attention modulates dual-judgment accuracy in Duncan's (1984) one- versus two-object report paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 26* (4), 1332-1351.

Müller, H.J., & Rabbitt, P.M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15* (2), 315-330.

Müller, H.J., Reimann, B., & Krummenacher, J. (2003). Visual search for singleton feature targets across dimensions: Stimulus and expectancy-driven effects in dimensional weighting. *Journal of Experimental Psychology: Human Perception and Performance, 29* (5), 1021–1035.

Neisser, U. (1964). Visual search. *Scientific American, 210*, 94-102.

Neisser, U., & Beller, H.K. (1965). Searching through word lists. *British Journal of Psychology, 56* (4), 349-358.

Nubel, K., Starzacher, E., & Grohmann, G. (2006). *CAPT. Continuous Attention Performance Test.* Göttingen: Hogrefe.

Nydén, A., Gillberg, C., Hjelmquist, E., & Heiman, M. (1999). Executive Function/attention deficits in boys with Asperger syndrome, attention disorder and reading/writing disorder. *Autism, 3* (3), 213-228.

O'Riordan, M. A. (2004). Superior visual search in adults with autism. *Autism, 8,* 229-248.

O'Riordan, M., & Plaisted, K. (2001). Enhanced discrimination in autism. *The Quarterly Journal of Experimental Psychology, 54A* (4), 961-979.

O'Riordan, M., Plaisted, K., Driver, J., & Baron-Cohen, S. (2001). Superior visual search in autism. *Journal of Experimental Psychology: Human Perception and Performance, 27* (3), 719-730.

Ozonoff, S., Pennington, B.F., & Rogers, S.J. (1991). Executive function deficits in high functioning autistic individuals: Relationship to theory of mind. *Journal of Child Psychology and Psychiatry, 32*, 1081-1105.

Peers, P.V., Ludwig, C.J.H., Rorden, C., Cusack, R., Bonfiglioli, C., Bundesen, C., Driver, J., Antoun, N., & Duncan, J. (2005). Attentional functions of parietal and frontal cortex. *Cerebral Cortex, 15*, 1469-1484.

Plaisted, K., O'Riordan, M., & Baron-Cohen, S. (1998a). Enhanced discrimination of novel, highly similar stimuli by adults with autism during a perceptual learning task. *Journal of Child Psychology and Psychiatry*, *39*, 765-775.

Plaisted, K., O'Riordan, M., & Baron-Cohen, S. (1998b). Enhanced visual search for a conjunctive target in autism: A research note. *Journal of Child Psychology and Psychiatry, 39,* 777-783.

Posner, M. I. (1980). Orienting of attention. The VIIth Sir Frederic Bartlett Lecture. *Quarterly Journal of Experimental Psychology, 32*, 3-25.

Posner, M.I., & Snyder, C.R. (1975). Attention and cognitive control. In R.L. Solso (Ed.), *Information processing and cognition: The Loyola symposium* (pp. 55-85). Hillsdale, NJ: Lawrence Erlbaum Associates.

Pritchard, V.E., & Neumann, E. (2009). Avoiding the pitfalls of using negative priming tasks in developmental studies: assessing inhibitory control in children, adolescents, and adults. *Developmental Psychology, 45* (1), 272-283.

Rose, S.A., Feldman, J.F., & Jankowski, J.J. (2001). Visual short-term memory in the first year of life. Capacity and recency effects. *Developmental Psychology, 37*, 539-549.

Rovamo, J., & Virsu, V. (1979). An estimation and application of the human cortical magnification factor. *Experimental Brain Research, 37*, 495-510.

Rumelhart, D.E. (1970). A multicomponent theory of the perception of briefly exposed visual displays. *Journal of Mathematical Psychology, 7*, 191-218.

Schatz, A.M., Weimer, A.K., & Trauner, D.A. (2002). Brief report: Attention differences in Asperger syndrome. *Journal of Autism and Developmental Disorders, 32* (4), 333-336.

Shah, A., & Frith, U. (1993). An islet of ability in autistic children: A research note. *Journal of Child Psychology and Psychiatry, 24*, 613-620.

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*, 591-600.

Sligte, I.G., Scholte, H.S., & Lamme, V.A.F. (2008). Are there multiple visual short-term memory stores? *PLoS ONE 3*(2), 1699.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs, 74* (11), 1-29.

Sperling, G. (1963). A model for visual memory tasks. *Human Factors, 5*, 19-31.

Sperling, G. (1967). Successive approximations to a model for short-term memory. *Acta Psychologica, 27*, 285-292.

Spreen, O., & Benton, A.L. (1969). Embedded Figures Test. Neuropsychological Laboratory, University of Victoria, Victoria, BC.

Tipper, S.P. (1985). The negative priming effect: Inhibitory priming by ignored objects. *Quarterly Journal of Experimental Psychology,* 37 (A), 571-590.

Treisman, A.M. (1960). Contextual cues in selective listening. *Quarterly Journal of Experimental Psychology, 12*, 242-248.

Treisman, A.M. (1964). Selective attention in man. *British Medical Bulletin, 20*, 12-16.

Treisman, A.M. (1969). Strategies and models of selective attention. *Psychological Review, 76*, 282–299.

Treisman, A.M. (1988). Features and objects: The 14th Barlett Memorial Lecture. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 40* (A), 201–237.

Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology, 12*, 97-136.

Treisman, A.M., & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance, 16* (3), 459-478.

Treisman, A.M., & Schmidt, H. (1982). Illusory conjunctions in the perception of objects. *Cognitive Psychology, 14*, 107-141.

Van Oeffelen, M.P., & Vos, P.G. (1982). Configurational effects on the enumeration of dots: Counting by groups. *Memory and Cognition, 10*, 396-404.

Virsu, V., & Rovamo, J. (1979). Visual resolution, contrast sensitivity, and the cortical magnification factor. *Experimental Brain Research, 37*, 475-494.

Watson, D.G., & Humphreys, G.W. (1997). Visual marking: Prioritizing selection for new objects by top-down attentional inhibition. *Psychological Review, 104*, 90-122.

Watson, D.G., Humphreys, G.W., & Olivers, C.N.L. (2003). Visual marking: using time in visual selection. *Trends in Cognitive Sciences, 7* (4), 180-185.

Welford, A.T. (1952). The ‘psychological refractory period’ and the timing of high-speed performance – a review and a theory. *British Journal of Psychology, 43*, 2-19.

Wickens, C.D. (1974). Temporal limits of human information processing: a developmental study. *Psychological Bulletin, 81*, 739-755.

Wilson, J.T., Scott, J.H., & Power, K.G. (1987). Developmental differences in span of visual memory for pattern. *British Journal of Developmental Psychology, 5*, 249-255.

Wing, A., & Allport, D.A. (1972). Multidimensional encoding of visual form. *Perception & Psychophysics, 12* (6), 474-476.

Wolfe, J.M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review, 1* (2), 202-238.

Wolfe, J.M. (2007). Guided Search 4.0: Current Progress with a model of visual search. In W. Gray (Ed.), *Integrated Models of Cognitive Systems*. New York: Oxford.

Wolfe, J.M., Cave, K.R., & Franzel, S.L. (1989). Guided Search: An alternative to the Feature Integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 419-433.

Woodbury-Smith, M.R., Robinson, J., Wheelwright, S., & Baron-Cohen, S. (2005). Screening adults for Asperger syndrome using the AQ: A preliminary study of its diagnostic validity in clinical practice. *Journal of Autism and Developmental Disorders, 35 (3),* 331-335.

World Health Organisation. (1994). *The International Classification of Diseases (Classification of Mental and Behavioural Disorders)*, 10th Edition. Geneva: World Health Organization.

Zehetleitner, M., Krummenacher, J., & Müller, H.J. (2009). The detection of feature singletons defined in two dimensions is based on salience summation, rather than on serial exhaustive or interactive race architectures. *Attention, Perception, & Psychophysics, 71* (8), 1739-1759.

Zelazo, P.D., Craik, F.I.M., & Booth, L. (2004). Executive functions across life span. *Acta Psychologica, 115*, 167-183.

8. Acknowledgements

I have been indebted in the preparation of this thesis to my supervisor, Prof. Dr. Joseph Krummenacher of the University of Fribourg, whose academic experience, have been invaluable to me. He shared with me a lot of his expertise and research insight. Joe has made available his support in a number of ways. I also like to express my gratitude to Prof. Dr. Hermann Müller, who kindly agreed to review this thesis.

I am deeply grateful to the Swiss National Science Foundation for the trust and support that they gave me in order to do my doctoral studies in Switzerland.

At the Department of Psychology, I owe my deepest graditude to my PhD colleague Alain Chavaillaz for many fruitful discussions, fun when both of us were not able to work any further, for helping me in my ongoing struggle with Matlab and Authorware and for much more. Patrick, Anna (special thanks for the emotional support in the last days), Ester, Jonas, Anna H. for nice discussions and for the good collaboration all the time. Special thanks to Jonas for helping us with technical problems and his big humour when our online-lab did repeatedly not work and I was on the verge of going crazy. Especially in the last weeks when finishing this thesis seemed so impossible, thank you Patrick for all your entertaining and encouraging actions. The guys from general psychology, namely Prof. Dr. Oswald Huber, Arlette Bär and Odilo Huber for drinking coffee with us every morning at 9:45. It was furthermore a pleasure to work together with my enthusiastic and highly motivated master student Eva. We had a great time not only during testing almost 70 children together at different primary schools but also in the remaining time.

Outside the Fribourg University, I benefitted from discussions and helpful advices from Prof. Dr. Kathrin Finke and Petra Redel (thank you for letting me test your Munich students) and from discussions in our inter-university graduate school with Prof. Dr. Fred Mast, Prof. Dr. Dirk Kerzel, Prof. Dr. Michael Herzog, and Prof. Dr. Friedrich Wilkening. In this context, I would like to thank especially Sabine Born, David Souto, Luzia Grabherr, Marco Boi, Christoffer Aberg, and Bilge Sayim for making the workshops and summer schools a good time. I enjoyed the company and support of many others whom I fail to mention here, and I'm thankful for your help and friendship.

Even though I had a good time at work, I could not have coped without some time off. Chrissie and Andrea S. persuaded me often to turn off the computer and have a drink (especially Andrea S. for going out when it was Friday evening at 22:00 and we were still at work), a chat, a swim, a barbecue on the Sarine, an Aldi shopping trip or an ice-cream. Thank you both very, very much! In that respect I also want to thank Kirsten, Vero, Daniela, Arlette, Andrea H., Jesko, Daniel, Jörg and Claudia - especially for your emotional support in the last days of this thesis. In conclusion: without your help, the moments of rest far away from Psychology would be less nice and finishing this thesis would have been a lot harder.

For her emotional support I would like to thank our team cat, which slept all day long in front of our office window. Cuddling her was sometimes more than any encouraging word or discussion.

This thesis would not have been possible without all of my friends at home (or by now in Switzerland) – Stocki (thank you for all your encouraging, helpful and caring words), Leonie, Sarah, Heinzi, Flanders, Martin, Caro, Julia, Nicki, Kamü (thank you for the entertaining hours during the long train rides), Sonja, Kathi, Marcus, Susi, Tanja, Kerstin, Xandi, Lieblingsbernd - I would like to thank for visiting me here in Fribourg, for their emotional support, camaraderie, entertainment, searching for subjects and caring they provided. To the friends I met during my studies at the University of Eichstätt (Steffi, Kristina, Senta, Anji, Sandy, and Beate) I want to thank you for relaxing wellness weekends, birthday and Eichstätt revival parties, and for a never ending contact.With the gift of their company they made my days more enjoyable and worth living.

It is a pleasure to thank Biggi for being always there when needed, for many exploration tours through Switzerland, for hiking tours with fear of death, for proofreading my thesis, and simply for our long lasting and deep friendship. Furthermore I have to thank Emma for her indispensable help in correcting all my Sandra-English.

I am grateful to my goddaughter Lea Marie and her family for helping me to forget my entire thesis stuff, enjoy wonderful hours with them and regenerate from all my work.

Lastly, but most importantly, I owe my deepest gratitude to my mom and dad. They created an environment for me where everything seems to be possible. They bore me, raised me, supported me in everything I did in my life, cheered me up and encouraged me whenever necessary and simply loved me. To them I dedicate this thesis.