Investigating Oculomotor Control in Visual Search: From Development to Culture

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Patrick Lüthold, Alpnach OW, 2017

"Ich erkläre ehrenwörtlich, dass ich meine Dissertation selbständig und ohne unzulässige fremde Hilfe verfasst habe und sie noch keiner anderen Fakultät vorgelegt habe."

“The true mystery of the world is the visible, not the invisible.”

- Oscar Wilde

To my parents

Rea & Marcel Lüthold

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1 Introduction

In order to interact with our environment every being (creature) on this earth is equipped with senses or sensors permanently collecting information from our surroundings. This input comes as a vast stream, flooding the different input channels, providing us with information about every little detail around us. Over time, evolution has brought forward many different species, each equipped with the appropriate senses or sensors to receive signals relevant for their survival. As some animals with poor vision have a more enhanced sense of smell or even a sophisticated sonar navigation system, like the bat for example, each species owns a system, which is most functional to their lives. To each of these animals the world appears differently, presenting itself most relevant to their behavior and rich in viable signals. For some insects, for example, there are attracting patterns visible on flowers, which are invisible to us (Figure 1). This makes sense in the way that neither we need to discover these flowers for our survival nor do the flowers depend on us to spread their pollen.

Figure 1. Evening primrose (Oenothera biennis): To the human eye the flower looks solid yellow but insects can aim for the bullseye in the centre. [Bjorn Roselett Professional Nature Photographer, (2008). Oenothera biennis [Photograph]. Retrieved March 04, 2015 from: http://www.dailymail.co.uk/sciencetech/article-473897/A-bees-eye-view-How-insects-flowers-differently-us.html#ixzz246hRn23i.

The fact that the world appears to us as it does, already accounts for the first stage of information filtering. Only perceiving signals that are relevant to our survival presents the world in a manner best suitable to our behavior. Still, exhaustively processing all information perceived by our senses would soon lead to an overload of our cognitive resources (Broadbent, 1954) paralyzing us in every action. Which information becomes relevant to our behavior or our intentions must be somewhat selected and given a priority at certain moments in time. Evolution has solved the problem of selection by providing us with the mechanism of ‘attention’. Over the past thousands of years, our senses and especially our visual system has succeeded in guiding our perception of our surroundings, making it possible to maneuver through the world, securing our continued survival. As a basis for understanding the visual system, the following section is going to describe our sense of sight with its anatomical and neural specifications. From the moment we wake up in the morning until we shut our eyes to fall asleep at night, our eyes function like active video cameras sending all information to our brain. The organs involved are the eyes, part of the central nerve system including large areas of the brain. What we take for granted and describe as ‘seeing an object’ are actually electromagnetic waves bouncing of an object and traveling into our eyes. The following section is going to functionally segment the phenomenon of seeing according to the eye’s anatomy from the front to the back.

1.1 The Eye

The visual system transforms electromagnetic waves within the visible range (about 390-750nm), into a representation of the world around us (color, shapes, sizes, patterns, etc.). An illustration of the anatomical components of the human eye can be seen in Figure 2. Its composition is often compared to that of a camera. Whereas the camera leaves us with a two-dimensional copy of the viewed scene, our brain creates three-dimensional objects with depth and meaning. The eyes feed the brain with electrical impulses, which the brain codes into neural activity, translated into the perception of objects. Light enters through the lens, which is a transparent, biconvex structure at the frontal part of the eye. Its elastic characteristic allows refracting of entering light onto the retina. There, light is transformed from electromagnetic waves (light) into electrical pulses - the language of the nervous system (Gregory, 1978, p. 60). The retina is equipped with two types of photoreceptors: rods and cones, which are densely populated on the retina with an exceeding distribution of cones at its central region, called the fovea (for more detail see section Fovea, Parafovea and Periphery). There are approximately 120 million rods and 7 million cones on the retina. The cones are more sensitive to chromatic light (daylight vision) whereas the rods respond to more sensitive dim and achromatic light (night vision) (Duchowski, 2013). For a more detailed description of the physiological optics and the cells within the retina, see (Hendee & Wells, 1997). Further, the electrical transposed visual information travels across the optic nerves via visual pathways, towards higher cortical areas.

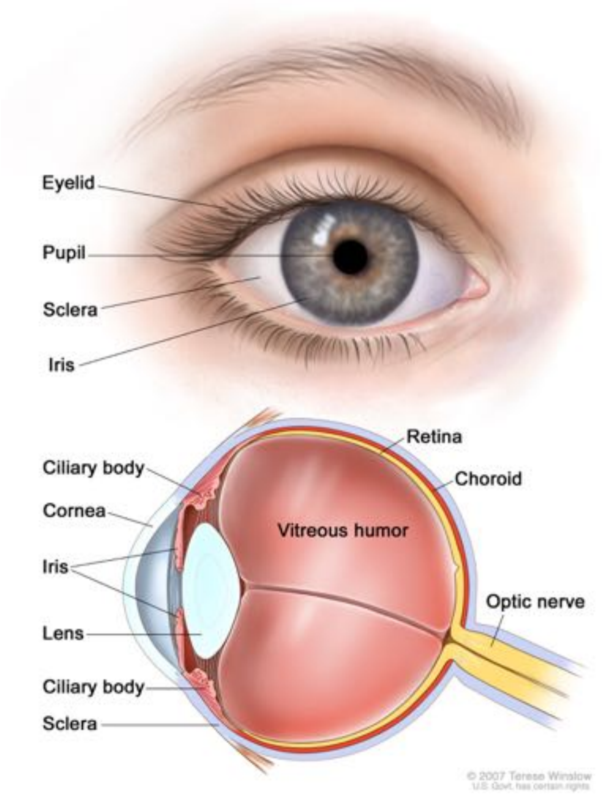


Figure 2. Anatomy of the eye, form outside and inside view. Retrieved May 26, 2015 from: http://www.uchospitals.edu/online-library/content=CDR258015.

1.2 The Fovea, Parafovea and Periphery

The fovea describes the central two degrees of the retina. A 1.5 mm diameter rod-free area characterized by a high density of cones (Polyak, 1941), resulting in the highest degree of visual acuity. The region immediately surrounding the fovea by a 0.5 mm ring is called the parafovea, beyond which the remaining area is termed the periphery. With further distance away form the fovea visual acuity deteriorates (Anstis, 1998). Figure 3 demonstrates the perceived acuity of a retinal image.

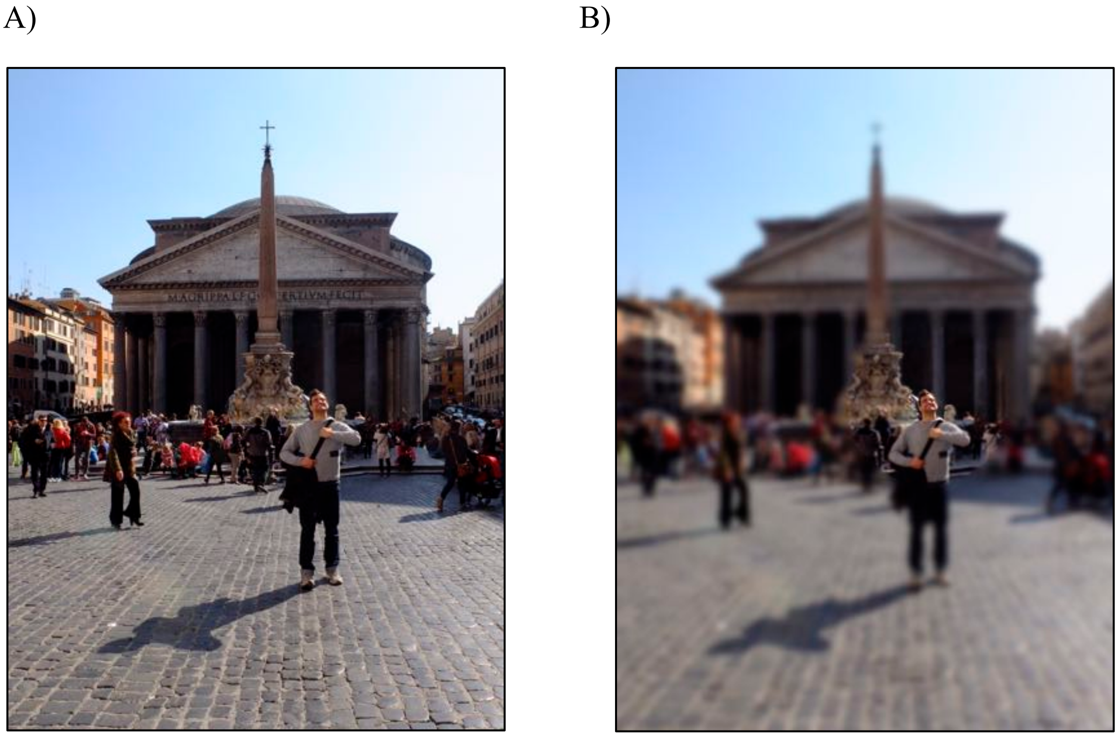


Figure 3. A) Image of the author originally taken by a camera. B) Image of the author blurred by applying radial blur, simulating the progressive loss of acuity with eccentricity.

Peripheral vision is outside of the stereoscopic vision. It can be conceived as bounded at the center by a circle 60° in radius or 120° in diameter, centered around the fixation point, i.e., the point at which one’s gaze is directed. The normal human visual fields extends to approximately 60° nasally from the vertical meridian in each eye to 100° temporality from the ventral meridian, and approximately 60° above and 75° below the horizontal meridian.

1.3 Eye Muscles

To allow the highest visual resolution to be altered across the visual field, the eye is constructed in a way, which allows it to move. The eye lies in the orbital socket where three antagonistic muscle pairs manipulate its position (illustrated in Figure 4). The lateral and medial recti together control the horizontal position. A contraction of the lateral rectus of the left eye and a relaxation of the medial rectus of the left eye would produce a left sided turn of the eye. The second pair consists of the superior rectus and inferior rectus. Together this pair controls the vertical movement of the eye. A contraction of the superior rectus and relaxation of the inferior rectus would elevate the eye whereas the opposite would depress the eye. In combination with horizontal deviation this muscle pair also contribute to torsion eye movements. The final muscle pair is the superior oblique and inferior oblique. Their main function is the torsion of the eye, making the top of the eye rotate nasally and the bottom of the eye temporally. Additionally in combination with horizontal shifts the oblique muscle pair supports vertical eye movements. These three muscle pairs allow the eye to be moved along three axis of rotation (horizontal, vertical and torsion) making it possible to guide any object in the field of view onto the fovea.

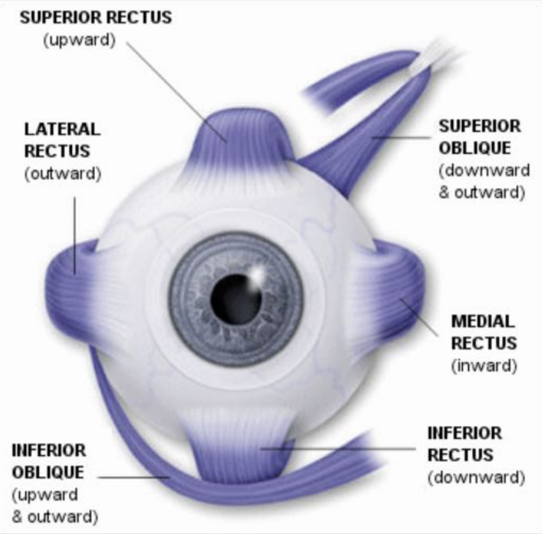


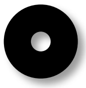
Figure 4. Illustration of the right eye and its extra-ocular muscles (lateral rectus, medial rectus, superior rectus, inferior rectus, superior oblique and inferior oblique). Retrieved May 26, 2015 form: http://www.begin2dig.com/2010/08/eyes-have-it-sometimes-using-eye.html.

1.4 Eye movements

Having discussed the anatomical properties of the eye and its muscles, the following paragraph will focus more on its functional categorization. Eye movements are our fastest and most frequent muscular activities. We move them over 100’000 times each day which breaks down to about three times per second. They can be distinguished in their function to *stabilize* or to *shift* gaze. *Gaze stabilization* is necessary if we want to keep our visual inspection fixed on a specific area either while stationary or when in motion with respect to our surrounding (e.g. looking at a tree out of a moving train). To keep the retinal image on a high resolution, and therefore on the fovea, the eyes need to be held steady or have to compensate any self-motion. During *gaze shift* however, the eyes move while the body or head stay still. This enables us to sweep through our surrounding with minor effort (e.g. reading). There are two main types of eye movement relevant to visual experiments: fixations and saccades. Fixations keep the visual gaze stable on a single location, allowing sufficient time for its exploration. Characteristically fixations last for 200 – 500 ms but increase depending on the depth of analysis. Saccades are fast ballistic movements between fixations. A typical saccade lasts about 30 ms with an average latency of 150 – 250 ms (Krauzlis, 2008). Depending on the saccade amplitude, the duration increases by 2-3 ms per degree and leaves us blind during the time of travel.

1.5 Eye Tracking

Knowing that we move our eyes to gather information about our surroundings renders the recording of eye movement interesting. With data about the oculomotor behavior, researchers infer cognitive models about the visual information processing. The following paragraph gives a brief technical explanation on how eye movements are tracked. The development of eye-tracking techniques date back to the early nineteen hundreds (for a historical overview on eye movement research see (Wade & Tatler, 2005). Currently there are three types of eye-tracking methods in practice. Firstly and most intrusively, the scleral search coil, measures electromagnetic induction from a metal ring, placed on a contact lens, within a magnetic field. Secondly, electrooculography (EOG) records the electrical activity generated by the eye muscles with electrodes attached to the side of each eye. Thirdly and least intrusive, video-based eye trackers use a continuous image of the pupil to follow its movement and compute the current gaze position. For a thorough historical and technical overview on the different eye-tracking methods consult the excellent review by Duchowski (2013). In this thesis, a video-based desktop-mounted eye-tracking device, namely the Eyelink 1000 (SR research, Canada) was used. The Eyelink uses an infrared sensitive camera



to pick up the reflection of an infrared light source. Both are mounted beneath a testing monitor directed towards the participant. The benefit of using an infrared light is its invisibility and harmlessness to the eyes. Two reflections from the pupil and the cornea are detected and allow for calculation of eye rotation. While the corneal reflection stays stable due to the bulb shape of the eye, the pupil's reflection rotates along with changes of gaze direction. Differences between these two signals in combination with a simple calibration (nine points on the screen) allow for calculation of gaze direction on the screen. Although minor head movements can be balanced out by the corneal reflection, a headrest can provide further stabilization of recording. Next, the continuous stream (a data point each 2 ms on a 500 Hz resolution) of temporal and spatial information of gaze direction is distinguished into different meaningful events such as blink, fixations and saccades. While identification of a blink follows a gap of data recording due to the closing of the eyelid, fixations and saccades are identified on the basis of an empirical velocity-threshold. Data points below the threshold are summed to a fixation, whereas data points above the threshold become a saccade.

Relevant variables for this thesis are the following:

Fixation duration: the time the eyes spend on a specific location.

Number of fixations: the maximal amount of fixations within one experimental trial.

Fixation location: the area of the visual display in exploration

Number of saccades: maximal amount of saccades within one experimental trial.

Saccade peak velocity: the maximum speed at which the eye moved across the display.

Saccade latency: the time between display onset and first movement of the eye, indicating the time it took to program the movement.

1.6 What Drives the Eye?

Given the potential sequences of fixations and saccades when exploring a visual scene, the nature of control over eye movements can have different origins. For example, as you are reading this, you have voluntarily decided to direct your eyes onto this page, scanning the text, reading these words. As you turned to this page, however, you could not help but notice the black dot at the top right corner. Whereas goal-driven movements are directed by the intention of the observer, stimulus-driven movements are solely dependent on stimulus properties (also known as saliency). Michael Posner

(1980) was one of the first to show these two different attentional deployments with his cueing paradigm. Whether or not, you actually made an eye movement towards the dot is yet another question. For example you can continue reading this and determine whether the black dot has a white disc in the center without moving your eyes towards it. Yet, knowing if it casts a shadow is only possible after fixation. In order to understand what is going on during the example above, we need to keep in mind, that there is an underlying process at work, namely visual attention. In attention research eye movements are referred to as overt shifts of attention, whereas the scanning of a scene without eye movements is termed covert shift of attention. The analogy of a 'spotlight' is commonly used to describe the way that covert attention is shifted among items within a visual scene (Posner, Nissen and Ogden, 1978). Posner's cueing paradigm is an experimental procedure, in which observers are presented with a probable valid visual cue and need to quickly respond to an appearing stimulus. Additionally, Posner used endogenous (an arrow at the location of the fixation cross) and an exogenous cues (a flashing of the stimuli location) to direct the observer's attention. Independently of cue type, observer show a speeded response for valid cue trials, evidencing a successful preceding shift of attention. With this experiment Posner showed that, stimulus feature, just as, observers volition can guide attention. The case of the stimulus properties guiding attention is referred to as *bottom-up* process. Any voluntary or knowledge-based control is referred to as *top-down* process (Carrasco, 2011). The relationship between *bottom-up* and *top-down* influence on search stays widely discussed (Connor, Egeth, & Yantis, 2004; Pinto, van der Leij, Sligte, Lamme, & Scholte, 2013) and is subject to theories of visual attention. First experiments in visual search come from Treisman and her colleagues using the visual search paradigm.

1.7 Feature-integration theory

One of the first to publish a theory about the selection process was Anne Treisman (1988; 1980). Her Feature Integration Theory (FiT) of selective attention explains how for example a target object is selected among other distracting objects. The FiT operates in a two-step fashion first coding each object in the scene into its single features (color, orientation, spatial frequency, brightness, direction of movement, etc.) and then, in a second step binding (joining) these features together to form an apparent object. The main assumption of the FIT is that each object can be broken down into its features. Certain features together form a higher order classification called dimension. The brain's architecture corresponds to these features with cells in the area V1, which respond to certain orientations or light-dark contours (Conway, Hubel, & Livingstone, 2002; Livingstone, Freeman, & Hubel, 1996). Importantly, the FiT assumes that in the first step "simple features can be detected in *parallel* with no attention limits" (Treisman & Gelade, 1980, p. 99). The second step, however, requires focal attention, that "provides the glue which integrates the initially separable features into unitary objects" (Treisman & Gelade, 1980, p. 98). These objects are then compared with stored representations for recognition. Depending on the nature of the stimuli a search can already be successfully completed after the first step, which would be the case for stimuli distinguishable by simple features (e.g., looking for a red vertical bar among green vertical bars) – a so called feature search (see Figure 5a) - or require the second step of focal attention to bind conjoined features for the detection in a more complex stimuli environment (e.g., looking for a red vertical bar among green vertical and red horizontal bars) – a so called conjunction search (Figure 6b). The two-step architecture of the FiT splits the notion of search into a pre-attentive (effortless) search and an attentive (capacity-limited) search. In the latter case, search time analysis has lead to the assumption that attention travels from one object to the next, binding their features to discern the current object from previous investigated object locations. Therefore spending more time to serially search a display with increasing set size.

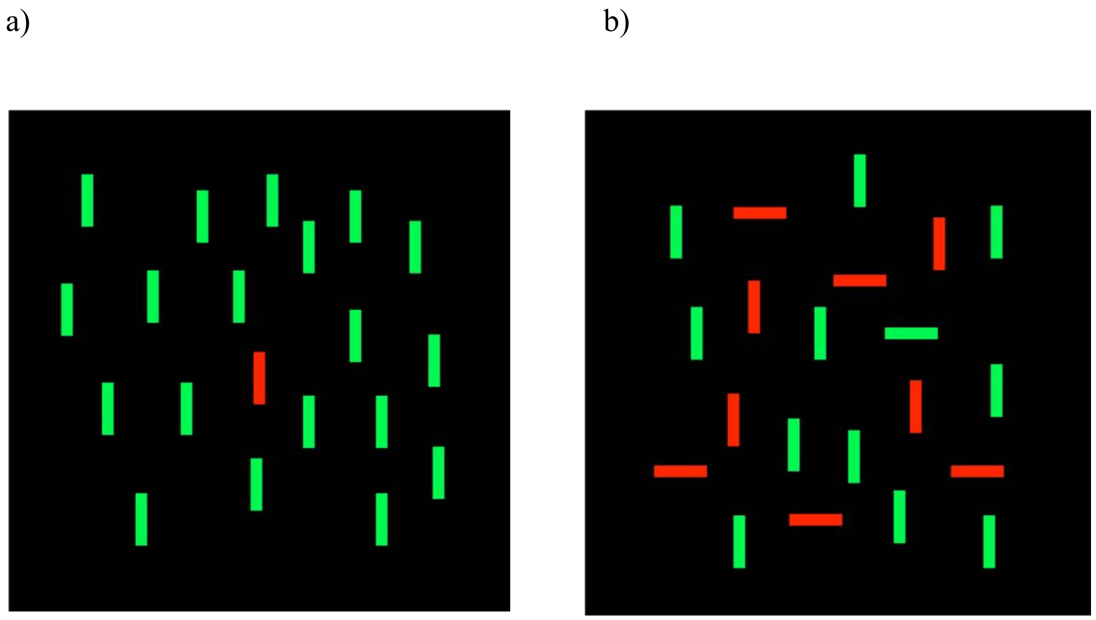


Figure 5. Two possible search displays. A) shows a feature-search with the red vertical bar (target) popping out between the green vertical distractors. B) shows a conjunction-search (distractor sharing feature with target). The target is the green horizontal bar.

1.8 Limitation of the Feature Integration Theory

Research investigating into the FiT provided counterevidence to the idea of the strict dichotomy of search into parallel or serial processes. Nakayama and Silverman (1986) found the conjunction of dichoptic separation and color to produce flat search functions across increasing set sizes. Observers were able to “perform a parallel search in one depth plane without interference from target-like distractors in another depth plane” (Nakayama & Silverman, 1986, p. 265). With this experiment, Nakayama and Silverman could show that within a complex search environment, attention can be restricted to a certain dimension (in this case depth plane) and operate in a parallel manner within this separation. Using the same line of criticism, Wolfe has argued that, “all searches require the deployment of attention to the target and that different tasks vary only in the degree to which they can use parallel processes to guide the deployment of attention” (Wolfe, 1998, p. 33). In regard to the reaction time slopes this translates into more attentional guidance yield shallower slopes (Wolfe, 1994). Cave and Wolfe (1990) picked up on these limitations and developed an advanced theory, namely the guides search theory.

1.9 Guided Search Theory

Similar to the FiT the guided search (GS) theory by Cave and Wolfe (1990) resumes the idea of a two-stage architecture of selective attention. However, this time describing how attention is allocated to certain locations by a so called "saliency signal". Again, this model assumes that the visual field is represented by a set of modules each of which representing basic attributes of the stimulus. In this case these basic attributes are summarized on dimensional maps (e.g., color, orientation, size, etc.) representing subordinate features. Each dimension specific modules simultaneously computes a salience signal for every object location, signaling how different it is compared to the surrounding information within the same module. In other words, objects are still broken down into their features, yet represented in a dimensional manner including more than one feature. A dimension map representing one red target among green distracters, for example, would have the highest amplitudes of activation at the location of the red target indicating its greatest overall difference. Thus, dimension-based salience signals are integrated into an *overall map of activation*. Focal attention will be allocated to the location of highest activation. To illustrate the different results during simple and conjunction search tasks the GS can contribute as follows. During conjunction tasks the target shares certain features with the distracters making them more similar, and therefore, the saliency signal less discriminative from other signals. Thus, overall activation of the target will not be at large difference to distracters forcing focal attention to serially inspect target candidates before detecting the target. During simple search, however, the target-defining dimension triggers a saliency signal of remarkable difference compared to distracters leaving only one possible location for target detection. The difference between the FiT lies in the introduction of a master map signal deploying the attention to the location of highest activation. This means that attention is not required to bind feature information for certain objects, rather the highest saliency signal attracts attention.

1.10 Visual Search Paradigm

In a typical visual search task, observers are presented with a variable set of visual stimuli. Each display contains a number of distractor items and may hold a specific target item. The total number of items presented on a display is referred to as the 'set size'. In a display there is either a target present or absent, and the observer's task is to rapidly decide by pressing a predefined target-present or target-absent button. The type of stimuli used are usually artificial, yet meet the analogy to search behavior in the real world. For example looking for one red vertical bar among a variable number of green vertical bars (Figure 6). The time form display onset until button press is termed reaction time (RT), which in relation with the set size results in a search RT function (slope). Differences in search slopes lead to two distinct modes of visual search, which by the Feature-integration Theory (FiT) have been termed *parallel-* and *serial*-search.

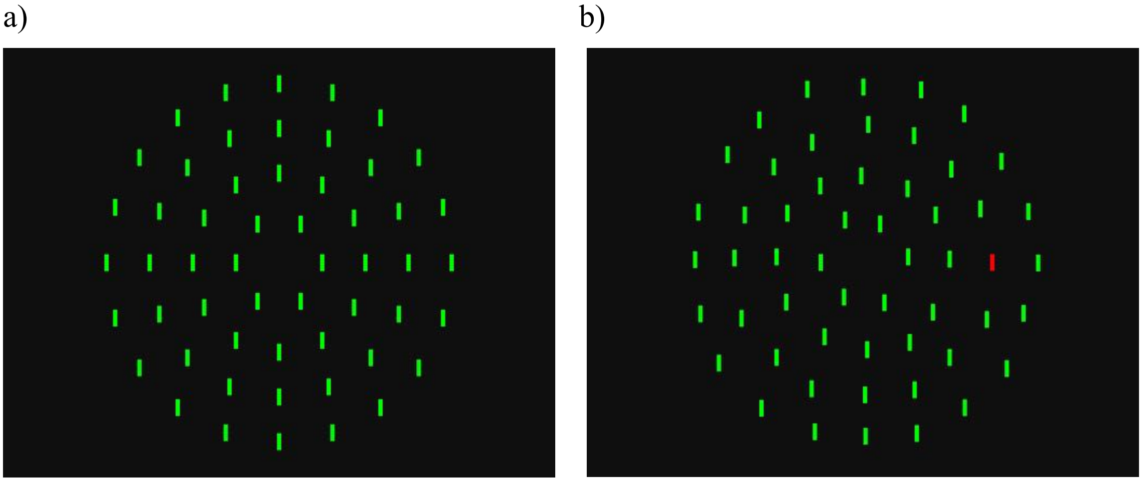


Figure 6. Example for a feature-search target-absent trial (a) and a target-present trial (b); set size is 54

1.11 Overt and covert attention

The theories summarized above characterize the spread of covert attention in visual search. Note that both theories, the feature-integration theory (FiT) and the guided search (GS) disregard any eye movements and postulate item search times at speeds well below the threshold for eye movements (Treisman & Gelade, 1980; Wolfe & Horowitz, 2004). Recall that attention can be allocated either covertly or overtly across the visual field. Therefore it seems somehow logical that visual attention and eye movements must have some relation to each other. Yet the link between overt and covert attention remains unclear. A possible explanation is that these two processes are completely independent of each other (Klein, 1980). A target may draw both covert and overt attention, however each system receiving an independent signal, without any causal link between these mechanisms (Remington, 1980). Recent evidence for an independent approach comes from Hunt and Kingstone (2003) showing no benefit of stimuli detection when programing a saccade to that location in advance. As an alternative, covert attention may be a forerunner of overt attention, in order to program a saccade towards a location of interest (Shepherd, Findlay, & Hockey, 1986). In this case, overt shifts depend on preceding covert shifts of attention without the inverse being possible. Deubel and Schneider (1996) conducted an experiment where saccade location could coincide with a possible target location and investigated the precision of detection. Participants showed higher accuracy when the target fell on the saccade location compared to any mismatch of saccade location and target location. The authors relate the response enhancement to a strong coupling between both systems and term their findings 'preview benefit'. The final alternative for the link between covert and overt shift of attention is put forward by the "premotor hypothesis" by Rizzolatti, Riggio, Dascola and Umilta (1987). The main idea being, that covert attention solely serves to prepare saccades towards target locations. And only a go-signal executes that program. There is no separation between the underlying mechanisms of attention and eye movement, rather a combination into a single oculomotor program. Conclusively, there is still more research required to settle the debate on the nature of the relationship between attention and eye movements. Irrespective of the nature of the relationship between both systems, eye movements remain a useful measure of information processing. In regard to visual search, Zelinsky and Scheinberg (1997) investigated eye movements during parallel- and serial-search. They linked eye movement measures to manual reaction times (RTs) and found correlations between the number of fixations and RTs. An increase in set size resulted in additional saccades for serial but not for parallel search. Putting forward that during parallel-search eye movement do not contribute to successful task completion. Again, one can say that parallel-search is strictly solved by the covert attentional mechanisms. In serial-search however, eye movements engage in finding a target among strongly disturbing distracters with more saccades being required for larger set sizes. The resulting longer RTs for serial-search can therefore be accounted by the search interruption during the execution of saccades. Support also comes from the increase in saccade number for absent- compared to present-trials with a ratio of 2:1. Additionally to RT analysis, eye movement analysis allows the integration of participants natural search behavior and fosters development of search theories.

1.12 Current Investigation

The goal of this work is to contribute to the understanding of the interplay between overt and covert attention during visual search. The environment serves as a great place of stimulation and we navigate following two main strategies: first, stimuli around us compete for attention of our sight to attract us towards beneficial objects (food) or away from detrimental objects (potential threat). This means our system is set to rapidly detect specific stimulus properties. Second, with our great set of cognitive skills we can alter our perception to follow our self-set goals and plans to fit our needs. We therefore integrate different information necessary to succeed in daily visual tasks and seemingly achieve this by relying on the visual processes. Here, I will focus on the visual selection and processing of information. In general the visual system contributes along different aspects to form a suited sense of tackling daily problems. First of all it is subject to development over the time course of maturation. In *chapter I,* I will focus on specific eye movement parameters and their development along childhood in a typical visual search paradigm. In daily life we see people of all ages visually orienting themselves in the environment. You can walk along a street avoiding other people crossing your path, greet a recognized face and look for traffic signal ordering you to stop walking. You share this with all the people that surround you and their behavior will be guided accordingly. Yet it is not unusual to observe that children often requiring a lot of time in a search for their desired toy in their room or have difficulties to direct their focus onto a designated task when there are other things happening around them. It is obvious that there are some components of the visual system that underlie maturation and improve with age. Especially in a designed visual search experiment we can investigate such differences on a millisecond level for behavioral output such as manual response time and oculomotor parameters. After having explored how certain parameters develop over time, *chapter II* focuses on the bottom-up and top-down influence on information processing. In other words, our system adapts depending on requirements set by the stimuli or the task. Again, behavior in a visual search is altered by either the stimulus properties or the observer's intentions. While the redundant single effect is known for manual reaction times, its effect on the oculomotor system is yet unclear. Looking for a friend within a crowded place becomes much more efficient if that person is wearing a hat distinguishable from others in a combination of color and shape for example. In the laboratory this translates into a target differing from distractors by color and shape. If the oculomotor system however responds with the same advantage as the covert shift of attention stays yet to be investigated. Any oculomotor benefit would speak for an effect on an early level of information processing rather than a late effect on the response level. Additionally, the observation of the same redundant signal effect across manual and saccadic reaction times supports a strong link between the oculomotor and the attention system. To conclude the idea of this work to explore known factors influencing perception the third chapter aims for an intercultural comparison. From the impact development has on the system (chapter I) to factors more dependent on stimuli and task set (chapter II), *chapter III* will expand the visual stimuli from the basic visual search paradigm to a more complex scene search with the emphasis to investigate the influencing factor culture has on perception. Over the past years research has accumulated evidence that people form Western and Eastern cultures differ in their cognitive mind-set, postulating that Westerners are more analytic and Easterners more holistic. While looking for Waldo, known to hide in cluttered scenes, I will investigate the search pattern of observers of both cultures to explore yet another influencing factor on attention, namely culture. Specifically, I will be looking for the mechanism known as inhibition of return, which I assume shows a direct influence of the analytical and holistic cognitive style prone to the observers of specific cultures. To sum up, this work will pivot on developmental, bottom-up, top-down and cultural influences on the control of eye movements.

2 Chapter I

Saccadic and Motor Development in Feature Search in Children

2.1 Abstract

While the characteristics of saccadic eye movements have been extensively studied in adults, oculomotor data on children and adolescents are scarce and contradictory. In this study we recorded eye movements of 160 children aged five to 13 years. Children completed two visual search tasks. The first task involved visual search for targets that differed from distractors (green vertical bars) in color (red or blue) or orientation (tilted to the left or right). Children had to manually indicate the presence or absence of a target by button press. Manual reaction times (RTs) were recorded along with eye movements. The results showed a decrease of manual RTs and saccadic latencies, that is, the time between display onset and the initiation of the first saccade with increasing age. Saccade peak velocity is higher in younger (age 5 to 7) compared to older children (age 9 to 13). In the second task, the same visual displays were shown as in the first task, however, children had to respond by pressing, as quickly as possible, a single button at display onset, irrespective of whether a target was present in the display or not. Manual RTs of the second task, together with the search RTs of the first task, allow differentiating a sensory-motor component and a cognitive component reflecting visual search and response selection. The results show that the completion time of the cognitive component decreases with increasing age; further, decreasing saccadic latencies were again found with increasing participant age. Since the detection of the target was not task relevant, older (age 10 to 13) children showed a reduced frequency of eye movements in the second task compared to younger (age 5 to 7) children.

2.2 Introduction

Across our life span we orient ourselves through the visual sense starting at the instance we first open our eyes to the point of our terminal blink. That is, people are typically looking for an object within a distracting environment. Be it a child looking for a specific Lego-piece in a box, or later, as an adult, locating one's car key on the desk. Research on the development of visual search suggests that search proficiency increases from childhood to adulthood, culminating in adolescence (Trick & Enns, 1998). In regard to search speed Trick and Enns (1998) describe an inverted U-shape function as the common pattern in information processing across life span. So far, the typical method of investigating such developmental differences has been the measure of reaction time (RT) and accuracy within the two typical search types of *feature search* and *conjunction search*. Whereas in a *feature search* one is looking for a single-defined target among homogeneous distractors (red vertical bar among green vertical distractor bars), in a *conjunction search,* one has to detect a target defined as a conjunction of features shared with heterogeneous distractors (a vertical red bar among vertical green and horizontal red distractor bars). Based on visual search theories (e.g. Treisman & Gelade, 1980; Wolfe, 1994) the two search types explained in the introduction section of this thesis, evoke different underlying search mechanisms. In *feature search,* all objects are processed in *parallel* making the target literally pop out of the display, whereas in co*njunction search* each object has to be *serially* checked in order to find the target. RT analysis support the idea of different search mechanisms by showing prolonged search times for serial- compared to parallel-search. While the visual search paradigm has merely been devoted to examining the spread of covert attention, Zelinsky and Scheinberg (1997) investigated the overt shift of attention (i.e., eye movements) during *parallel* and *serial* visual search. They reported high correlations between the number of saccades made and response times during search. Although the nature of the relationship between attention and eye movements is cause for much debate, Deubel and Schneider (1996) speak of a "close coupling between visual attention on the one hand and saccade programming on the other" (*p.* 1836). For any further elaboration read the section about overt and covert attention. In spite of considerable interest in the development of selective attention and the saccadic control in children, surprisingly no study has investigated children's eye movement parameters in visual search. Combining both sources of information, search time and eye movement data, promises to contribute to the understanding of developmental differences in search processes. Thus, we collect data by two measures investigate behavioral and oculomotor parameters of visual search in children. The succeeding paragraph gives a summary of reaction time results, followed by findings on eye movement data across childhood.

2.3 Visual search in children

2.3.1 Reaction time

Early studies testing the *Feature Integration Theory* (FIT) by Treisman and Gelade (1980) comparing search times between children and adults showed that children lag in processing speed compared to adults (Lobaugh, Cole, & Rovet, 1998; Thompson & Massaro, 1989). Thompson and Massaro tested preschool children's (4 to 5 years of age) responses towards a target differing in brightness or size from a set of distractors (set size: 4, 9, 16 and 25). Reaction times augmented with set size for serial-search but not for parallel-search in children as well as for adults. Although these results correspond to the pattern of FIT, children had a higher Y-intercept in regard to their reaction time functions than adults. Higher Y-intercepts represent an overall augmented reaction time, which is composed of distinct processing components, such as response choice and execution. To disentangle the motor response from the overall search time, Hommel, Li and Li (2004) introduced a simple RT task in which participants responded to any single stimulus (square or circle) appearing on the center of the screen. In the age groups of 6 to 22 years, the comparison between RT in a single-item (simple RT) and RT in a two-item feature search showed a significant interaction, describing an acceleration of mere motor response time with increasing age up to adulthood. Further, in their results concerning feature search across the life span (6 to 89 years) they included simple RT as a covariant, providing an almost pure search time analysis across age groups. In regard to the relation between RT and age, they reported an U-shaped function with slower search times for participants at either side of the continuum. The authors suppose however, the underlying processes to be different. In summary, children need more time to locate and respond to targets within a set of distractors compared to adults. Some of this delay is caused by slower responds executions, yet leaving a temporal margin for any differences occurring during search phase. Although, acceleration in search speed along childhood has been confirmed in a number of studies (Hommel et al., 2004; Thompson & Massaro, 1989), the exact mechanisms responsible could not be identified. Some authors argue along the side of neurological development (i.e. myelination) to be responsible for faster information processing and therefore leading to speeded responses (Gerhardstein & Rovee-Collier, 2002; Trick & Enns, 1998). Others make different search strategies accountable for temporal differences in basic feature search (Donnelly, Cave, & Greenway, 2007). Reaction time differences between colored and oriented targets found by Donnelly and Cave (2007) and Lobaugh et al. (1998) in the range of 6 to 8 year-old children (7-8 years in Lobaugh et al. (1998); 6-7 years in Donnelly & Cave (2007) supply evidence for dissimilar processing on the basis of a single dimension. Additional support in line with processing differences occurring before the age of 8 years come form a study investigating the ability to categorize objects into its dimension or features. Grubert, Indigo and Krummenacher (2014) showed that children prior to the age of 8 years categorize a target within a feature search by its feature (red or blue; left or right tilted) rather than by its dimension (color; orientation). Using the paradigm of inter-trial-transitions (Müller, Heller, & Ziegler, 1995), in which the target's feature is either repeated or changed across two consecutive trials, switching cost occurred on the feature level for children aged below 8 years and on the dimension level for older children up to adulthood. Thus, supplying a possible explanation for differences in processing time of visual stimuli prior to the age of 8 years. To further enquire about differences in visual search strategies or abilities across development, measurement of eye movement make a promising candidate, as they correlate with RT performance (Zelinsky & Sheinberg, 1997). The succeeding paragraph gives a summary of findings on eye movement data across childhood.

2.3.2 Eye movements

As just described, RT could be broken down into mere motor response time and search time. Adding eye movement recordings as a measurement during search, allows for a more detailed insight into what is going on during search time. In the past three decades much has been learned about the eye movements system (for a review see Kowler, 2011). Most of the research, however, has been carried out on human adults or primates, whereas little research bas been directed to these parameters in children. The oculomotor behavior develops in several stages along childhood. For instance, the ability to fixate develops during the first months (Chandna, 1991), yet is still reduced in children aged 4 and 5 years old (Kowler & Martins, 1982). For example, if participants between the ages of 4 to 15 years are asked to fixate a target, fixation duration increase and the number of reflexive saccades decrease with age (Aring, Grönlund, Hellström, & Ygge, 2007; Ygge, Aring, Han, Bolzani, & Hellström, 2006). Additionally, between the ages of 8 to 10 years the capability to persist fixation in the presence of peripheral distractors increases. Paus, Babenko and Radil (1990) thus suggest, that cognitive control of fixation mature up to the age of 10 years. Brain development, such as the neuronal evidence of synaptic pruning and myelination contribute to the maturation of cognitive control (Luna, Velanova, & Geier, 2008). Their behavior outcomes on the deployment of eye movement however, stay ambiguous. While some studies found saccade latencies to be shorter in young adults compared to infants and children (Irving, 2006; Klein, 2001; Yang, Bucci, & Kapoula, 2002), others like Accardo, Pensiero, Da Pozzo and Perissutti (1992) and Wilson, Glue, Ball and Nutt (1993) failed to find these early developmental differences. Their findings showed an increase in saccade latency for elderly subjects. Munoz, Broughton, Goldring and Armstrong (1998) investigated saccade latencies of subjects across an age range of 5 to 79 years, describing an asymmetric ‘U’-shape function with the lowest plateau for subject between 18 to 22 years of age. They found the explanation of developmental processes and normal degeneration to fit this pattern. The standpoint on the influence of age on saccade peak velocity is still under considerable debate, since all possible outcomes have been reported. For example, Accardo (1992) and Irving, Steinbach, Lillakas, Babu and Hutchings (2006) noted saccadic peak velocities to be higher in children (< 7 years) than in adults, additionally Fioravanti, Inchingolo, Pensiero and Spanio (1995) tested 12 children aged 5 to 13 years of age, with the younger children (5 to 9 years old) producing saccades greater in peak velocity than those of older children (11 to 13 years old) and adults. In contrast, Matsuzawa and Shimojo (1997) showed no difference in saccade peak velocity for infants compared to adults. In contrast, Munoz et al. (1998) and Fukushima, Hatta and Fukushima (2000) could not find any age-related differences in saccadic peak velocity. Apparent from these controversies around the relationship between age and eye movement dynamics, further investigations are required to obtain constant results. A concluding remark concerning most of the studies investigating saccadic eye movements in children yields the strict use of the pro- and anti-saccade task. Subjects are instructed to repeatedly move towards a single saccade goal, set at defined distances from the initial fixation point. Additionally, due to historical and technical reasons most studies limit their investigation to only horizontal movements, isolating eye movements as a mechanical motion rather than a search instrument. This could explain the different results obtained, in previous studies using different settings such as different stimuli or distances. Considering the strong linkage between eye movements and visual attention (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995) it is advised to use the visual search paradigm for a combination of attentional and oculomotor measurement. As authors like Posner (1980) and Rizzolatti et al. (1987) have argued that an allocation of attention is imperative for an eye movement, the outcome on these recordings would shed light into the processes between display onset and manual response from an attentional and oculomotor perspective. In contrast to the pro- and anti-saccade task, examination with the visual search paradigm emulates finding a target object among distractor objects. Setting a stage for the interplay between selective attentional mechanisms and oculomotor control and therefore being closer to a natural search behavior. No study until now has looked at eye movement data in combination with manual reaction times in a visual search performed by children.

The present study reflects an attempt to examine oculomotor age differences in visual search across early childhood. To present a manageable and comparable task for all age groups we had children perform a feature-search task and a motor task. Moreover, we generally focused on global information-processing aspects that are expected to improve in early life. With the addition of oculomotor measurements the search time is segmented into more concise units allowing deeper understanding of what is going on during search.

2.4 Method Search Task

2.4.1 Participants

160 pupils from the primary school Obernau, Kriens (Switzerland), took part in this experiment. There were 76 female and 84 male. Children of all classes were tested: 34 from kinder garden (KG), 20 from 1st class, 24 from 2nd class, 9 from 3rd class, 30 from 4th class, 23 from 5th class and 20 from 6th class. All participants had normal or

corrected-to-normal vision and were naive to the purpose of the experiment. Two participants aborted the experiment due to motivational reasons (did not want to continue).

2.4.2 Materials

Participants, were seated in a darkened room (to avoid reflection on the screen), viewed the stimuli on a LCD 17“ color monitor run at a resolution of 1280 pixels horizontally and 1024 pixels vertically and a temporal resolution of 60 Hz driven by an Intel Core 2 Quad CPU 2.66GHz PC running Windows XP and MATLAB (R2008b). A desktop-mounted, video-based infrared eye-tracking system was used (Eyelink I, SR Research, Ontario, Canada) with a spatial resolution of 0.1° and a temporal resolution of 500 Hz. The experiment was written in MATLAB, using the Psychophysics and Eyelink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; Pelli, 1997). Participants could move their head freely, however were instructed to keep it as still as possible at a distance of 60 cm of the display.

2.4.3 Stimuli

Stimulus display consisted of 54 bars arranged around four imaginary circles centered in the middle of the screen (see Fig. 7 for illustration of a possible search display). The inner most circle holding 6 bars with a radius of 80 pixel (2.73°), the outwardly circles holding 12 bars (radius: 160 px (5.45°)), 16 bars (radius: 240 px (8.17°)) and 20 bars (radius: 320 px (10.88°)). All stimuli were independently jittered by +/-30 pixel (1.02°). Presentation of target items was restricted to the inner three circles resulting in 34 possible target positions (1 to 34).

The bars were 1.02° of visual angle in height and 0.27° in width. The titled bars were rotated either 45° to the left or to the right (red: VGA RGB 255,0,0; green: RGB 0,255,0; blue RGB 0,0,255; black screen background RGB 15,15,15).

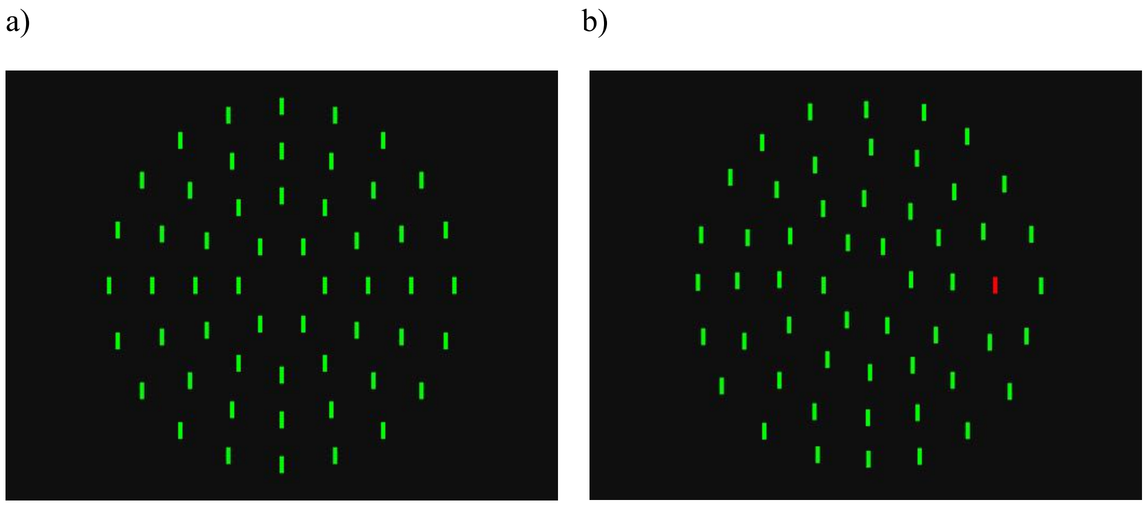


Figure 7. Search task: target-absent trial (a) and a target-present trial (b); set size is 54

2.4.4 Design

Prior to the experiment, participants were told to search for a target bar, differing from green vertical distractor bars either in color (red, blue) or in orientation (left, right). The task was to rapidly indicate, by button press, whether a target item was present in the display or not (left: absent, right: present). Apart from this instruction no reference to eye movements was made.

The experiment consisted of six blocks whereas the first block served as practice block, which was not included in the analysis. Overall, participants completed 200 experimental trials.

2.4.5 Procedure

Before every session participants underwent a 10-point calibration and before every block a drift correction was applied. Each trial started with the presentation of a white central fixation cross ('+' Times, 20 pt.) for 500 ms, followed by a black screen for 500 ms before the search display was presented. The search display was presented until the participant gave a manual response. Between each trial a black screen was interposed for 1000 ms. Between blocks, participants were encouraged to take a break.

2.5 Method Motor Task

2.5.1 Participants

The same pupils also participated in the motor task except for four participants who did not complete the experiment due to motivational reasons (did not want to continue), leaving a total of 156 participants.

2.5.2 Materials, Stimuli, Design and Procedure

The motor experiment was similar in method to the visual search experiment, except that this time participants did not have to distinguish between present and absent trials but had to press the same button at any appearance of the visual search display. The respond hand was counterbalanced and alternated after half of the experiment. The stimuli and the spatial arrangement were the same as in the visual search experiment. The timing was also the same apart for the blank preceding the search display, which lasted for a variable interval between xx and xx ms, to avoid the possibility of generating a response rhythm.

2.6 Search Task Results

2.6.1 Reaction Time Removal of Outliers

In a first step reaction times were inspected for each individual to determine a suitable cut-off for the RT data (examined by visual exploration of RT distribution). After that, 2.6% of all search task trials were excluded from analysis for being responded to extremely fast (anticipatory answers) or extremely slow (failure to respond in time). RTs with more than three standard deviations from the mean were calculated for each participant separately and excluded from analysis (1.0% of the remaining data). Furthermore, two participants aborted the search task due to personal reasons.

2.6.2 Errors

Over all, the average error rates in the search task were very low (see Figure 8); kindergarten 4.9%, first class 2.8%, second class, 3.5%, third class 2.3%, fourth class 2.7%, fifth class 2.5% and sixth class 3.1%. An one-way ANOVA with the factor class (between: KG, 1st, 2nd, 3rd, 4th, 5th, 6th) revealed a significant main effect of class, *F*(6,152) = 3.442, *MSE* = 7.177, p = .003, η_p^2 = .120. Repeated contrasts, by comparing every class with the corresponding next higher class, showed a significant difference between the KG (4.9%) and the first class (2.8%) (p = .003). However, if participants with an error rate above 10% are excluded from the analysis (KG: three cases, 2nd class: one case) the difference between the classes disappears, *F*(6,148) = 1.964, *MSE* = 5.121, p = .074, η_p2 = .074.

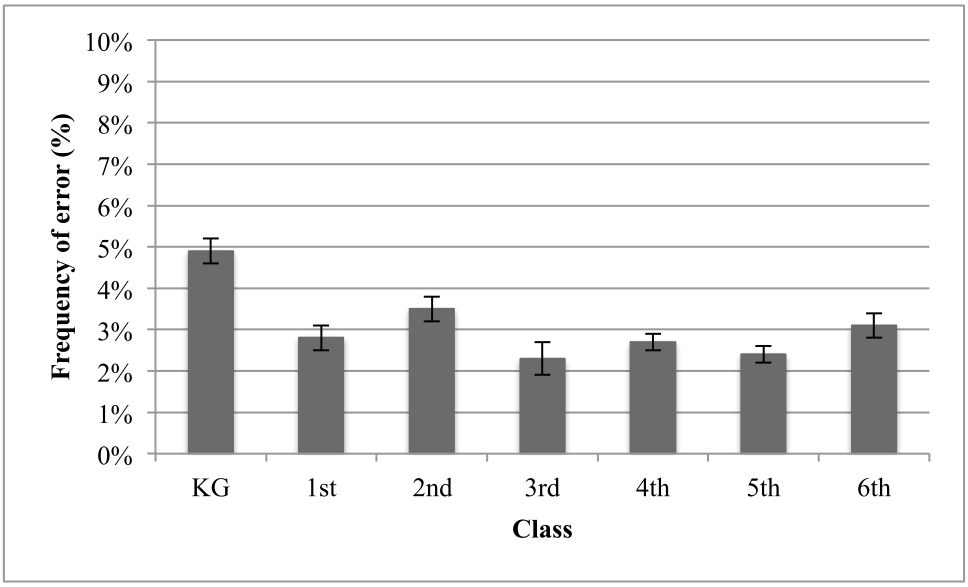


Figure 8. Bars are reporting the mean error frequency (%) for each class. Error bars reflect the standard error of the mean.

2.6.3 Reaction Times

The RTs of the search task for target-absent and present-trials were analyzed with a repeated measures ANOVA with the factor trial-type (absent, present) and the between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th). The main effect of trial-type showed a significant result *F*(1,152) = 141.982, *MSE* = 17593.002, $p < .001$ η_p^2 = .483. To summarize participants were faster in target-present trials (1109.1 ms) compared to target-absent trials (917.3 ms) (see Figure 9). This pattern of decreased RTs in target-present trials compared to target-absent trials was significant across all classes, as shown in the following seven paired t-tests: KG: $t(33) = 6.545$, two-tailed $p < .001$; 1st class: $t(19) = 5.147$, two-tailed $p < .001$; 2nd class: $t(22) = 8.29$, two-tailed $p < .001$; 3rd class: $t(8) = 3.621$, two-tailed $p = .007$; 4th class: $t(29) = 4.793$, two-tailed $p < .001$; 5th class: $t(22) = 5.165$, two-tailed $p < .001$; 6th class: $t(19) = 4.275$, two-tailed $p < .001$.

The between factor of class also showed a significant effect of faster RTs for increasing class, $F(6,152) = 31.202$, $MSE = 63342.597$, $p < .001$, $\eta_p^2 = .552$. The interaction of trial-type and class revealed to be significant $F(6,152) = 6.66$, $MSE = 17593.002$, $p < .001$, $\eta_p^2 = .208$.

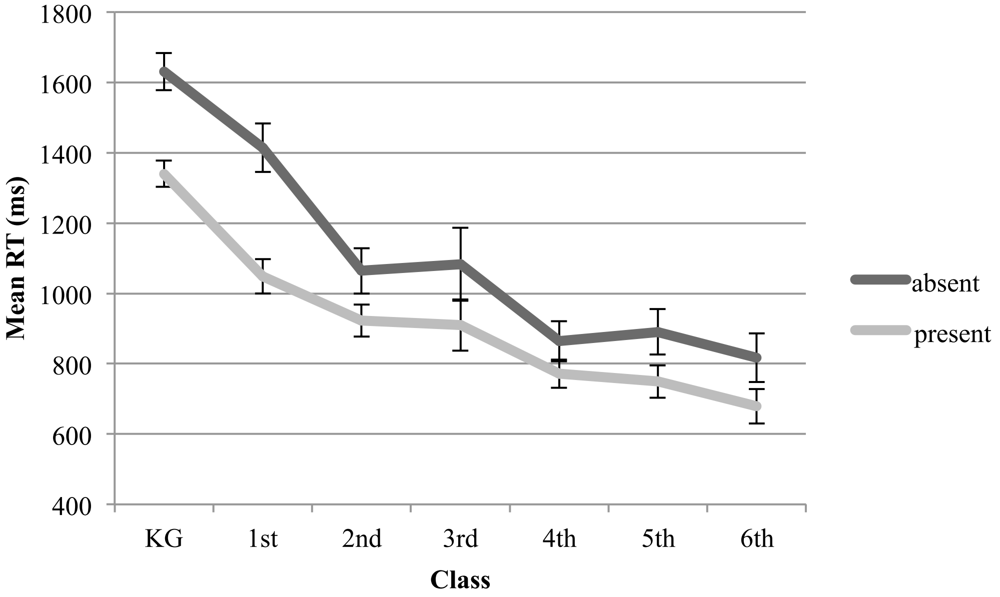


Figure 9. Mean RTs (ms) in target-absent (dark gray line) and target-present (light gray line) for each class. Error bars reflect the standard error of the mean.

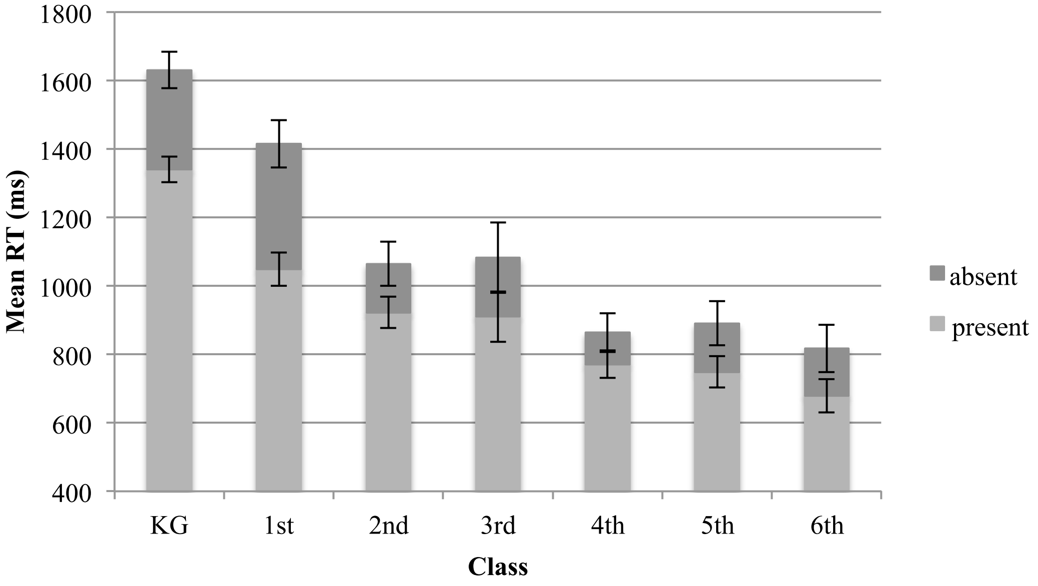


Figure 10. Mean RTs (ms) in target-absent (dark gray bar) and target-present (light gray bar) for each class. The difference between the two bars of each class depicts the

diminishing RT-difference between target-absent and target-present trials with increasing class. Error bars reflect the standard error of the mean.

A closer look at the interactions revealed that the ratio between target absent and target-present trials (calculated by the difference between absent and present RTs) decreases from the KG to the 6th class (290.2 ms, 365.9 ms, 141.7 ms, 172.6 ms, 92.8 ms, 141.7 ms. 137.9 ms), however, not in a linear fashion (see Figure 10). Further, target present RTs were analyzed depending on the target dimension of each trial. In a repeated measures ANOVA the factor target dimension (color, orientation) and the between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) were compared. The main effect of target dimension was significant, $F(1,152) = 55.312$, $MSE = 4124.444$, $p < .001$, $\eta_p^2 = .267$, once again emphasizing the advantage of color processing (888.8 ms) over orientation (946.8 ms) processing. The between factor of class was significant, $F(6,152) = 30.217$, $MSE = 48298.213$, $p < .001$, $\eta_p^2 = .544$, revealing a decrease in overall RTs the higher the class (KG: 1340.9 ms, 1st: 1049.2 ms, 2nd 923.4 ms, 3rd 910.6 ms, 4th 771.5 ms, 5th 749.5 ms, 6th 679,8 ms). There was no significant interaction, $F(6,152) < 1$, *n.s.*.

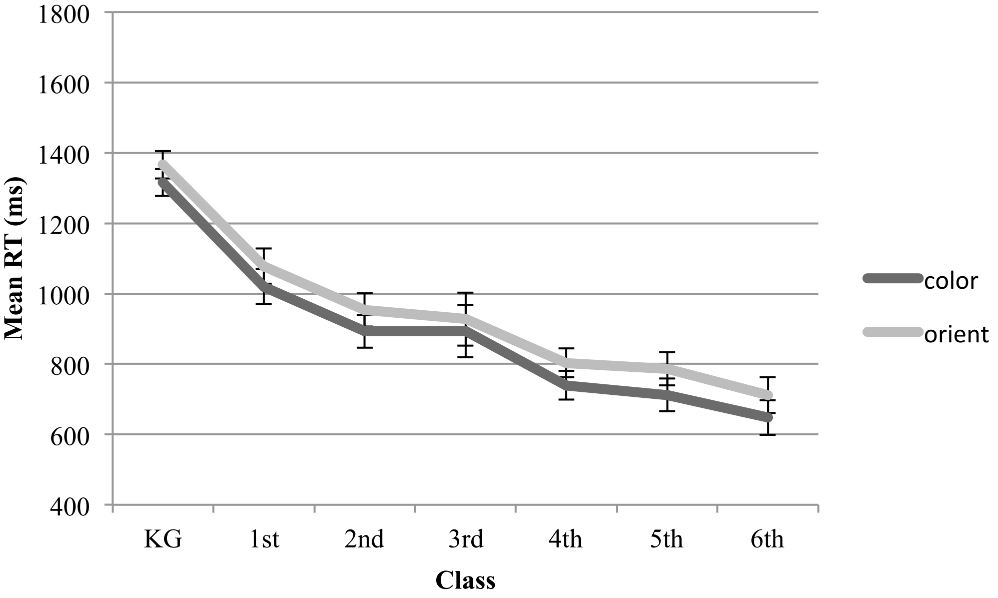


Figure 11. Target-present mean RTs (ms) towards colored targets (dark gray line) and oriented targets (light gray line) for each class. Error bars reflect the standard error of the mean.

The decreased RTs towards color targets compared to oriented targets was not significant for the KG and the 3rd class, as revealed by paired t-tests: KG: $t(33) = 1.875$, two-tailed $p = .070$; 3rd class: $t(8) = 1.206$, two-tailed $p = .262$; for the other classes however, the difference was significant with faster RTs towards colored targets: 1st class: $t(19) = 3.084$, two-tailed $p = .006$; 2nd class: $t(22) = 4.413$, two-tailed $p < .001$; 4th class: $t(29) = 7.534$, two-tailed $p < .001$; 5th class: $t(22) = 9.789$, two-tailed $p < .001$; 6th class: $t(19) = 5.475$, two-tailed $p < .001$.

Further RT examination compared responses towards targets depending on their distance from the fixation cross. Targets could appear on the inner, the second or third circle. The repeated measures ANOVA with the within factor target distance (circle1, circle2, circle3) and the between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) revealed the distance to have a significant effect of faster RTs for targets closer to the middle of the display (circle1: 892.7 ms, circle2: 911.3 ms, cirlce3: 931.4 ms), $F(1.876,285.155) = 12.32$, $MSE = 4397.903$, $p < .001$, $\eta_p^2 = .075$ [Huynth-Feldt corrected]. The between factor of class was significant, $F(6,152) = 29.914$, $MSE = 49289.817$, $p < .001$, $\eta_p^2 = .541$. There was no significant interaction between target circle and class $F(11.256,285.155) < 1$, *n.s.* [Huynth-Feldt corrected]. To look into the data separately a repeated measure ANOVA was calculated for each class (see Table 1).

Table 1. Mean Reaction Time for Target Distance

Comparison of mean reaction time for target-present trials with different target distances from the center of the screen by class

Class	Circle	*M* RT (*SD*)		Diff. *M* RT	*df*	*t*	*p*
KG	1	1325.9 (399.1)	c1-c2	-11.1	33	-0.356	.724
	2	1337.0 (389.7)	c2-c3	-17.3		-0.719	.477
	3	1354.3 (352.5)	c1-c3	-28.4		-1.23	.227
1st	1	1007.5 (257.3)	c1-c2	-33.4	19	-1.102	.284
	2	1040.9 (259.0)	c2-c3	-28.2		-1.593	.128
	3	1069.1 (234.7)	c1-c3	-61.6		-2.507	**.021**
2nd	1	905.1 (189.5)	c1-c2	-1.7	22	-0.179	.860
	2	906.8 (185.7)	c2-c3	-35.5		-2.405	**.025**
	3	942.3 (200.6)	c1-c3	-37.2		-2.426	**.024**
3rd	1	880.4 (207.6)	c1-c2	-28.9	8	-1.264	.242
	2	909.3 (225.0)	c2-c3	-9.0		-0.717	.494
	3	918.3 (202.1)	c1-c3	-37.9		-2.086	.070
4th	1	749.7 (95.5)	c1-c2	-12.0	29	-1.203	.239
	2	761.7 (108.2)	c2-c3	-22.5		-3.012	**.005**
	3	784.2 (99.1)	c1-c3	-34.5		-4.889	**< .001**
5th	1	717.6 (111.9)	c1-c2	-37.0	22	-3.504	**.002**
	2	754.7 (137.9)	c2-c3	-3.4		-0.325	.748
	3	758.1 (124.8)	c1-c3	-40.5		-6.63	**< .001**
6th	1	662.5 (89.3)	c1-c2	-5.9	19	-0.828	.418
	2	668.4 (77.1)	c2-c3	-24.8		-3.595	**.002**
	3	693.2 (65.4)	c1-c3	-30.7		-3.38	**.003**

Note. Significant comparisons emphasized by bold numbers.

2.7 Eye Movement Results

2.7.1 Eye Movements Removal of Outliers

Only trials that met the RT analysis criteria were considered for analysis of eye movement parameters. Before any further analysis, the eye movement data was checked for validity. For instance trials in which a blink occurred (10.6%) were excluded ('interruption of processing'). Additionally, any trials containing a saccade duration longer than 500 ms ('aberrant value for display size') were also rejected from subsequent analysis, which reduced the data set by another 5.2%.

2.7.2 Eye Movement Percentage

The remaining trials were split into eye movement (EM-trial) trials and no eye movement trials (noEM-trial). A trial was considered as an EM-trial when there was at least one fixation (initial fixation) followed by a saccade. Trials with only one initial fixation (in most cases close to the position of the fixation cross) and no movement of the eye (i.e. saccade), was considered as a noEM-trial. Overall 97.2% of the remaining trials were EM-trials compared to 2.8% of noEM-trials, $t(158) = -89.3$, $p < .001$. Comparing the percentage of EM-trials between the different target dimensions, with a repeated-measures ANOVA with the factors trial-type (absent, color, orientation) and between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th), revealed the main effects of trial-type to be significant with a slightly lower percentage of eye movements for target-absent (96.1%) compared to colored target (98.6%) and oriented target (98.7%) trials: $F(1.217,184.99) = 26.802$, $MSE = 17.562$, $p < .001$, $\eta_p^2 = .150$ [Huynth-Feldt corrected]. There was no effect of the between factor of class $F(6,152) = 1.773$, *n.s.*. Planned simple contrasts revealed the difference to be significant for each target dimension compared to absent trials (absent vs. color: $F(1,152) = 27.506$, $MSE = 29.616$, $p < .001$, $\eta_p^2 = .153$, absent vs. orient: $F(1,152) = 28.935$, $MSE = 31.165$, $p < .001$, $\eta_p^2 = .160$). There was no significant difference between color and orientation trials $F(6,152) < 1$, *n.s.*.

Table 2. Excluded Eye Movement Trials

Percentage of trials excluded from analysis due to blink and saccade duration criterion

	Class							
Exclusion criteria	KG	1st	2nd	3rd	4th	5th	6th	Average
Blink (%)	27.3	12.9	10.0	8.2	4.0	7.9	4.1	10.6
Saccade duration > 500 ms (%)	12.9	6.3	3.8	4.9	1.8	4.7	1.9	5.2
Total	40.9	19.2	13.8	13.1	5.8	12.6	6.0	15.8

The next step was to investigate the number of fixations made within a trial. The value of one was given to trials with only the initial fixation (usually near the fixation cross). The value two, therefore, means that this trial involved an initial fixation and an additional fixation during the display onset. The more fixations there were the higher the value. Comparing the number of fixations across classes, showed the same pattern of the highest percentage of trials with two fixation (average 39.9%), then followed by three (average 33.3%) and then decreasing in frequency with increasing number of fixations (see table below).

Table 3. Fixations per Trial in Search Task

Frequency (%) of the sum of fixations in a trial by class

	Number of fixations							
Class	1	2	3	4	5	6	7	> 7
KG	1.8	**37.3**	29.8	15.6	7.7	3.8	1.9	2.1
1st	0.5	**36.5**	28.8	15.8	8.9	4.7	2.4	2.4
2nd	2.1	**41.1**	34.4	14.1	5.2	2	0.6	0.4
3rd	1.6	**35.2**	34.9	16.2	5.8	3.6	1.3	1.4
4th	4.3	**44.6**	35.4	11.2	3.1	1	0.4	0.1
5th	6.1	**41.5**	33.7	11.8	4.2	1.3	0.9	0.4
6th	2.2	**43.1**	36.3	13.2	3.5	1.1	0.3	0.4
Average	2.7	**39.9**	33.3	14.0	5.5	2.5	1.1	1.0

Note. Bold value indicates the highest percentage.

2.7.3 Saccade Latency Removal of Outliers

Saccade latency is defined by the time between the onset of the search display and start of first fixation. Saccade latency data were analyzed in two steps. First, for each participant, a histogram distribution of all target present latencies of first saccades after display onset was generated. The histogram allowed the identification, by visual inspection, of the component-distribution of fast saccade latencies that were not related to the display onset. The procedure to determine the cut off point of fast saccade latencies was to identify the lowest point of the first trough. Based on this criterion, saccades with latencies shorter than 150 ms were excluded from latency analysis (7.7%). Further, saccades with latencies above 500 ms (lowest point of the trough after peak of distribution) were excluded from the analysis, (0.5%).[1]

2.7.4 Saccade Latency Results

Saccade latencies of the first saccade were compared in a UNIANOVA with the factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) to reveal a significant effect of shorter saccade latencies the higher the class: $F(6,152) = 35.019$, $MSE = 355.086$, $p < .001$, $\eta_p^2 = .580$. Repeated contrasts, by comparing every class with the corresponding next higher grade, showed only a significant difference between the KG (293.9 ms) and the 1st class (277.9 ms) ($p = .003$), the 1st class and 2nd class (264.2 ms) ($p = .018$), and between the 4th (250.1 ms) and 5th class (236.0 ms) ($p = .013$).

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[1] Eye movement analysis calculated without the cutoff led to the same pattern of results.

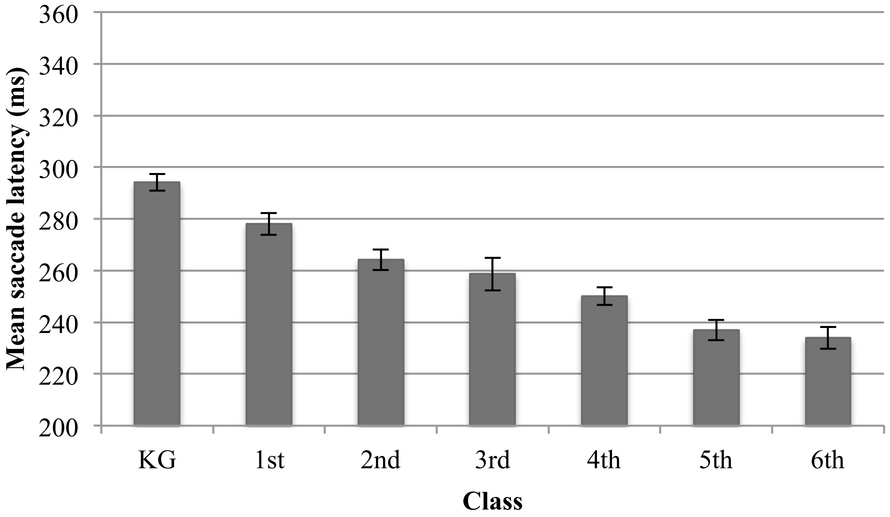

Figure 12. Target-present mean saccade latencies (ms) for each class. Error bars reflect the standard error of the mean.

As observed in some of the classes for the manual RTs responses towards colored targets were faster than responses towards oriented targets. To find out whether this dissociation already precedes the manual RT we investigated the first saccade latency depending on the target property. The repeated measures ANOVA with the factor target dimension (color, orientation) and the between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) revealed a significant main effect of shorter saccade latencies towards colored (245.6 ms) compared to oriented (275.2 ms) targets: $F(1,152) = 694.259$, $MSE = 97.672$, $p < .001$, $\eta_p^2 = .82$. The saccade latencies showed a significant effect by accelerated saccades for higher classes: $F(6,152) = 34.69$, $MSE = 356.274$, $p < .001$, $\eta_p^2 = .578$. There was no significant interaction, $F(6,152) < 1$, *n.s.*.

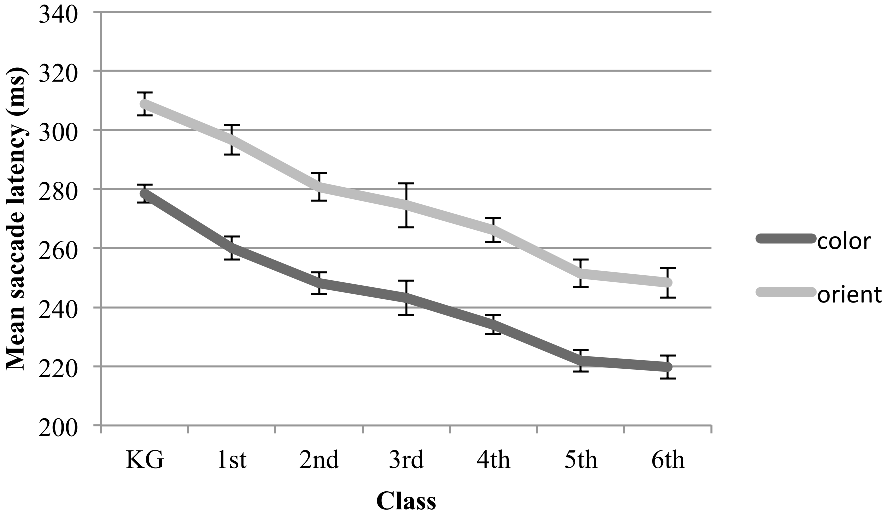

Figure 13. Target-present mean saccade latencies (ms) in colored target (dark gray line) and oriented target (light gray line) trials for each class. Error bars reflect the standard error of the mean.

The decreased saccade latencies towards color targets compared to orientation targets was significant across all classes, as revealed by seven paired t-tests: KG: $t(33) = 10.126$, two-tailed $p < .001$; 1st class: $t(19) = 10.961$, two-tailed $p < .001$; 2nd class: $t(22) = 14.058$, two-tailed $p < .001$; 3rd class: $t(8) = 4.85$, two-tailed $p = .001$; 4th class: $t(29) = 12.298$, two-tailed $p < .001$; 5th class: $t(22) = 13.71$, two-tailed $p < .001$; 6th class: $t(19) = 12.24$, two-tailed $p < .001$.

Further saccade examination compared latencies towards targets depending on its distance from the fixation cross. As reminder targets could appear on the inner, the second or third circle. The repeated measures ANOVA with the within factor target distance (circle1, circle2, circle3) and the between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) revealed the distance to have a significant effect of shorter latencies in trials with targets closer to the middle of the display (circle 1: 253.1 ms, circle2: 254.8 ms, cirlce3: 265.0 ms), $F(1.779,270.463) = 82.834$, $MSE = 76.224$, $p < .001$, $\eta_p^2 = .353$ [Greenhouse-Geisser corrected]. The between factor of class showed an effect of decreases saccade latencies in higher classes $F(6,152) = 34.343$, $MSE = 335.738$; $p < .001$, $\eta_p^2 = .575$. The interaction between target distance and class showed a significant effect, a consequence of different pattern for the target distance between classes $F(10.676,270.463) = 3.909$, $MSE = 76.224$, $p < .001$, $\eta_p^2 = .134$ [Greenhouse-Geisser corrected]. To look into the data for each class, three paired sample t-tests were conducted, comparing the saccade latencies towards each target distance (see Table 4).

Table 4. Mean Saccade Latencies for Target Distance

Comparison of mean saccade latencies for target-present trials with different target distances from the center of the screen by class

Class	Circle	*M* RT (*SD*)		Diff. *M* RT	*df*	*t*	*p*
KG	1	282.9 (21.8)	c1-c2	-7.1	33	-2.837	**.008**
	2	290.0 (20.9)	c2-c3	-10.8		-5.320	< **.001**
	3	300.8 (27.7)	c1-c3	-17.9		-6.086	< **.001**
1st	1	268.9 (20.2)	c1-c2	-4.4	19	-1.490	.153
	2	273.2 (24.0)	c2-c3	-11.7		-4.236	**< .001**
	3	284.9 (27.0)	c1-c3	-16.0		-5.156	**< .001**
2nd	1	257.9 (12.0)	c1-c2	-0.4	22	-0.223	.826
	2	258.3 (13.8)	c2-c3	-12.6		-5.967	**< .001**
	3	270.9 (17.3)	c1-c3	-13.0		-5.027	**< .001**
3rd	1	247.8 (23.9)	c1-c2	-6.2	8	-1.568	.155
	2	254.0 (23.6)	c2-c3	-11.4		-4.125	**.003**
	3	265.4 (19.9)	c1-c3	-17.7		-5.203	**.001**
4th	1	244.5 (16.7)	c1-c2	-1.5	29	-0.754	.457
	2	246.0 (17.1)	c2-c3	-9.6		-6.701	**< .001**
	3	255.6 (18.7)	c1-c3	-11.1		-4.638	**< .001**
5th	1	239.5 (19.9)	c1-c2	8.3	22	3.198	**.004**
	2	231.3 (14.2)	c2-c3	-8.9		-5.269	**< .001**
	3	240.2 (18.3)	c1-c3	-0.7		-0.295	.771
6th	1	230.2 (14.7)	c1-c2	-0.7	19	-0.391	.700
	2	230.9 (14.3)	c2-c3	-6.3		-4.526	**< .001**
	3	237.2 (15.3)	c1-c3	-7.0		-3.194	**.005**

Note. Significant comparisons emphasized by bold numbers.

2.7.5 Saccade Peak Velocity

The saccade peak velocity was calculated for each first saccade among all the EM-trials. Between classes the peal velocity revealed a significant main effect of lower velocities with increasing class (KG: 196.3°/s; 1st 196.2°/s; 2nd 189.1°/s; 3rd 185.1°/s; 4th 183.5°/s; 5th 177.6°/s; 6th 181.9°/s), $F(6,152) = 2.448$, $MSE = 520.683$, $p = .027$, $\eta_p^2 = .088$. Comparing each class with the next higher did not yield any significant difference. However, comparing the highest peak velocity from the KG group (196.3 °/s) against the other classes showed significant differences compared to the 4th class (183,5 °/s, $p = .027$), 5th class (177.6 °/s, $p = .003$) and 6th class (181.9 °/s, $p = .026$).

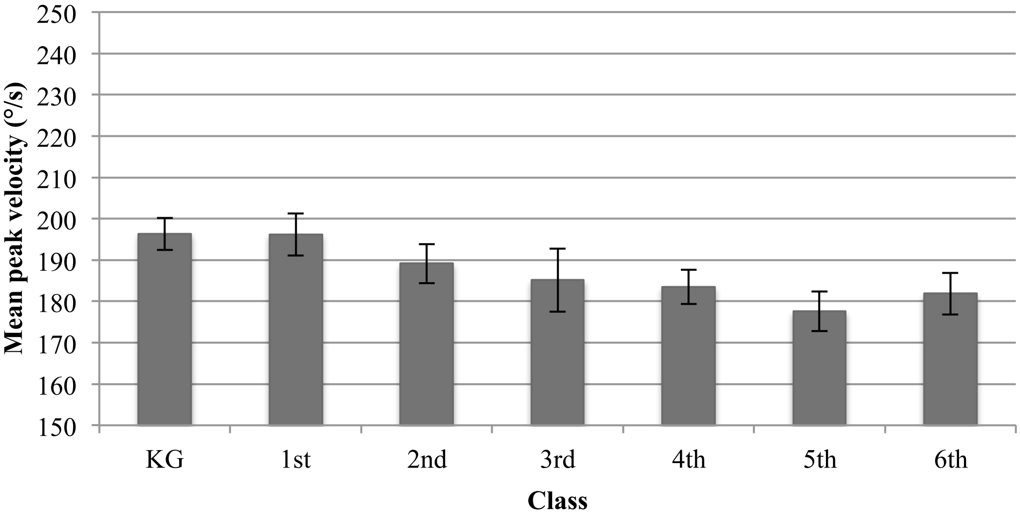

Figure 14. Saccades peak velocity in degree per second for each class. Error bars reflect the standard error of the mean.

2.7.6 Saccade Amplitude

The saccade amplitude was calculated for each first saccade of all EM-trials revealing a significant effect of higher saccade amplitudes for lower classes (KG: 3.9°; 1st 3.7°; 2nd 3.5°; 3rd 3.4°; 4th 3.4°; 5th 3.2; 6th 3.2°), $F(6,152) = 7.084$, $MSE = 1.645$, $p < .001$, $\eta_p^2 = .219$ (see Figure 15). Comparing each class with the next higher did not yield any significant difference. However, comparing the highest saccade amplitude from the KG group (3.9°) against the other classes showed significant differences compared to the 2nd class (3.7°, $p = .006$), 3rd class (3.5°, $p = .021$), 4th class (3.4°, $p < .001$), 5th class (3.2°, $p < .001$) and 6th class (3.2°, $p < .001$). A correlation between saccade peak velocity and saccade amplitude revealed a positive correlation, *r*(157) = .774, *p* < .01 (see Figure 16).

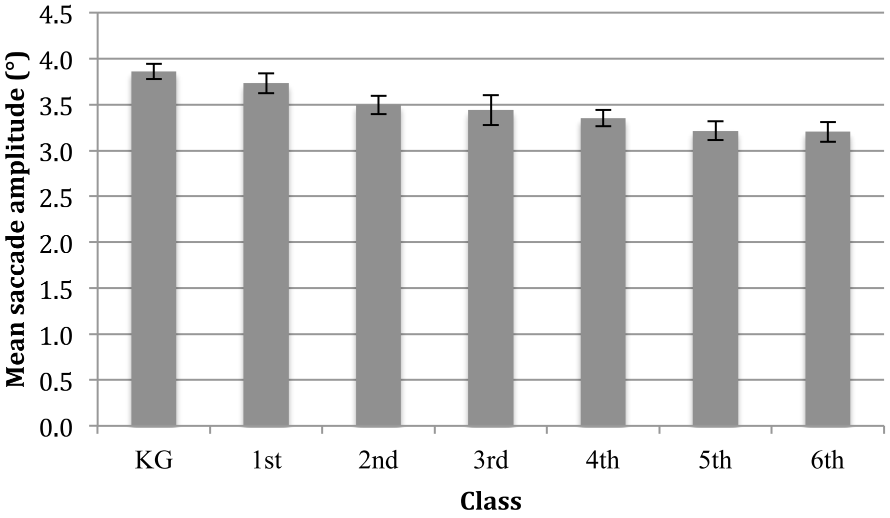

Figure 15. Mean saccade amplitude in degree for each class. Error bars reflect the standard error of the mean.

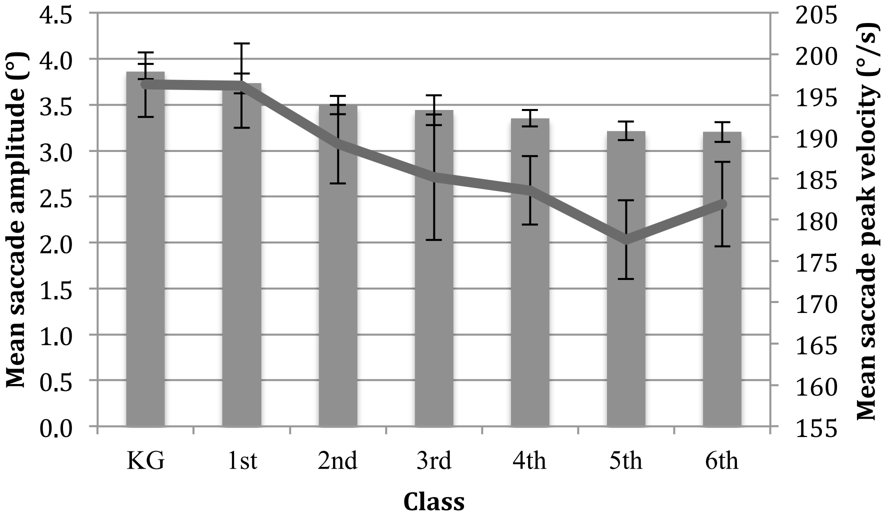

Figure 16. Mean saccade amplitude in degree for each class (grey bars). Mean saccade peak velocity in degree per second (dark grey line). Error bars reflect the standard error of the mean.

2.8 Method Motor Task

2.8.1 Participants

The same pupils also participated in the motor task except for four participants who did not complete the experiment due to motivational reasons (did not want to continue), leaving a total of 156 participants.

2.8.2 Method

The motor experiment was similar in method to the visual search experiment, except that this time participants did not have to distinguish between present and absent trials but had to press the same button at any appearance of the visual search display. The respond hand was counterbalanced and alternated after half of the experiment. The stimuli and the spatial arrangement were the same as in the visual search experiment. The timing was also the same apart for the blank preceding the search display, which lasted for a variable interval of 400, 500 or 600 ms, to avoid the possibility of generating a response rhythm.

2.8.3 Reaction Time Removal of Outliers

As in the Search Task the first step for RT analysis in the Motor Task was to inspect a suitable cut-off for each individual (examined by visual exploration of RT distribution) in their RT data. 11.3% of all trials in the Motor Task were excluded from analysis for being either responded to extremely slow or extremely fast (anticipatory answers or failure to respond in time). RTs with more than three standard deviations from the mean were calculated for each participant separately and excluded from analysis (0.8% of the remaining data).

2.8.4 Reaction Time Results

RTs in the Motor Task analyzed across the different classes in a UNIANOVA with the factor class revealed a significant effect of decreasing motor RTs with increasing class (see Figure 17) $F(6,148) = 15.982$, $MSE = 27684.293$, $p < .001$, $\eta_p^2 = .393$. Comparing the motor RTs between the classes in a consecutive manner with repeated contrasts, revealed significant increased RTs for the KG (668.3 ms) compared to the 1st class (530.0 ms) ($p = .005$) and significantly increased RTs for the 3rd class (549.6 ms) compared to the 4th (371.2 ms) (p = .006). The other comparisons did not yield any significant results but at least decreased in value to the previous class with the exception of the relative high RTs for the third class.

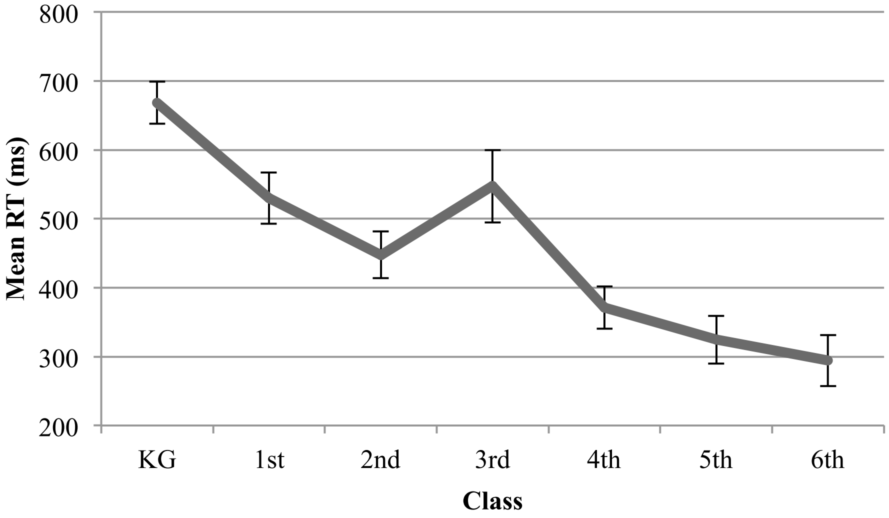

Figure 17. Motor RT (ms) for each class. Error bars reflect the standard error of the mean.

To compare the RT between the trial type of target-absent and target-present trials, a repeated measures ANOVA with the within factor trial-type (absent, present) and between factor of class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) was calculated, revealing no significant effect, $F(1,148) = 2.341$, $MSE = 840.639$, $p = .128$, $\eta_p^2 = .016$ (see Figure 18). The effect of class was significant showing an overall decrease in RTs for increasing class effect, $F(6,148) = 15.745$, $MSE = 28282.866$, $p < .001$, $\eta_p^2 = .870$, except for the third class, who seems to be an outlier in regards to the RTs.

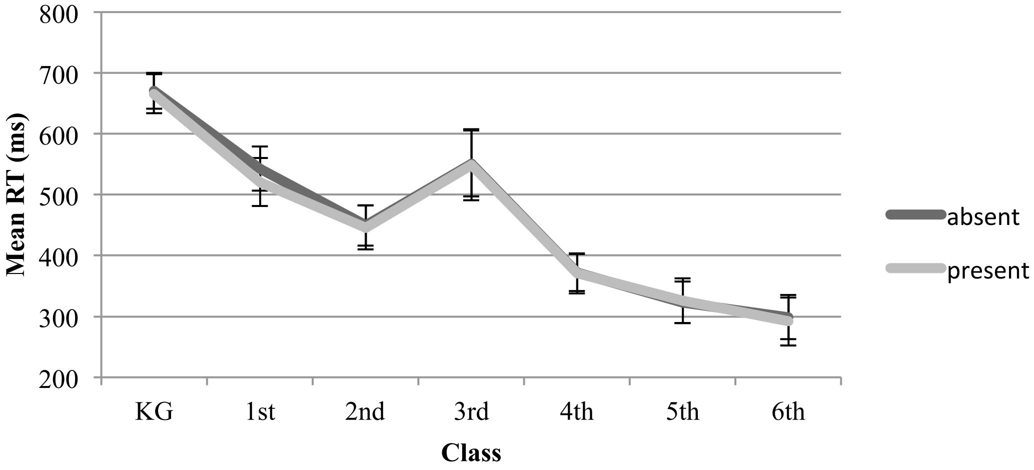

Figure 18. Motor RT (ms) in target-absent (dark gray line) and target-present (light gray line) trials for each class. Error bars reflect the standard error of the mean.

Further, target present RTs were analyzed depending on the target dimension of each trial. In a repeated measures ANOVA the factor target dimension (color, orientation) and the between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) were compared. The main effect of target dimension was not significant, $F(1,148) = 1.825$, $MSE = 968.674$, $p = .179$, $\eta_p^2 = .012$. The between factor of class was significant, $F(6,148) = 16.629$, $MSE = 26205.767$, $p < .001$, $\eta_p^2 = .878$, revealing a decrease in overall RTs the higher the class (KG: 665.9 ms, 1st: 523.1 ms, 2nd 448.9 ms, 3rd 557.1 ms, 4th 372.2 ms, 5th 325.4 ms, 6th 294.0 ms). There was no significant interaction, $F(6,148) = 1.396$, $p = .22$, $\eta_p^2 = .054$.

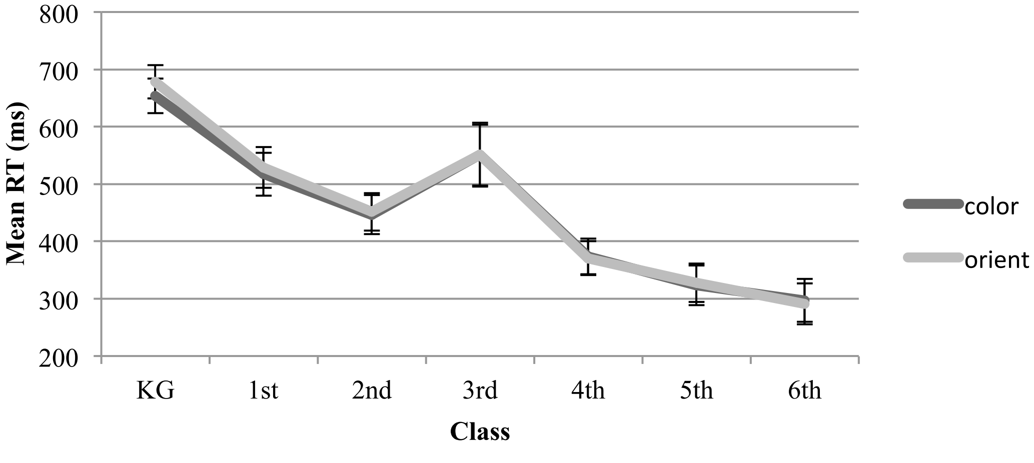

Figure 19. Motor RT (ms) in colored target (dark gray line) and oriented target (light gray line) trials for each class. Error bars reflect the standard error of the mean.

To examine the RT responses dependent on the target distance in the Motor Task a repeated measures ANOVA with the within factor target distance (circle1, circle2, circle3) and the between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) revealed the distance to have a no significant effect, $F(1.883,276.809) < 1$, *n.s.*. The between factor of class showed a significant effect of decreasing with increasing of class $F(1,147) = 16.046$, $MSE = 26869.371$, $p < .001$, $\eta_p^2 = .875$. A look at the interaction of target distance and class, revealed a significant effect $F(11.298,276.809) = 2.023$, $MSE= 1830.763$, $p = .025$, $\eta_p^2 = .076$ [Greenhouse-Geisser corrected], however, the deployed paired t-tests only revealed significant effects for the 2nd class comparing circle 1 RTs (479.4 ms) to circle 2 RTs (439.4 ms) ($p = .01$) and circle 3 RTs (441.7 ms) ($p = .02$).

The cognitive RT was calculated by subtracting the motor RT from target-present RT in the search task (cognitiveRT = presentRT-motorRT). The cognitive RT analyzed across the different classes in a UNIANOVA with the factor class revealed a significant effect of decreasing cognitive RT with increasing class $F(6,147) = 10.636$, $MSE = 37476.734$, $p < .001$, $\eta_p^2 = .303$.

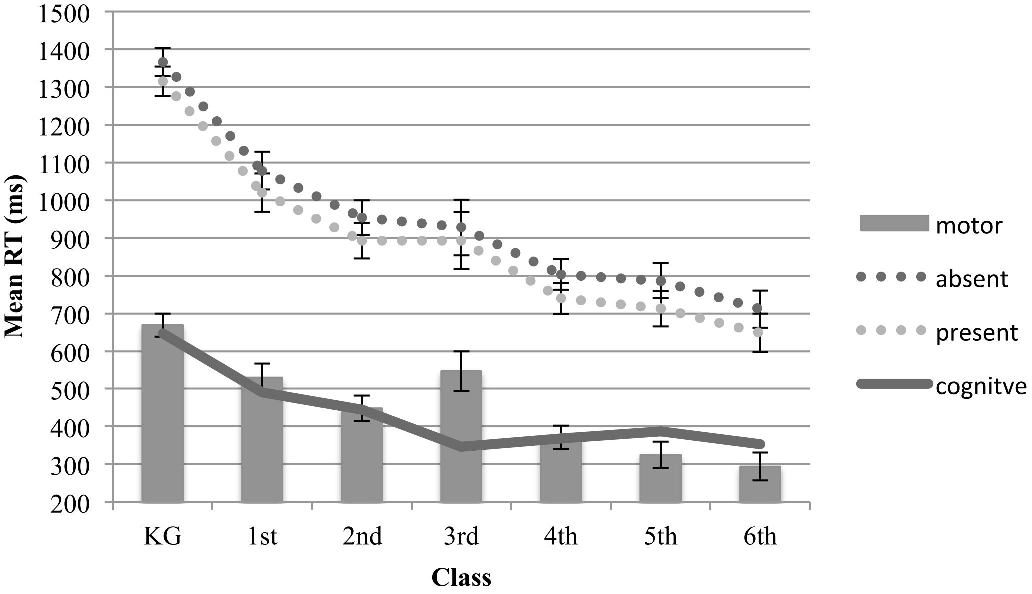

Figure 20. Reaction time (ms) depending on task and conditions by class. The dotted dark gray line shows target-absent RTs, the dotted light gray line shows target-present RTs in the Search Task. The solid light gray bars show the RT in the Motor Task, which by subtracting form the target-present RT computes a cognitive RT depicted as the solid dark gray line. Error bars reflect the standard error of the mean.

2.8.5 *Eye Movements Removal of Outliers*

Only trials that met the RT analysis criteria were considered for analysis of eye movement parameters. Before any further analysis, the eye movement data was checked for validity. Trials in which a blink occurred (5.6%) were excluded ('interruption of processing'). Additionally, any trials containing a saccade duration longer than 500 ms ('aberrant value for display size') was also rejected from subsequent analysis, which reduced the data set by another 4.4%.

Table 5. Excluded Eye Movement Trials Motor Task
Percentage of trials excluded from analysis due to blink and saccade duration criterion

			Class					
Exclusion criteria	KG	1st	2nd	3rd	4th	5th	6th	Average
Blink (%)	15.6	5.1	5.8	6.6	1.6	3.2	1.1	5.6
Saccade duration > 500 ms (%)	12.2	4.0	4.9	5.5	1.0	2.2	0.9	4.4
Total	27.8	9.1	10.7	12.1	2.6	5.4	2.0	10.0

2.8.6 *Eye Movement Percentage*

The remaining trials were split into eye movement (EM-trial) trials and no eye movement trials (noEM-trial). A trial was considered as an EM-trial when there was at least one fixation (initial fixation) followed by a saccade. Trials with only one initial fixation (in most cases close to the position of the fixation cross) and no movement of the eye (i.e. saccade), was considered as a noEM-trial. Overall, the distribution was leveled at 52.3% of noEM-trials and 47.7% EM-trials. However, a repeated measures ANOVA with the within factor of EM-trial (noEM, EM) and the between factor of class did not show any significant effect for either main effect: EM-trial: $F(1,148) = 1.383$, $MSE = 986.646$, $p = .241$, $\eta_p^2 = .009$; class: $F(1,6) < 1$, *n.s.* but showed a significant interaction between EM-trial and class: $F(6.148) = 20.051$, $MSE = 986.646$, $p < .001$, $\eta_p^2 = .448$. Consecutive paired sample t-tests comparing the eye movement frequency across classes showed that there is a switch in pattern after the 2nd class. At the stage of KG and the 1st class the ratio of eye movements is in favor towards making eye movements: KG: noEM: 25.9% vs. EM: 74.1%, $t(29) = -7.994$, $p < .001$;

1st class: noEM: 36.7% vs. EM: 63.3%, *t*(19) = -3.190 , *p* = .005. For the 2nd and 3rd class the frequency of eye movement did not differ significantly: 2nd class: noEM: 48.7% vs. EM: 51.3%, *t*(23) = -0.268, *p* = .791; 3rd class: noEM: 36.0% vs. 64.0%, *t*(8) = -1.655; *p* = .137. From the 4th class upwards the ratio switches to be in favor of a lower frequency of eye movements: 4th class: noEM: 69.3% vs. EM: 30.7%, *t*(28) = 3.943, *p* < .001; 5th class: noEM: 67.6% vs. EM: 32.4%, *t*(22) = 3.426, *p* = .002; 6th class: noEM: 81.5% vs. EM: 18.5%, *t*(19) = 7.225, *p* < .001).

The next step was to investigate the number of fixations made within a trial. The value of one was given to trials with only the initial fixation (usually near the fixation cross). The value two, therefore, means that this trial involved an initial fixation and an additional fixation during the display onset. The more fixations there were the higher the value. Comparing the number of fixations across classes, showed a differing pattern depending on the class. Whereas, for the KG, trials with only an initial fixation occurred in 28.9% of the trials and a second fixation reached the highest value of 50.6%, this pattern changed across classes. Already in the first class the tendency can be observed, that trials with only initial fixations increase (38.4%) and the necessity for a second fixation decreases (48.0%). At the stage of the sixth class the pattern has reached the exact opposite with 82.2% of trials with only an initial fixation and 14.5% of the trials elicited a second fixation (fore more detail see table below).

Table 6. Fixations per Trial in Motor Task

Frequency (%) of the sum of fixations in a trial by class

			Number of fixations					
Class	1	2	3	4	5	6	7	> 7
KG	28.9	**50.6**	15.8	3.2	1.1	0.3	28.9	50.6
1st	38.4	**48.0**	10.5	2.6	0.5	0.0	38.4	48.0
2nd	**50.3**	40.5	7.5	1.6	0.1	0.0	50.3	40.5
3rd	38.6	**45.3**	11.9	2.8	1.3	0.2	38.6	45.3
4th	**69.9**	25.3	4.1	0.5	0.1	0.0	69.9	25.3
5th	**69.5**	24.4	4.6	1.3	0.3	0.0	69.5	24.4
6th	**82.2**	14.5	2.4	0.8	0.1	0.0	82.2	14.5
Average	**54.0**	35.5	8.1	1.8	0.5	0.1	54.0	35.5

Note. Bold value indicates the highest percentage.

2.8.7 Saccade Latency Clean

Saccade latency data were analyzed in two steps. First, for each participant, a histogram distribution of all target present latencies of first saccades after display onset was generated. The histogram allowed the identification, by visual inspection, of the component-distribution of fast saccade latencies that were not related to the display onset. The procedure to determine the cut off point of fast saccade latencies was to identify the lowest point of the first trough. Based on this criterion, saccades with latencies shorter than 150 ms were excluded from latency analysis (8.0%). Further, saccades with latencies above 500 ms (lowest point of the trough after peak of distribution) were excluded from the analysis, (0.8%)[2].

2.8.8 Saccade Latency Results

Following saccade latencies (i.e. time between the onset of the search display and start of first fixation) of the first saccade were compared in a UNIANOVA with the factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) to reveal a significant effect of faster saccade latencies the higher the class: $F(6,147) = 13.144$, $MSE = 588.372$, $p < .001$, $\eta_p^2 = .349$.

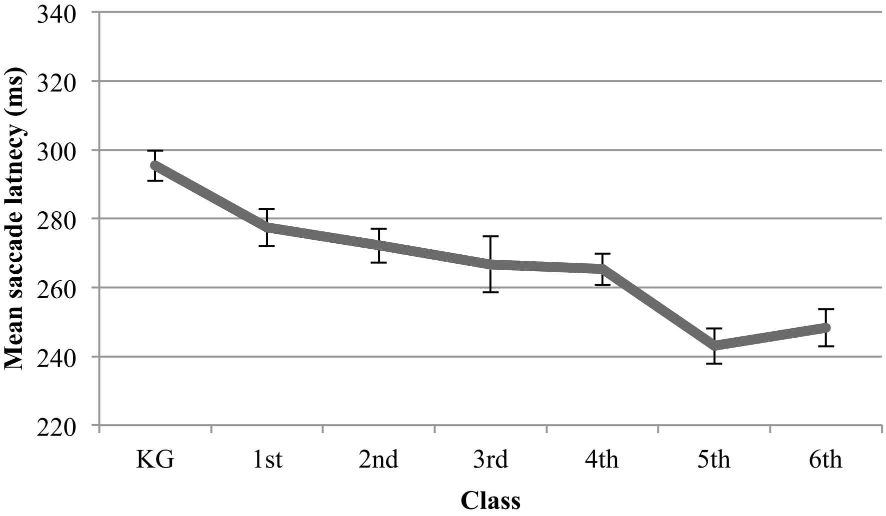

Figure 21. Target-present mean saccade latencies (ms) for each class. Error bars reflect the standard error of the mean.

Comparing the saccade latency between the classes in a consecutive manner with repeated contrasts, revealed significant increased saccade latencies for the KG (295.4 ms) compared to the 1st class (277.4 ms) ($p = .011$) and significantly increased saccade

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[2] Eye movement analysis calculated without the cutoff led to the same pattern of results.

latencies for the 4th class (265.3 ms) compared to the 5th class (243.0 ms) (p = .001). The other comparisons did not yield any significant results but decreased in value to the previous class with the exception of the 6th class, which showed a slight, but not significant, increase compared to the 5th class. Note that with increasing class the frequency of EM-trials decreased and therefore the 6th class had the least EM-trials for analysis.

Next we investigated saccade latency depending on the target property. The repeated measures ANOVA with the factor target dimension (color, orientation) and the between factor class (KG, 1st, 2nd, 3rd, 4th, 5th, 6th) revealed a significant main effect of faster saccade latencies towards color (255.5 ms) compared to orientation (282.4 ms) targets: $F(1,133) = 179.244$, $MSE = 247.818$, $p < .001$, $\eta_p^2 = .574$. The saccade latencies showed a significant effect by shorter saccade latencies for higher classes: $F(6,133) = 10.761$, $MSE = 565.964$, $p < .001$, $\eta_p^2 = .327$.

2.9 Discussion

2.9.1 Reaction Time

In general, the present study has refined the knowledge with regard to the role of developmental cognitive processes in search performance increasing with age, previously investigated in other studies (Donnelly et al., 2007; Gerhardstein & Rovee-Collier, 2002; Gerhardstein, Kraebel, Gillis, & Lassiter, 2002; Trick & Enns, 1998). While reaction time measures show expected improvements over age, eye movement measurements also revealed differences in single parameters and in overall strategies across different age groups. Regarding the manual reaction times in a feature search, all children of each class showed the typical RT pattern of faster responses in target-present trials compared to target-absent trials (Chun & Wolfe, 1996), supporting the notion of the feature integration theory by Treisman and Gelade (1980). This can be seen as evidence that children and adults identically search for a target differing from distractors in a single feature. The RTs form the motor task could partly explain the higher Y-intercept of the younger children's RTs and support the idea of myelination accelerating information processing (Trick & Enns, 1998). Also, it accounts for the reduction of the RT difference between target-absent and target-present trials across age. With increasing age the pure motor response expedites, shortening the overall search time by the time required for the execution of a response. Previous results of faster responses towards colored targets compared to oriented targets found in young children by Donnelly and Cave (2007), Lobaugh (1998) could be replicated, however persisted all the way up to the 6th class with children up to the age of 13 years. Therefore, the assumption of different processing of certain dimension (in this case orientation) within a feature search only for younger children can be ruled out. The overall faster RTs towards colored targets can be explained with a higher saliency signal, favoring its detection against oriented targets. Additionally, children above the kindergarten age show an advantage for responding towards targets closer to the center of the screen. This translates to a broader focus of attention compared to the children at KG age (5 to 6 years of age). Children at KG level need to shift their attention towards targets at each circle whereas older children can comprise the first to circles in one glance yet the furthest circle requires a longer traveling time for the attentional spotlight. Research on the visual span in children during reading (Rayner, 1986) showed that there is a developmental growth in visual span size around the 3rd grade (Kwon, Legge, & Dubbels, 2007). To transfer the findings from the reading literature to visual search pattern in children, further studies should focus on the visual span during visual search in children.

In general, the RT findings of the present experiments across children of different ages, ranging from 5 to 13 years, indicate the direction of approaching adult performances in a feature search task. This is in line with Grubert, Indigo and Krummenacher (2014), who postulate that from the age of 16 years search performance is equivalent to the level of adults. To summarize, significant RT drops were revealed across children of all school classes across age groups from 5 to 13 years fitting the pattern of adult-like search performance at all ages. Overall, the reduction of search RTs related to age can be accounted for by sensory-motor maturation as seen in the mere motor RT.

2.9.2 Eye Movements

To obtain a deeper understanding of underlying processes in children's performance within a feature search, looking at the eye movements revealed different strategies across the different classes and showed certain eye movement characteristics to develop over time. All children used the global strategy of locating the target within two fixations during the feature search, an initial fixation close to the fixation cross, and a second fixation towards the target. The programming of that saccade (saccade latency) however, required more time for younger children and decreases with age supporting findings by Munoz et al. (1998). As the saccade latency happens earlier in the search process it is an immediate result of the segregation of the search display. Alternatively one can assume that the programming of saccades requires more time for children of younger age, yet develops over time. In accordance with the motor RT acceleration, this can be attributed to faster information processing due to myelination. In accordance with the RT, saccade latencies show the same disparity of faster responses towards colored compared to oriented targets. The temporal increase of on average 30 ms on the saccade latency level extends to on average 60 ms on the manual RT level. There seems to be an additive effect delaying the prior processing time by a margin of 30 ms. Future work is required here to investigate the source and transfer of the retained temporal interval. Regarding the target distance, the pattern of saccade latency stayed fairly constant across all classes with increasing saccade latencies for targets further away form the center. Given the fact, that saccade latencies temporally precede the manual RTs, it is not surprising to find the same pattern for both responses (latency and RT) towards response-relevant targets. Results on the peak velocity support the results previously described by Accardo et al.(1992), Irving et al. (2006) and Fioravanti et al. (1995) with saccade peak velocity greater for children of younger ages, specially at KG level. As previously mentioned the uncoupling of the mere motor response time form the search time allowed for observation of acceleration over age. Additionally it yielded some more insight into changing oculomotor pattern within a simple task yet using the same architecture of the search task. As a confirmation that children of all classes understood the task there was neither a significant difference between the target-absent and target-present, nor was there a significant difference between the target dimensions (color, orientation). Children responded as soon as the display appeared. Surprisingly, when looking at the eye movement occurrences during the motor task, interesting findings were revealed. Although the task did not require any detection of a target, younger children up to the 3rd class executed more eye movement trials than no eye movement trials. At the age of the 4th class this pattern reverses by dwindling eye movement trials. As the response is irrelevant of any target detection children form the 4th class upwards inhibit moving their eyes across the visual search display. This shows the inhibitory advantage elderly children have over younger ones as mentioned in (Luna et al., 2008). Acik, Sarwary, Schultze-Kraft, Onat and König (2010) also put forward that children from the age of 7 to 9 years were more influenced by features of an image and that top-down influences become more apparent with increasing age. The relatively stubborn system of younger children could either improve by further learning or could indicate that several strategies could be generated according to the experiences. Children of younger age have yet to experience daily tasks in which inhibition and top-down control are necessary.

In general this study has proven that the visual search task fits the purpose to obtain reliable data of children as young as 5 years of age in regard to manual and oculomotor responses. This allows having a comparable and uncomplicated task for manual reaction time and eye movement recording across all ages. Thus, the present study provides the first overview of the relationship between manual and ocular responses in a visual feature search in children of different ages. It is now necessary to carry out further investigations along the age range in visual search tasks including reaction time and eye movement data. The difference between the age groups can clarify ongoing developmental changes and allow a more comprehensive understanding of underlying processes. Just as the motor response accelerates with increasing age other temporal components have shown to vary across the life span. In regard to the younger population it is of great importance to better understand attentional pattern in order to compare them to any malfunction or anything of the unordinary to introduce them as diagnostic tools. As the visual search task has been intensively used to investigate the nature of selective attention in adults, now, research with children with ADHD are increasingly examined and compared to control groups (Karatekin and Asarnow (1998); Hazell et al. (1999). Karategin and Asarnow (1998) showed that children with ADHD did not differ significantly in search times nor errors from controls and therefore they suggest same underlying search mechanisms within both groups. Although in a similar study by Hazell et al. (1999) ADHD children had augmented search times, similar search functions were reported for both groups. Research investigating search times postulate that there is no deficit in selective attention for children with ADHD compared to controls. By including oculomotor parameters any deficit hidden within the course of the manual reaction time could reveal different strategies in oculomotor control of children with ADHD. Karategin and Asarnow (1998) analyzed saccade latencies for ADHD compared to controls showing longer latencies for ADHD children, however only for absent trials. Future research should continue investigating additional oculomotor parameters, which allows dividing the search process into smaller segments.

3 Chapter II

Redundancy Gains in pop-out Visual Search are Determined by Top-down Task set: Behavioural and Saccadic Evidence.

3.1 Abstract

We combined behavioral and oculomotor measures to investigate whether redundancy gain effects in pop-out visual search are exclusively determined by bottom-up salience or are modulated by top-down search goals. Participants had to search for feature singeltons defined in a single dimension (color or shape) or redundantly in both dimensions. In the baseline condition, both color and shape were task-relevant, and behavioral redundancy gain effects (RSE) were preceded by shortened saccade latencies towards redundant as compared to single-dimension targets. This demonstrates that redundancy gains are generated early on the visual perception level making the RSE available for saccade programming. In the color target and shape target condition, only one dimension was task-relevant, while the other could be ignored. In these two conditions, behavioral and oculomotor redundancy gains were eliminated. We conclude that redundant-signals effects in pop-out visual search underlie the oculomotor system and depend on top-down modulation.

3.2 Introduction

The world around us should be the same for all of us; at least its objective reality. However, how we perceive it, more or less depends on the section we extract from it. In other words, the selection we make. This makes us seem like the instance that voluntarily chooses what enters our perception or not. This is only half of the truth. While attention can be guided voluntarily, following our will, attention can also be involuntarily attracted by external events. A sudden loud bang or a flash of light, to give a visual example, always elicits an orientation towards its source, irrespective of our will. In the literature these two types of attention are referred to as *top-down* (goal-oriented) and *bottom-up* (stimulus-driven) attention (Carrasco, 2011). From the early days on, however, attention was subject to debate over the question whether selection occurs on an early or late processing stage (Broadbent, 1954; J. A. Deutsch & Deutsch, 1963). Together, the question is not only about the *bottom-up* versus *top-down* influence on the attentional selection process but also if either influence happens at an early or late processing stage. Theories about visual attention, such as the guided search theory (Wolfe, 2007), postulates that any object we perceive is fundamentally processes by its features. Our brain possesses dimension-based modules for the processing of the object's features and attention is guided to the location of highest contrast compared to its surroundings. Thus, stimulus properties dictate information processing prior to shifts of attention (early stage) by integrating multiple object dimensions into a single response-relevant signal on a saliency map. Yet, this signal stays modifiable by higher order information by adding computational weight for any further processing (Found & Müller, 1996). In visual search a well-known phenomenon named the *redundant signal effect* (RSE) supports the idea of integration of dimension-specific processing systems, however its exact point of influence stays under debate (Feintuch & Cohen, 2002; Töllner, Zehetleitner, Krummenacher, & Müller, 2011). The RSE is the acceleration of responses triggered by two (or more), compared to just one response-relevant signal. Redundancy is usually composed of either two separate targets, as in the original studies by Miller (1982), or of two dimensions within the same target (Mordkoff & Yantis, 1993). In a typical redundancy experiment by Mordkoff and Yantis (1993), participants respond either to the letter X, the color green or the combination of both (a green X) presented at the same location. No response is required for any other appearance of letters or colors. Later, the RSE was investigated in visual search tasks (Krummenacher, Müller, & Heller, 2001; 2002) making participants search for targets either differing in one dimension (color or orientation) or in two dimensions (color and orientation) from homogeneous distractors. By using the visual search paradigm, the target location is randomly spread, making the participant engage in a search task, mitigating the original identification task (identify letter X or color green) to a simple detection task. In a recent paper, Grubert, Krummenacher and Eimer (2011) provided behavioral and electrophysiological evidence that the locus of redundancy gains, observed in responses towards dual-dimension singletons, lies at an early pre-attentive stage of processing and is modular by top-down information. In a visual pop-out search experiment participants had to detect and respond to a predefined target dimension (color, shape, color and shape) among distractors and to withhold a response in the absence of that particular target dimension. The experiment was divided into three conditions (color, shape, baseline), whereas the task instruction changed but the physical properties of the stimuli persisted. In the color condition, participants had to respond to a single-defined color singletons or dual-defined color and shape singletons (Go-trial). No response was necessary towards single-defined shape singletons and target absent trials (NoGo-trial). The equivalent was the case for the shape condition, in which participants had to respond towards single-defined shape singletons and dual-defined color and shape singletons (Go-trial). No response was necessary towards single-defined color singletons and target absent trials (NoGo-trial). In the baseline condition, participants had to respond towards the presence of any singleton differing from the distractors, in either single- (color or shape) or dual-dimension (color and shape), and had to withhold their response in the absence of any target. The crucial difference between both single conditions compared to the baseline conditions was the presence of a response-irrelevant dimension. In other words, in both (color and shape) conditions one dimension had to be ignored, if appeared as a singleton, however, requiring a response in combination with the target-defining dimension. The concluding result pattern of this design revealed behavioral redundancy gains in the baseline condition for dual-dimension targets compared to single-dimension targets as for example previously reported by Krummenacher et al. (2001; 2002). Additionally, Grubert et al. (2011) reported electrophysiological evidence using the N2pc, an electrophysiological marker of the spatially selective visual processing of targets (e.g., (Ansorge, Kiss, Worschech, & Eimer, 2011; Eimer & Kiss, 2008; Hopf, Luck, Girelli, & Hagner, 2000; Kiss & Eimer, 2010). N2pc onset latencies following dual-dimension targets were significantly shorter compared to N2pc onset latencies following single-dimension targets, which adds support to the pre-attentive locus of this effect (see also Töllner et al., 2011). In the appending single conditions (color, shape) the redundancy gain could no longer be observed, neither in the behavioral reaction times nor in the electrophysiological measure of N2pc onset latencies. The authors use the finding of redundancy gains on the level of the N2pc onset latency and the vanishing of the RSE in both single conditions to declare the origin of the effect to an early stage of processing. Namely, at the stage of weight allocation towards a predefined dimension as suggested by Müller, Reimann and Krummenacher (2003). In the baseline condition, both dimension of redundantly defined targets are coactively integrated at the saliency map level, leading to an increase of signal spike and thus speed the attraction of attention. In both single conditions, however, the weight of the response-irrelevant dimension is diminished, causing an attenuated impact of integration at the saliency map level. Thus, accounting for a lower contrast signal, apparent in delayed N2pc onset latencies and delayed manual reaction times. The assumption, that the RSE springs from an pre-attentive increased saliency signal (due to the coactive integration of both dimension-signals), and the understanding that the control of eye movements is closely linked to this saliency signal (Deubel & Schneider, 1996; Rizzolatti et al., 1987), raises the question, whether the same pattern of effects (shortened latencies) can be observed at the level of saccade latencies? Until now redundancy gains were mainly investigated in manual RTs for visual and multimodal stimuli (Miller, 1982). In regard to saccadic latencies however, only redundant signals consisting of auditory and visual stimuli were presented against unimodal stimuli (Arndt & Colonius, 2003; Hughes, Reuter-Lorenz, Nozawa, & Fendrich, 1994). In a study by Turatto and Betta (2006), they looked at saccade execution towards a predefined location (saccade goal) after the presentation of a single versus a dual visual transient acting as a Go-signal. They report shorter saccade latencies following a dual Go-signals (compared to one single Go-signal). Thus, saccade latencies are boosted by the presence of redundant information. In the present study we want to further investigate whether this effect can also be triggered by dual-defined dimension singletons, which would serve as redundant information at the same spatial location as the saccade goal. Additionally, we address the issue whether the top-down influence that abolishes behavioral and EEG redundancy gains also affect latencies of eye movements to single- and dual-defined dimension targets in a feature search condition.

Given the link between the attentional and oculomotor system, RSE in the baseline condition should go along with the RSE in both manual and saccadic RTs. Any disparity of the RSE between both measures would argue against a link of both systems and support the idea of two independent signals or at least a conditional link. For the single conditions the same line of argument accounts for the outcome of the RSE. In case of the same underlying signal for the control of attention and eye movements we would expect the signal to be modulated by top-down information, in this case the inability of guidance for a suppressed dimension. If however, the modulation does not occur at the early stage of saccade programming, and RSE are found similar to a bottom-up processing of the dimension at hand, suggests that the interference of the top-down information takes place after the saccade programming.

3.3 Method

3.3.1 Participants

Twelve students from the University of Fribourg, Switzerland, took part in this experiment for course credit (10 females; age range = 19 to 28 years, median age = 20.5 years). All participants were naïve as to the purpose of the experiment. All of them had normal or corrected-to-normal vision and all reported normal color vision.

3.3.2 Apparatus

Participants were seated in a darkened room to avoid reflection on the screen. They viewed the stimuli on a 17“ CRT color monitor run at a resolution of 1024 pixels horizontally and 768 pixels vertically and a screen refresh rate of 60 Hz driven by an Intel Core 2 Quad CPU 2.66GHz PC running the Windows XP operating system. MATLAB (version R2008b) and the Psychophysics and Eyelink (Brainard, 1997; Cornelissen et al., 2002; Pelli, 1997) toolbox extensions were used to program stimulus displays, the recording of manual responses and eye movements, and storage of raw data for offline analysis. A head-mounted, video-based infrared eye-tracking system (Eyelink II, SR Research, Ontario, Canada) with a spatial resolution of 0.1° and a temporal resolution of 500 Hz was used for eye movement registration. The participant’s head position was maintained in a stable position using a chin rest and forehead support (Eyelink). Participants viewed the display from a distance of 60 cm.

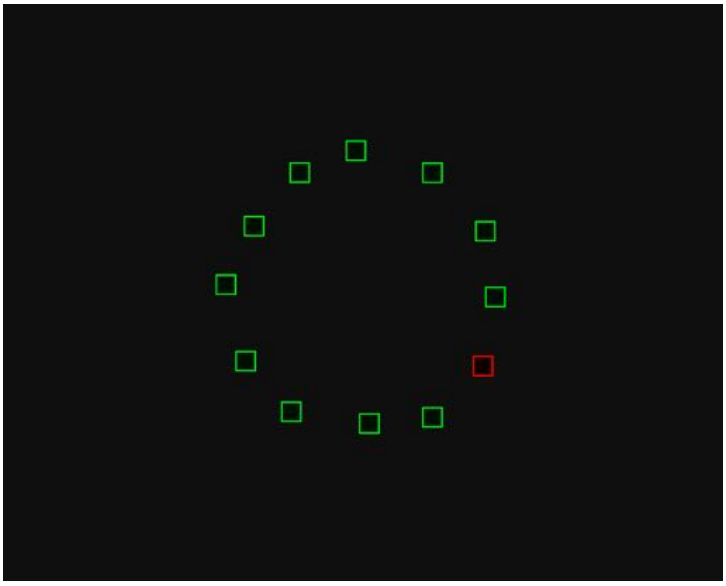

Figure 22. Example of a search display with a red color square presented among green distractor squares.

3.3.3 Stimuli and Design

Search displays consisted of 12 stimuli arranged on an imaginary circle with a radius of 8.17° of visual angle centered in the middle of the screen (see Figure 22 for an illustration of the search display). All item locations were randomly and independently 'jittered' by a maximum of +/-30 pixel (1.02°) on the vertical and horizontal axes. Stimuli were presented against a dark grey (RGB 15,15,15) background. Search items were red (RGB 255,0,0) or green (RGB 0,255,0) outline squares or diamonds (edge length: 1.26° x 1.26°; line width: 0.1°). Target items, on target-present trials, always appeared at a randomly selected location on the imaginary circle with equal probability of appearance at one of the 12 locations. Targets were defined either on the color (red square) or the shape (green diamond, i.e., square rotated by 45°) dimension (single-dimension target) or on both the color and shape (red diamond) dimensions (dual-dimension target). Distractors were green squares. The experiment comprised three conditions that were identical in terms of physical stimulus properties but differed with respect to task instructions. In all conditions, observers were instructed to respond when a predefined target item was present (go-response) and to refrain from a response when the predefined target was absent (no go-response). The sequence of completion of the three conditions was counterbalanced across observers.

In the *baseline condition,* observers were instructed to detect the presence of any odd-one-out item and to respond, by pressing the spacebar, irrespective of whether the target differed from distractors on the color, shape (single-dimension target) or the combination of color and shape (dual-dimension target) dimensions. On target-absent trials, that is, trials on which all search items were green squares, observers were instructed not to respond. Observers were instructed to indicate the presence of a singleton item as rapidly as possible; they were also instructed to avoid making errors. The baseline condition consisted of four blocks of 120 trials each, for a total of 480 trials. In each block, in 50% of the trials (60 trials) a target was shown, no target was shown in the other 50% of trials. Numbers of single-dimension color and shape and dual-dimension color plus shape trials were equally shown (20 trials each).

In the *color condition* observers were instructed to respond whenever one of the display items differed from the distractors by its color (go-trial) and to refrain from a response when no odd-one-out item was shown or when the odd item differed from distractors by its shape (no go-trials). Stated differently, observers responded to a red square (target dimension) or a red diamond (target plus non-target dimension) and they refrained from a response when a green diamond (non-target dimension) was present or when all the display items were green squares. The color condition consisted of six blocks of 80 trials each, for a total of 480 trials. In each block, in 75% of trials (60 trials) a singleton was shown, no target was shown in the other 25% of trials. Numbers of single dimension color and shape and dual dimension color plus shape trials were equally shown (20 trials each).

In the *shape condition*, observers were instructed to respond whenever one of the display items differed from distractors by its shape (go-trial) and to refrain from a response when no odd-one-out item was shown or when the odd item differed from distractors by its color (no go-trials). Observers responded to a green diamond (target dimension) or a red diamond (target plus non-target dimension) and they refrained from a response when a red square (non-target dimension) was present or when all the display items were green squares. The shape condition consisted of six blocks of 80 trials each, for a total of 480 trials. In each block, in 75% of trials (60 trials) a singleton was shown, no target was shown in the other 25% of trials. Numbers of single dimension shape and color and dual dimension color plus shape trials were equally shown (20 trials each). Observers completed a short training block of 20 trials prior to each condition to become familiar with the task. In the training blocks, observers were given feedback on whether they responded correctly or not. The experiment, including training, took about one and a half hours to complete.

3.3.4 Procedure

Before each condition participants underwent a 10-point calibration and each block started with a drift correction. Each trial started with the presentation of a white central fixation cross ('+' Times, 20 pt.) for 500 ms, followed by a black screen for 500 ms before the search display was presented. The search display was presented for a maximum of 1500 ms whereas by button-press (spacebar) the presentation would terminate. After each trial a black screen was interposed for 800 ms.. Between conditions, participants were encouraged to take a break.

3.4 Results

3.4.1 Reaction Time Removal of Outliers

Response trials with reaction times (RTs) shorter than 200 ms ('anticipation') and longer than 800 ms ('failure to respond in time') were excluded from analysis (0.57%). Further, trials with RTs exceeding the mean RT by more or less than three standard deviations (SD) were excluded from analysis on an individual basis (0.52%).

3.4.2 Errors

Error rates were low, overall 0.49%. Comparison between both single-feature conditions (color 0.31%, shape 0.83%) yielded no significant difference, $t(11) = -2.135$, $p = .056$. Neither did the baseline condition (0.33%) differ significantly form the color condition, $t(11) = 0.132$, $p = .898$. The remaining comparison between the baseline condition and the shape condition resulted in a higher error rate in the shape condition, $t(11) = -2.615$, $p = .024$. Profound analysis of the errors types (false alarm, miss) was not possible due to the overall low error rate. In all three conditions not a single response target was missed. This is a result of the maximum display time set to 1500 ms, giving the participants enough time to indubitable find and respond to the presence of a target. Error trials were excluded from further analysis.

3.4.3 Reaction Time Results

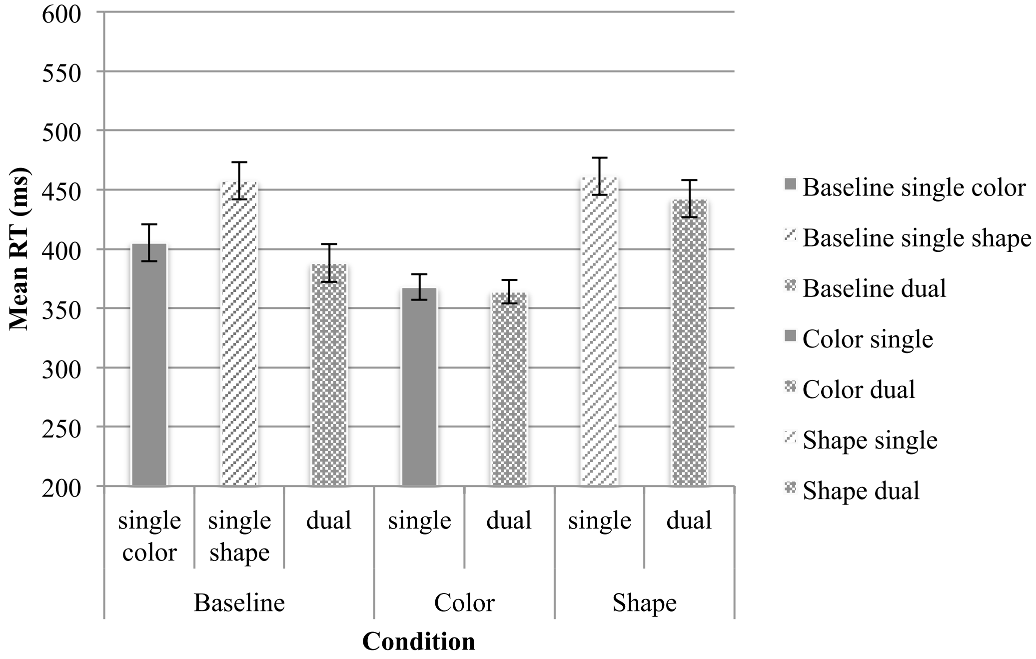

Figure 23. Mean RTs in target present trials split up into the three conditions (baseline, color and shape), and the different target-defined dimensions (single and dual).

Mean RTs of the *baseline condition* were subject to one-way repeated-measures ANOVA with the factor target-defined dimension (color single-dimension, shape single-dimension, color and shape dual-dimension). The ANOVA revealed the main effect of target-defined dimension to be significant, $F(2,22) = 77.407$, $MSE = 204.301$, $p < .001$, $\eta_p^2 = .876$. To follow up on the main effect, two-tailed paired *t*-tests were applied and yielded significantly faster RTs for dual-dimension (388 ms) compared to color single-dimension (405 ms) singletons, $t(11) = -7.929$, $p < .001$ and faster RTs for dual-dimension compared to shape single-dimension (458 ms) singletons, $t(11) = -9.877$, $p < .001$. In addition, RTs to color targets were faster than RTs to shape targets, $t(11) = -7.597$, $p < .001$. The effect of speeded RTs in response to dual-dimension singletons compared to single-dimension singletons is termed the redundant signal effect (RSE) and suggest a co-activation of both target-relevant dimension (Mordkoff & Miller, 1993).

In the *color condition* mean RTs towards dual-dimension (364 ms) and color single-dimension (368 ms) singletons did not differ significantly, $t(11) = -1.775$, $p =$

.104. To compare RTs towards the color single-dimension and dual-dimension singleton across conditions, a two-factor repeated-measures ANOVA with the factors condition (color, baseline) and target-defined dimension (single-dimension, dual-dimension) was calculated. The ANOVA yielded a significant main effect of condition with faster RTs in the color condition (376 ms) compared to the baseline (387 ms) condition, $F(1,11) = 5.508$, $MSE = 2071.379$, $p = .039$, $\eta_p^2 = .334$. The main effect of target-defined dimension yielded a significant effect of faster RTs towards dual-dimension (376 ms) compared to single-dimension (387 ms) targets, $F(1,11) = 37.531$, $MSE = 36.379$, $p < .001$, $\eta_p^2 = .773$. The interaction between condition and target-defined dimension yielded a significant effect, $F(1,11) = 25.086$, $MSE = 21.795$, $p < .001$, $\eta_p^2 = .695$. To follow up on the interaction two-tailed paired *t*-tests were applied and revealed RTs to single-dimension color targets to be faster in the color (368 ms) compared to the baseline (405 ms) condition, $t(11) = -2.918$, $p = .014$. RTs to the dual-dimension targets did not differ significantly across the two conditions (color: 364 ms, baseline: 388 ms), $t(11) = -1.781$, $p = .103$.

In the *shape condition* mean RTs towards dual-dimension (443 ms) singletons were faster than RTs towards shape single-dimension (461 ms) singletons, $t(11) = -3.93$, $p = .002$. To compare RTs towards the shape single-dimension and dual-dimension singleton across conditions, a two-factor repeated-measures ANOVA with the factors condition (shape, baseline) and target-defined dimension (single-dimension, dual-dimension) was calculated. The ANOVA yielded a significant main effect of condition with faster RTs in the baseline (423 ms) condition compared to the shape (453 ms) condition, $F(1,11) = 21.171$, $MSE = 478.066$, $p < .001$, $\eta_p^2 = .658$. The main effect of target-defined dimension yielded a significant effect of faster RTs towards dual-dimension (415 ms) compared to single-dimension targets (460 ms), $F(1,11) = 135.525$, $MSE = 173.703$, $p < .001$, $\eta_p^2 = .925$. The interaction between condition and target-defined dimension yielded a significant effect, $F(1,11) = 29.539$, $MSE = 263.294$, $p < .001$, $\eta_p^2 = .729$. To follow up on the interaction two-tailed paired *t*-tests were applied and revealed RTs to shape single-dimension targets to be as fast in the shape (461 ms) condition as in the baseline (458 ms) condition, $t(11) = 0.575$, $p = .577$. RTs to the dual-dimension targets were significantly faster in the baseline (388 ms) condition compared to the shape (443 ms) condition, $t(11) = 5.919$, $p < .001$.

To further investigate the appearance of the RSE within the three task conditions (color, shape, baseline), redundancy gains measured in the baseline condition and the two single-feature target conditions were compared via a two-way repeated-measures ANOVA with the factors condition (single, baseline) and redundancy type (color-related, shape-related). The redundancy gains were calculated separately for each dimension it was related to. For example, redundancy gains for the color condition are calculated by the RTs towards dual-dimension targets subtracted from RTs towards color single-dimension targets. Thus, the reaction time advantage supplied by the additional shape dimension is measured referring to as shape-related redundancy gain. Redundancy gains for the shape condition are calculated by the RTs towards dual-dimension targets subtracted from RTs towards shape single-dimension targets. Thus, the reaction time advantage supplied by the additional color dimension is measured referring to as color-related redundancy gain. Redundancy gains for the baseline condition where calculated by subtracting RTs to dual-dimension targets from RTs towards each single dimension targets within the baseline condition. RT redundancy gains were higher for the baseline (43.2 ms) condition compared to the pure single-dimension (11.3 ms) conditions, $F(2,22) = 45.219$, $MSE = 271{,}039$, $p < .001$, $\eta_p^2 = .805$. Comparison between color- and shape-related RT redundancy gains showed a larger redundancy gain for the shape (44.0 ms) condition (color-related redundancy gain (associated with the addition of the color dimension)) opposed to the color (10.4 ms) condition (shape-related redundancy gain (associated with the addition of the shape dimension)), $F(2,22) = 76.517$, $MSE = 177.051$, $p < .001$, $\eta_p^2 = .874$. The interaction between the task condition (baseline, single) and redundancy type (color-, shape-related) yielded a significant difference, $F(2,22) = 13.967$, $MSE = 299.917$, $p = .003$, $\eta_p^2 = .559$. To follow up on this interaction, two-tailed paired *t*-test was conducted, comparing the color- and shape-related RT redundancy gain across both single versus baseline condition. The shape-related redundancy gains in the color condition were lower than the shape-related redundancy gain in the baseline condition (single: 3.8 ms, baseline: 17.1 ms), $t(11) = -4.872$, $p < .001$. The color-related redundancy gains in the shape condition were lower than the color-related redundancy gain in the baseline condition (single: 18.7 ms, baseline: 69.4 ms), $t(11) = -5.407$, $p < .001$. This results shows a larger increase in RT redundancy gain for the baseline (50.6 ms) condition for color- and shape-related redundancy gains, compared to the RT redundancy gain for the single (13.3 ms) condition. In other words, the redundancy gain is more pronounced in the baseline condition.

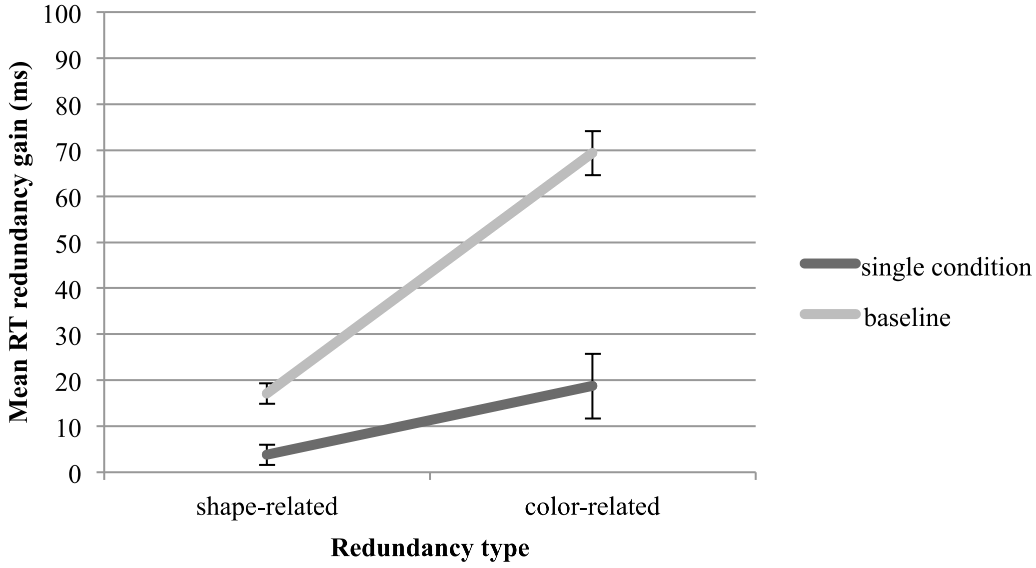

Figure 24. Mean manual RT redundancy gain relative to the associated dimension (color or shape) compared between conditions (single or baseline).

3.4.4 Eye Movement Percentage

Only trials that met the RT analysis criteria were considered for analysis of eye movement parameters (note: only go-response trials). Before any further analysis, the eye movement data was checked for validity. For instance trials in which a blink occurred (3.0%) were excluded ('interruption of processing'). Additionally, any trials containing a saccade duration longer than 80 ms ('aberrant value for display size') was also rejected from subsequent analysis, which reduced the data set by another 5.5%. The remaining trials were split into eye movement (EM-trial) trials and no eye movement trials (noEM-trial). A trial was considered as an EM-trial when there was at least one fixation (initial fixation) followed by a saccade. Trials with only one initial fixation (in most cases close to the fixation cross) and no movement of the eye (i.e. saccade) were considered as a noEM-trial. Overall of the remaining trials there were significantly more EM-trials (61.1%) compared to noEM-trials 39.0%, $t(11) = -2.212$, $p = .049$. Split up into the three task conditions the EM-noEM ratio was in favor for EM-trials except for the *color condition*. In the *baseline condition* there were more EM-trials (67.2%) compared to noEM-trials (32.8%), $t(11) = 2.228$, $p = .048$, which was also the case for the *shape condition*, with 77.7% EM-trials compared to 22.3% noEM-Trials, $t(11) = 3.767$, $p = .003$. In the *color condition* the reverse pattern was manifest in a lower percentage of EM-trials (38.0%) compared to noEM-trials (62.0%), $t(11) = -2.221$, $p = .048$.

3.4.5 Reaction Time Results for Eye Movement Trials

For the following RT analysis only EM-trials that met the criteria mentioned above were selected. Mean RTs of the *baseline condition* were subjected to one-way repeated-measures ANOVA with the factor target-defined dimension (color single-dimension, shape single-dimension, color and shape dual-dimension). The ANOVA revealed the main effect of target-defined dimension to be significant, $F(2,22) = 80.043$, $MSE = 224.205$, $p < .001$, $\eta_p^2 = .879$. To follow up on this main effect, two-tailed paired *t*-tests were applied and yielded significantly faster RTs for dual-dimension (400 ms) compared to color single-dimension (418 ms) singletons, $t(11) = -5.023$, $p < .001$ and faster RTs for dual-dimension compared to shape single-dimension (474 ms) singletons, $t(11) = -5.961$, $p < .001$. In addition, RTs to color targets were faster than RTs to shape targets, $t(11) = -8.985$, $p < .001$.

In the *color condition* mean RTs towards dual-dimension (383 ms) and color single-dimension (386 ms) singletons did not differ significant, $t(11) = 1.09$, $p = .299$. To compare RTs towards the color single-dimension and dual-dimension singleton across conditions, a two-factor repeated-measures ANOVA with the factors condition (color, baseline) and target-defined dimension (single-dimension, dual-dimension) was calculated. The ANOVA yielded no significant main effect of condition producing no difference between RTs in the color (385 ms) condition compared to the baseline (409 ms) condition, $F(1,11) = 4.456$, $MSE = 1551.045$, $p = .058$, $\eta_p^2 = .288$. The main effect of target-defined dimension yielded a significant effect of faster RTs towards dual-dimension (392 ms) compared to single-dimension (402 ms) targets $F(1,11) = 21.046$, $MSE = 62.864$, $p < .001$, $\eta_p^2 = .657$. The interaction between condition and target-defined dimension yielded a significant effect, $F(1,11) = 11.928$, $MSE = 57.856$, $p = .005$, $\eta_p^2 = .52$. To follow up on the interaction two-tailed paired *t*-tests were applied and revealed RTs to single-dimension color targets to be faster in the color (386 ms) versus baseline (418 ms) condition, $t(11) = -2.614$, $p = .024$. RTs to the dual-dimension targets did not differ significantly across the two conditions (color: 383 ms, baseline: 400 ms), $t(11) = -1.485$, $p = .166$.

In the *shape condition* mean RTs towards dual-dimension (449 ms) singletons were faster than RTs towards shape single-dimension (472 ms) singletons, $t(11) = -4.125$, $p = .002$. To compare RTs towards the shape single-dimension and dual-dimension singleton across conditions, a two-factor repeated-measures ANOVA with the factors condition (shape, baseline) and target-defined dimension (single-dimension, dual-dimension) was calculated. The ANOVA yielded a significant main effect of condition with faster RTs in the baseline (437 ms) condition compared to the shape (460 ms) condition, $F(1,11) = 10.301$, $MSE = 622.96$, $p = .008$, $\eta_p^2 = .484$. The main effect of target-defined dimension yielded a significant effect of faster RTs towards dual-dimension (424 ms) compared to single-dimension targets (473 ms), $F(1,11) = 88.987$, $MSE = 317.748$, $p < .001$, $\eta_p^2 = .890$. The interaction between condition and target-defined dimension yielded a significant effect, $F(1,11) = 34.477$, $MSE = 228.551$, $p < .001$, $\eta_p^2 = .758$. To follow up on the interaction two-tailed paired *t*-tests were applied and revealed RTs to shape single-dimension targets to be as fast in the shape (472 ms) condition as in the baseline (474 ms) condition, $t(11) = 0.368$, $p = .720$. RTs to the dual-dimension targets were significantly faster in the baseline (400 ms) condition compared to the shape (449 ms) condition, $t(11) = 4.979$, $p < .001$.

3.5 Saccade Latency

3.5.1 Saccade Latency Removal of Outliers

EM-trials were followed by examination of the first saccade latencies (i.e. time between the onset of the search display and start of first saccade). The first step was to generate a histogram distribution of all latencies of saccades after display onset[3]. The histogram allowed the identification, by visual inspection, of the component-distribution of fast saccade latencies that were not related to the display onset. The procedure to determine the cut off point of fast saccade latencies was to identify the lowest point of the first trough. Based on this criterion, saccades with latencies shorter than 100 ms were excluded from latency analysis (10.1% of trials). Further, saccades with latencies above 500 ms (‘failure to deploy in time’) were excluded from the analysis, (0.4% of trials). Subsequently, the same analysis as previously made for the manual RTs was now applied to the saccade latencies (saccadic RT).

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[3] Calculations with individual cut offs led to the same results.

3.5.2 Saccade Latency Results

Mean saccadic RTs of the *baseline condition* were subjected to one-way repeated-measures ANOVA with the factor target-defined dimension (color single-dimension, shape single-dimension, color and shape dual-dimension). The ANOVA revealed the main effect of target-defined dimension to be significant, $F(2,22) = 124.531$, $MSE = 79.295$, $p < .001$, $\eta_p^2 = .919$. To follow up on this main effect, two-tailed paired *t*-tests were applied and yielded significantly faster saccadic RTs for dual-dimension (219 ms) compared to saccadic RTs to color single-dimension (229 ms) singletons, $t(11) = -4.49$, $p < .001$ and faster saccadic RTs for dual-dimension compared to shape single-dimension (273 ms) singletons, $t(11) = -12.921$, $p < .001$. In addition, saccadic RTs to color targets were faster than saccadic RTs to shape targets, $t(11) = -10.469$, $p < .001$.

In the *color condition* mean saccadic RTs towards dual-dimension (233 ms) singletons were faster than saccadic RTs towards color single-dimension (240 ms) singletons, $t(11) = -2.798$, $p = .017$. To compare saccadic RTs towards the color single-dimension and dual-dimension singletons across conditions, a two-factor repeated-measures ANOVA with the factors condition (color, baseline) and target-defined dimension (single-dimension, dual-dimension) was calculated. The ANOVA yielded a significant main effect of condition with faster saccadic RTs in the baseline (224 ms) condition compared to the color (236 ms) condition, $F(1,11) = 6.355$, $MSE = 289.187$, $p = .028$, $\eta_p^2 = .366$. The main effect of target-defined dimension yielded a significant effect of faster saccadic RTs towards dual-dimension (226 ms) compared to single-dimension (234 ms) targets, $F(1,11) = 16.58$, $MSE = 47.778$, $p = .002$, $\eta_p^2 = .601$. The interaction between condition and target-defined dimension yielded no significant effect, $F(1,11) = 1.62$, $MSE = 14.006$, $p = .229$, $\eta_p^2 = .128$.

In the *shape condition* mean saccadic RTs towards dual-dimension (229 ms) singletons were faster than saccadic RTs towards shape single-dimension (264 ms) singletons, $t(11) = -10.118$, $p < .001$. To compare saccadic RTs towards the shape single-dimension and dual-dimension singleton across conditions, a two-factor repeated-measures ANOVA with the factors condition (shape, baseline) and target-defined dimension (single-dimension, dual-dimension) was calculated. The ANOVA yielded no significant main effect of condition with saccadic RTs as fast in the baseline (246 ms) condition as in the shape (246 ms) condition, $F(1,11) = 0.002$, $MSE = 105.642$, $p = .967$, $\eta_p^2 = .0$. The main effect of target-defined dimension yielded a significant effect of faster saccadic RTs towards dual-dimension (224 ms) compared to single-dimension targets (269 ms), *F*(1,11) = 181.34, *MSE* = 131.778, $p < .001$, η_p^2 = .943. The interaction between condition and target-defined dimension yielded a significant effect, *F*(1,11) = 21.762, *MSE* = 45.915, $p < .001$, η_p^2 = .664. To follow up on the interaction two-tailed paired *t*-tests were applied and revealed saccadic RTs to shape single-dimension targets to be faster in the shape (264 ms) condition compared to the baseline (273 ms) condition, *t*(11) = -2.695, $p = .021$. Saccadic RTs to the dual-dimension targets were significantly faster in the baseline (219 ms) condition compared to the shape (229 ms) condition, *t*(11) = 2.463, $p = .032$.

To further investigate the appearance of the RSE within the three task conditions (color, shape, baseline), redundancy gains measured in the baseline condition and the two single-dimension target conditions were compared via a two-way repeated-measures ANOVA with the factors condition (single, baseline) and redundancy type (color-related, shape-related). Saccadic RT redundancy gains were higher for the baseline (31.6 ms) condition compared to the single (21.1 ms) conditions, *F*(2,22) = 26.064, *MSE* = 50.318, $p < .001$, η_p^2 = .703. Comparison between color- and shape-related saccadic RT redundancy gains showed a larger redundancy gain for the shape (44.6 ms) condition (color-related redundancy gain (associated with the addition of the color dimension)) opposed to the color (8.1 ms) condition (shape-related redundancy gain (associated with the addition of the shape dimension)), *F*(2,22) = 80.9, *MSE* = 197.66, $p < .001$, η_p^2 = .880. The interaction between the task condition (baseline, single) and redundancy type (color-, shape-related) yielded a significance difference, *F*(2,22) = 10.475, *MSE* = 69.327, $p = .008$, η_p^2 = .488. To follow up on the interaction, two-tailed paired *t*-tests were conducted, comparing the color- or shape-related saccadic RT redundancy gain across both single versus baseline condition. There was no significant redundancy gains difference for shape-related redundancy gains across the conditions (single color: 6.8 ms, baseline color: 9.5 ms), *t*(11) = -1.285, $p = .225$. For the color-related redundancy gain between single and baseline conditions the redundancy gain increase significantly from the single (35.5 ms) compared to the baseline (53.7 ms) condition, *t*(11) = -4.615, $p < .001$.

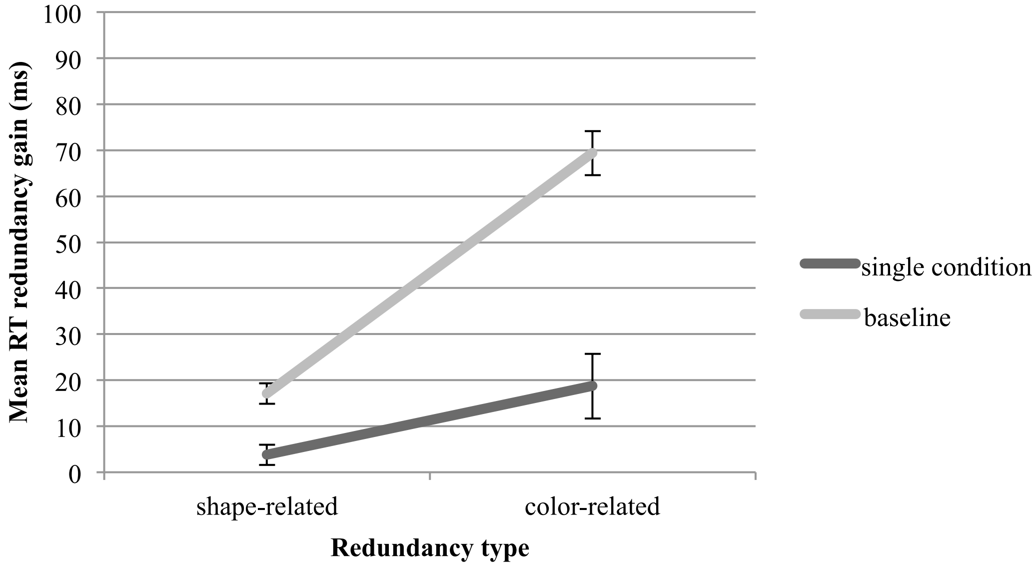

Figure 25. Mean saccadic RT redundancy gain relative to the associated dimension (color- or shape-related) compared between conditions (single or baseline).

To compare any pattern of the redundancy gain across all variables a thee-way ANOVA with the factor reaction time type (saccadic, manual), condition (single, baseline) and redundancy type (shape-, color-related) was conducted. The main effect of reaction time type showed no significant effect, $F(1,11) < 1$, $MSE = 89.505$, $p = .657$, $\eta_p^2 = .019$, making both response types benefit equally form redundancy gains (saccadic redundancy gain: 26.4 ms, manual redundancy gain: 27.3 ms. The main effect of condition yielded a significant effect of a larger redundancy gains for the baseline condition (37.4 ms) compared to the single condition (16.2 ms), $F(1,11) = 51.51$, $p < .001$, $MSE = 209.532$, $\eta_p^2 = .824$. The main effect of redundancy gain type revealed higher gains for color-related (44.3 ms) compared to shape-related (9.28 ms) gains, $F(1,11) = 92.495$, $MSE = 318.803$, $p < .001$, $\eta_p^2 = .894$. In regard to any interactions the interaction between reaction time type and condition revealed a significant effect, $F(1,11) = 24.669$, $MSE = 112.314$, $p < .001$, $\eta_p^2 = .692$, with larger redundancy gain increases for the baseline condition of the manual RTs (32.0 ms) in comparison to the increase in the baseline condition of the saccadic RTs (10.5 ms). The second significant interaction occurred between the condition and redundancy gain type, $F(1,11) = 22.0$, $MSE = 190.936$, $p = .001$, $\eta_p^2 = .667$, with a larger benefit for color-related redundancy gains in the baseline condition (48.3 ms) compared to the benefit of the color-related redundancy gain in the single condition (21.8 ms).

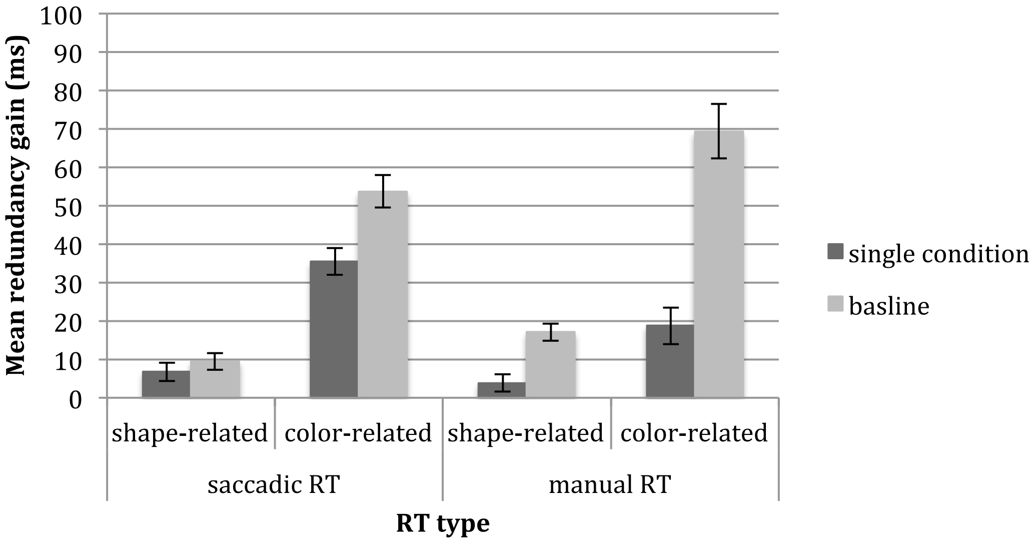

Figure 26. Mean redundancy gain relative to the associated dimension (color- or shape-related) compared between conditions (single or baseline) and RT type (saccadic or manual).

3.6 Discussion

To examine if redundancy gains in pop-out visual search are a bottom-up phenomenon, driven by stimuli salience, or are dependent on a top-down effect of task set, we compared manual RTs and saccadic RTs. Responses to singleton targets either defined in one dimension (color or shape) or redundantly in both dimension, allowed for redundant signal effect (RSE) investigation across three different task instructions. The baseline condition required both single dimensions of color and shape and their combination (color and shape) to be task-relevant. In both single conditions, only a single dimension (color or shape) was designated as task-relevant, making the other dimension in each case task-irrelevant. Results in the baseline condition were in line with previous behavioral studies (e.g., (Krummenacher et al., 2001; 2002), showing manual RT redundancy gains for targets defined in both task-relevant dimensions. Importantly, these behavioral redundancy gains were preceded by saccadic latencies differences: Saccade latencies were shorter in response to redundant color and shape targets relative to pure color or pure shape targets. As the saccade latency is a measure of the construction of a motor program for the execution of eye movements (Abrams & Jonides, 1988), it allows to be interpreted as search relevant and therefore linked to the manual response. The RSE on the saccade latency level thus suggest the same underlying signal for the saccadic and the manual response. The finding that the saccade latency mirrors behavioral redundancy gains in pop-out visual search supports the idea that RSE origin at early stages of visual processing (Krummenacher et al., 2002; Töllner et al., 2011) and against the hypothesis that The RSE is primarily connected to response-related stages (Feintuch & Cohen, 2002). A dissimilar pattern of the manual RT redundancy gains was observed in the two single conditions where only color or only shape singletons and their combination were defined as targets. Targets of the opposing single dimension had to be ignored. The RSE observed in the baseline conditions disappeared for the color condition and was reduced for the shape condition: As RTs in response to redundantly defined color and shape targets were not reliably faster than RTs to pure color targets (4 ms) in the color condition and responses were only marginally faster compared to pure shape targets (18 ms) in the shape condition. Figure 26 illustrates the significant interaction of the RSE across the conditions (baseline, single condition) by association of the RSE (color-, shape-related), supporting the idea that the introduction of a task-irrelevant dimension in each of the single condition reduces the RSE with higher redundancy gains in the baseline condition. Additionally, it shows the more pronounced effect of color-related redundancy gain compared to the rather mild shape-related redundancy gain. Thus, one can say that the top-down task set modulates the RSE, which is in line with previous studies (Grubert et al., 2011). The dominant effect of color has been reported before in visual search (Braithwaite, Humphreys, & Hulleman, 2005; Wolfe, 1994). Results of the single conditions on the saccade latency level however, resembled the pattern of the baseline condition with significant redundancy gains in either of the single conditions with shorter saccade latencies toward redundantly defined targets (color and shape) compared to each of the single defined targets (color or shape). Yet all reported RSE were more pronounced in the baseline condition compared to the single conditions with a significant interaction comprised form a higher color-related RSE. The top-down influence can be observed by the diminished value of the RSE yet does the effect on the manual RT carry a larger influence on the saliency signal. One can argue that the saccadic latency happens at an early stage when the contrast signal is already modulated by the top-down instruction, yet further unfolds its effect by diminishing the contrast signal up to the moment of manual RT which happen at a later time point. The reduced effect of RSE in the single color and single shape conditions for both measures show that bottom-up salience is not prominent enough to persist any influence of top-down search intentions. Figure 26 illustrates the lowered redundancy gains for manual and saccadic RTs observed in the single condition compared to the baseline condition. Further, color-related redundancy gains were larger than shape-related redundancy gains, which supports the idea of dominant color processing (Wolfe, 1994). Although the color dimension produces a stronger salience signal, top-down influence is strongly in play. Any argumentation on pure bottom-up mechanisms cannot be true as to the identical use of target characteristics across all conditions, thus only the different top-down search instructions modulated the target definition. These finding challenge any model that focus on the crucial role of bottom-up salience for target selection in visual search (Itti & Koch, 2000). Itti and Koch (Itti & Koch, 2000) predict redundancy gains to be driven solely by the present distribution of activation across a salience map that is setup by integrating contrast signals from different dimension-specific maps. If this was true, the same redundancy gains on manual and saccadic RTs should occur in all three conditions, which was not evident in this study.

The obtained results form this study suggest instead that the computed saliency signal is weighted according to the task set and certain search specific dimensions modulate this overall signal. Further, as the modulation is observed at both levels of saccadic and manual RT, it seems that any influence on the signal is continued along the temporal processing window of the target. This fits with the assumptions of the dimension-weighting model put forward by Müller et al. (2003). If one dimension becomes response-irrelevant, its top-down influence is reduced, which will diminish its impact as contrast signal on the overall salience map. As a result, the target signal is computed only by signals form the response-relevant dimension, thus loosing the redundancy gain effects emanating form the additional dimension on both manual and saccadic measures. Furthermore, although RSEs were small or even non-significant in the color single conditions, they were at least numerically present for most comparisons.

Concluding, one can say that task-dependent top-down control can strongly attenuate the impact of local feature contrast signals from irrelevant dimension on the activation profile of the salience map. The novel contribution of the current study is to demonstrate that this is even the case when task-relevant and task-irrelevant stimuli feature appear at the same location and are part of the same visual object on manual and saccadic RTs. Redundantly defined target singeltons are selected faster than pure color or pure shape singletons when both features dimension are task-relevant but the selection is slowed when one of the dimensions is irrelevant. In regards to the link between saccade latencies and manual reaction times, we can conclude form the presented results that over the coarse of time the impact of the top-down modulation increases form the saccade level to the response level. Therefore both systems show a temporally linked effect supporting the idea of a common signal source, namely the saliency map of attention. Further experiments should explore if this effect persists if the combination of dimension is spatially separated between juxtaposition targets.

4 Chapter III

Waldo Reveals Cultural Differences in Inhibition of Return

4.1 Abstract

Humans routinely perform visual search towards potential targets and locations to adapt to the environment. These sequences of ballistic eye movements are shaped by a combination of top-down and bottom-up factors. Interestingly, it has been recently documented that observers display cultural-specific preferential fixation patterns in a range of visual processing tasks. In particular, the eye movement strategies deployed to extract information from faces, clearly differs between Western Caucasian (WC) and East Asian (EA) observers. However, whether such cultural differences are presented during visual scene processing remains debated. To clarify this issue, we recorded the eye movements of WC and EA observers while they were solving one of the most famous visual search problems parametrically varying in terms of difficulty: *Where's Waldo*. Both groups had a comparable level of familiarity with the Waldo books and reached a comparable level of accuracy in finding the target. Westerners were, however, faster to locate Waldo. Importantly, this modulation of speed was related to differences occurring on the low-level mechanisms of inhibition of return, with EA observers returning more often to previously visited locations than the WC observers. This suboptimal eye movement strategy in the Easterners might be engendered by their perceptual bias in using more extra-foveal information. Overall, our data point towards the existence of a subtle, but significant difference, in the processing of visual scenes across observers from different cultures during active visual search.

4.2 Introduction

Visual search is a critical perceptual task routinely performed by humans to select objects and information of interest in the environment. Eye movements play a crucial role in achieving this visual challenge, by continuously selecting targets among distractors with a series of fixations and saccades (Liversedge & Findlay, 2000). Importantly, these scan paths are neither randomly distributed nor completely deterministic and extremely complex to understand. In fact, fixation patterns are highly stable *within* the same observer exploring a particular visual scene (Andrews & Coppola, 1999), but vary greatly *between* observers and as a function of diverse task constraints (Henderson, 2003).

In the past 50 years, many theories have been proposed to model and predict eye movement scan paths during visual scene processing. One of the most prominent approaches consists of quantifying the visual saliency of images by using a class of "bottom–up" computer vision models (Itti & Koch, 2001). For example, the seminal work by Itti, Koch and Niebur (1998) extracted saliency maps based on low-level properties of the images (i.e., spatial frequency, edge density, and local contrast) to predict free viewing eye movements. Nowadays, there are more than 50 saliency-inspired fixation prediction models, which also include the broader categories of visual attention models (Bylinskii et al., 2015; Kümmerer, Wallis, & Bethge, 2015). With the recent advance in deep learning with multi-layer neural networks, performance in modelling and predicting eye movement patterns on a benchmark dataset with saliency-inspired models continues to improve (e.g. Kümmerer, Wallis, & Bethge, 2016) - For more details see the MIT Saliency Benchmark website http://saliency.mit.edu. However, human observers display distinctive scan paths even on an identical image as a function of the task at hand, an effect already highlighted in the very early eye tracking studies (Buswell, 1935; Yarbus, 1967). Attention models have also been integrated as a set of predictors in those models (e.g., Torralba, Oliva, Castelhano, & Henderson, 2006) to account for this "top-down" information (i.e., task effects, scene-schema knowledge and other factors). Importantly, even with the consideration of both low-level bottom up visual information and high-level top-down information, predicting individual eye movement scan paths remains a scientific challenge (e.g., Greene, Liu, & Wolfe, 2012; Haji-Abolhassani & Clark, 2014), due to the variability present across observers. For example, scan paths for faces are idiosyncratic and quite robust (Chuk, Chan, & Hsiao, 2014; Mehoudar, Arizpe, Baker, & Yovel, 2014). Kanan, Bseiso, Ray, Hsiao and Cottrell, (2015) showed that observers do not exhibit universal scan path patterns while performing a series of face processing tasks. These obserations also resonate with the differences across observers from different cultures reported over the last decade. Cross-cultural studies comparing East Asians (EA) and Western Caucasians (WC) observers have reported distinct eye movement strategies during face identification (Blais, Jack, Scheepers, Fiset, & Caldara, 2008; Caldara, 2015; Calder & Young, 2005; Kelly et al., 2011; Kelly, Miellet, & Caldara, 2010; Miellet, He, Zhou, Lao, & Caldara, 2012; Rodger, Kelly, Blais, & Caldara, 2010) and the decoding of facial expressions of emotion (Jack, Blais, Scheepers, Schyns, & Caldara, 2009). Notably, Western observers fixate more *local* face features (i.e., the eye and the mouth) during face recognition, whereas Eastern observers deploy more *global* fixation to the center of the face while obtaining a comparable level of accuracy. More importantly, these culturally distinctive scan paths are also related to a cultural tuning towards distinct spatial frequency information, as demonstrated by eye movement studies using a gaze-contingent technique combined with retinal filter models (Miellet, Vizioli, He, Zhou, & Caldara, 2013) and psychophysical experiments (Tardif et al., 2016). Western observers use more high spatial frequency information sampling, whereas Eastern observers rely more on low-spatial frequencies to process faces.

While there are clear cultural differences in the visual sampling strategies across observers from different cultures during face processing, it still remains debated whether these cultural modulations extend to scene perception. Early studies have reported a similar local/global fixation bias between WCs and EAs during the viewing of scenes (Chua, Boland, & Nisbett, 2005; Goh, Tan, & Park, 2009; Masuda, Akase, Radford, & Wang, 2008). For example, Chua et al. (2005) showed that Americans spent a greater proportion of viewing time on focal objects relative to the background than Chinese participants, whereas Chinese observers made more fixations towards the background than Americans. Similarly, Goh et al. (2009) also found that Western Caucasian observers fixated more on the focal object in a picture, whereas East Asians constantly shifted their gaze between the focal object and the background. However, other studies reported little or no difference between the two cultures (Evans, Rotello, Li, & Rayner, 2009; Miellet, Zhou, He, Rodger, & Caldara, 2010; Rayner, Castelhano, & Yang, 2009; Rayner, Li, Williams, Cave, & Well, 2007). For example, a replication of the study by Chua et al. (2005) did not yield to any difference between the two cultural groups (Evans et al., 2009). Miellet et al. (2010) also did not find any difference in eye movement strategy between WCs and EAs in a visual search task involving the search of an animal in natural scenes with a gaze-contingent technique (i.e., *Blindspot*).

A possible explanation for such inconsistent results is that natural scenes as visual stimuli contain too rich information to reveal subtle scan path differences between WC and EA observers. In fact, however, when less complex stimuli are used during visual search (Cramer, Dusko, & Rensink, 2016; Petrova, Wentura, & Fu, 2013) or visual categorization (Lao, Vizioli, & Caldara, 2013; Boduroglu, Shah, & Nisbett, 2009) cultural differences do emerge. Cramer et al. (2016) showed that Easterners raised in an East Asian environment have no significant asymmetry in a visual search task involving the search of long versus short lines, whereas East Asian immigrants present this asymmetry. In addition, Boduroglu et al. (2009) showed EA observers were better than WCs in a color detection task with simple geometry shapes that required efficient parafoveal vision. Similarly, Petrova et al. (2013) found that task-irrelevant distractors had a greater influence on EAs than WCs during a simple saccade task. In summary, whether visual search differs across cultures remains to be clarified.

Importantly, previous cultural studies using high-level visual stimuli have overlooked the temporal dynamics of sequential scanning strategies, such as those measured by the *inhibition of return* (IOR, Posner & Cohen, 1984). IOR relates to the difficulty of reaction (delay in response) to a previously attended location. This effect was first observed in the Posner paradigm (Posner, 1980; Posner & Cohen, 1984), an experimental procedure where participants, after viewing a probable cue (valid, invalid), have to respond to a location next to the central fixation-cross that had been previously fixated. Since then, the effect of IOR has been extensively investigated in experimental psychology (for a review, see Klein, 2000) with the hypothesis that IOR helps the attentional system to reorganize information and plan forward movements during scene inspection. This bias in saccade direction is also shown in more general visual search tasks (Klein & MacInnes, 1999). One of these tasks was inspired by the famous children's book *Where is Waldo* (Hanford, 1987), where participants were asked to fixate a suddenly appearing probe during the search of Waldo. The probe was presented either at the previously located position or at one of five possible positions deflected by 60° around a circle orbiting at the radius of the previous saccade length. Saccade latencies were slowest when the probe was on the previously fixated location, supporting the idea of a foraging facilitator effect as a result of IOR, which was highlighted by a forward bias in the distribution of fixations. Smith and Henderson (2011) replicated Klein and MacInnes's Waldo study (1999) confirming elevated reflexive saccade latencies to probes at previously visited locations. However, they concluded that IOR was not responsible for the foraging facilitation. They instead referred to their findings of higher proportion of forward proceeding saccades, as a saccadic momentum (i.e. repetition of the saccadic program, rather than a consequence of IOR) (Smith & Henderson, 2009). Regardless of those theoretical explanations, it remains to be determined whether fine-grained measures of the temporal dynamics of eye movements during visual search are modulated by culture.

To address these open questions, we recorded the eye movements of WC and EA observers while they were solving one of the most famous visual search problems: *Where's Waldo*. All the observers shared a comparable level of visual experience with the famous book and no particular expertise in solving this visual problem. Notwithstanding, having previous experience with Waldo books hardly presents an advantage in the localization of Waldo (Olson, 2015). We then selected 30 vignettes with a parametric level of difficulty (see Figure 27 for an example of the stimuli). We analyzed the characteristics of the scan paths by projecting the spatial fixation distributions in reference to the 1-back and 2-back fixation, by using the relative saccade orientation and amplitude, similar to Smith and Henderson (2011; see also Figure 28). Importantly, to investigate the fine-grained differences between WC and EA observers, we applied Kernel density estimations on the empirical joint likelihood of the relative saccade orientation and amplitude. We then used a robust data-driven approach to statistically isolate the differences between WC and EA observers (Lao, Miellet, Pernet, Sokhn, & Caldara, 2016). Our results show that EA observers are more likely to orientate their gaze to a previously fixated location compared to WC observers. This fixation pattern might relate to a reduced sensitivity towards foveal information in the EA observers. Such an eye movement sampling strategy might also impair their performance in this visual search task, as finding *Waldo* involves the processing of high-spatial filtering information.

4.3 Methods

4.3.1 Participants

Twenty Western Caucasians (11 females) and Twenty East Asians (11 females) from the University of Fribourg participated in the current study. All participants were right-handed with normal or corrected-to-normal vision. Participants were interviewed before and after the experiment to ensure they were familiar with the Waldo task and had no memory of the exact images presented during the experiment. All the EA participants were from Mainland China, had never been to a Western country before, and had not spent more than three months in Switzerland. The experiment was approved by the local ethics committee and participants provided written informed consent upon arrival to the experiment.

4.3.2 Eye Tracking

Eye movements were recorded by means of a Desktop-Mount EyeLink 2K eye tracker (SR Research Ltd., Mississauga, Ont., Canada) with a temporal resolution of 1000 Hz and a spatial resolution of 0.01°of visual angle. The average gaze position error was about 0.25°. Eye movements were recorded monocularly via Matlab (R2006a), using the Psychophysics (PTB-3) and EyeLink Toolbox extensions (Brainard, 1997; Cornelissen et al., 2002; Pelli, 1997). Standard calibration and validation of the EyeLink were conducted before the experiment and repeated whenever necessary during the procedure.

4.3.3 Stimuli and Procedure

Stimuli were 30 unique full-color Where's Waldo illustrations scanned from the Solid Gold Collection (Handford, 2008). Images were typical Waldo illustrations, which contained an overly crowded scene with very rich background/foreground elements (see Figure 27). In each of the images there is one distinctively dressed Waldo character (red circle, Figure 27). The exact gesture and size of the target (Waldo) varied from scene to scene, yet never exceeded 1° of visual angle. The images were presented on a Dell P1130 19” CRT monitor with a 1280 × 960 pixel white background at a refresh rate of 170 Hz. The size of each image was 1280 × 795 pixels, subtending 31.13° × 19.63° of visual angle at a viewing distance of 70cm.

Figure 27. One of the *Where’s Waldo* illustrations presented to the participants. Stimuli were scanned from the Solid Gold Collection (Handford, 2008). The red circle, which was not visible during the experiment, indicates a Waldo target.

Participants were instructed to search for Waldo in each of the images. At the beginning of each trial, we used a central fixation cross as an automatic drift correction. If the participant’s eye gaze was more than 1° of visual angle away from the fixation cross, an additional calibration followed by validation was conducted. After the fixation cross, a Waldo illustration was presented at random until response. The participant responded by pressing the space bar upon the detection of Waldo. The same image would appear again after a blank screen (100 ms), and the participants were instructed to indicate the location of the target using their gaze. The next trial began after the experimenter confirmed the target detection. In case of unsuccessful detection of the target at hand within a maximum duration of 2 minutes, participants could either skip the current stimuli completely, or elect to resume searching at a later stage. They could try up to three times on the vignettes they were struggling with.

However, only the trials with successive identification on the first presentation were included in the eye movement analysis. The experimenter was in the same room with the subject throughout the experiment to closely monitor the eye drift and the accuracy of the subjects' detection. After the experiment, the participants verbally confirmed that they had never seen these particular Waldo stimuli before.

4.3.4 Eye Movement Preprocessing

Eye movements were preprocessed using a custom MATLAB script applying the same default threshold parameters as in the EyeLink software (Miellet, Zhou, He, Rodger, & Caldara, 2010). Gaze velocity above 30°/s were determined as saccades. Fixations falling within a spatial range of < 0.3° visual angle and a temporal range of < 20 ms were merged. We extracted saccade information (onset, offset, amplitude and orientation) for each participant. We analyzed the following oculomotor characteristic variables typically reported in eye movement literatures: number of fixations per second, average single fixation duration and average saccade length.

4.3.4.1 One-back and Two-back Fixation Distribution

During the search for Waldo, all fixations were described by the means of their variation from the previous fixation. In other words, for each saccade we computed the angle and amplitude difference in relations to the 1-back and 2-back position of the eye (Smith & Henderson, 2011). As shown in Figure 28, saccade vector from t_0 to t_1 is compared with the vector of t_0 to 1-back (α) or 2-back (β) fixation. For example, if the eye fixation at t_1 perfectly overlaps with the 1-back fixation, the angle and the amplitude between the two vectors would be [0°, 0°]. For n fixations in a given trial from one observer, we computed n-1 saccades, which return in n-2 pairs of 1-back saccadic information (relative orientation and amplitude) and n-3 pairs of 2-back saccadic information.

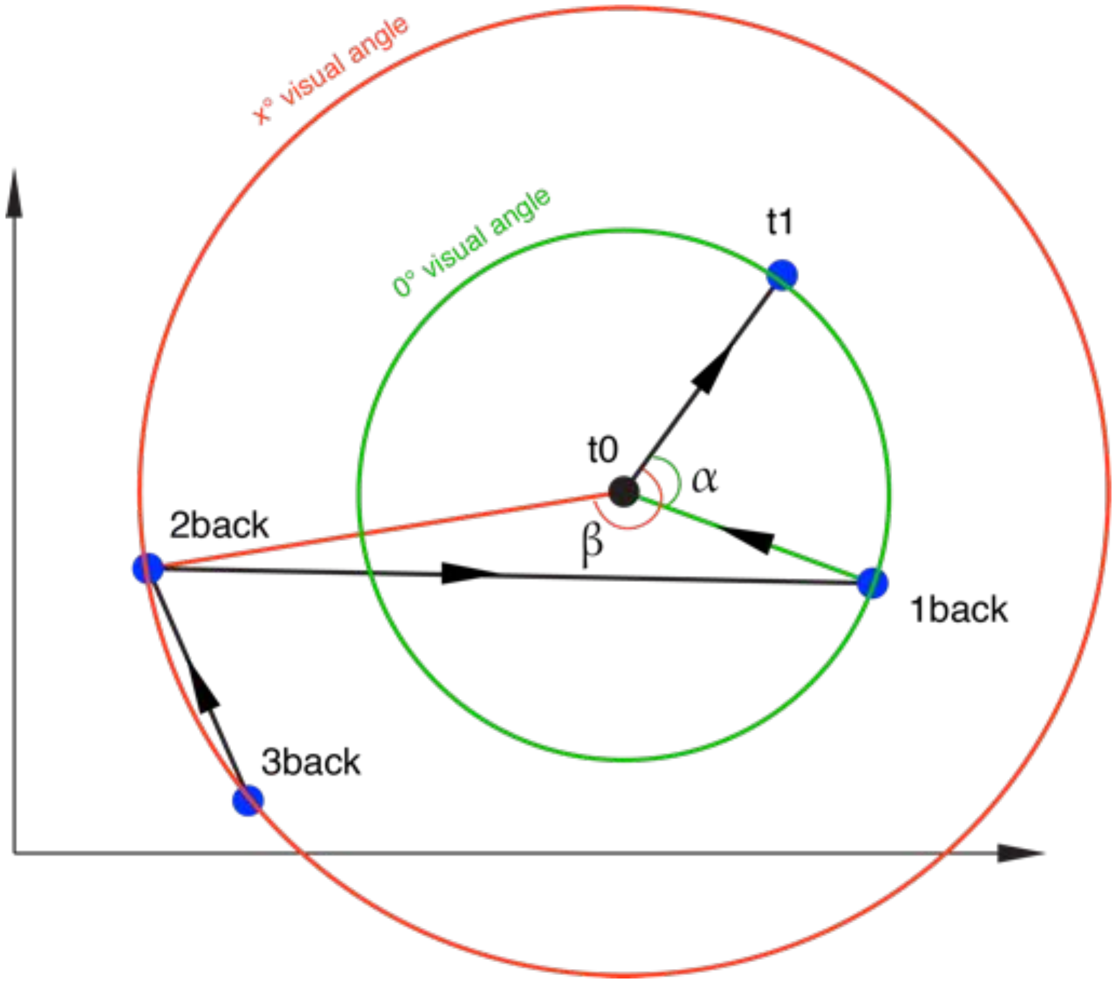

Figure 28. Illustration of the calculation of relative saccade orientation and amplitude (in reference to the 1-back or 2-back saccade). The black dot marks the penultimate fixation; blue dots mark visited fixation locations in sequence depicted by the black arrows. The green circle marks a distance of 0° of visual angle; the exterior red circle marks a larger distance at x° of visual angle. To calculate the angle between the current fixation (t_1) and any previous fixation (1-back and 2-back), the penultimate fixation location (t_0) serves as pivot. Angle α is calculated at t_0 between the current fixation (t_1) and the 1-back fixation. Angle β is calculated between the current fixation (t_1) and the 2-back fixation.

4.3.4.2 *Statistics on One-back and Two-back Fixation Distribution*

The statistical analysis on the relative fixation distribution was performed on the joint empirical likelihood function of the n-back saccade orientation and amplitude. We first projected the orientation and amplitude information into a two-dimensional space independently for each participant at a single-trial level. We applied kernel density estimation for the joint likelihood of relative fixation orientation and amplitude. The bandwidth of the kernel is determined automatically using Scott’s Rule (Scott, 1992).

We then performed statistical mapping on the Gaussian smoothed 2D histogram. Moreover, in order to avoid bias in the spatial mapping and smoothing, the angular–amplitude representation was modeled on a warp two-dimensional space as shown in Figure 29a. Intuitively, this is equivalent of applying a convolution on the surface of an open cylinder, with the smoothing kernel being a wrapped normal distribution on the azimuthal angle and a normal distribution on the polar angle. Individual angular–amplitude map was calculated by taking the 5% trimmean across trials. To assess the statistical differences between WC and EA, we applied a data-driven approach based on Linear Mixed Model and bootstrap clustering implemented in *i*Map4 (for the details of the algorithm, see (Lao, Miellet, Pernet, Sokhn, & Caldara, 2016). This is equivalent to a 2D kernel regression. We applied a random intercept model with the subject as random effect and the culture as fixed effect. The result is then presented in a radial histogram similar to Figure 29b. The colors in Figure 29 depict the frequency of relative saccade angle and amplitude. The color blue represents low frequencies; the color yellow represents high frequencies. Return to a previously fixated location has a value of [0°, 0°] (heat maps are inspired by the visualization used by Hooge, Over, van Wezel, & Frens, 2005; Motter & Belky, 1998).

4.4 Results

4.4.1 Search Performance

Before investigating the presence and impact of oculomotor IOR on eye movements, we assessed the participant's performance in the *Where's Waldo* search task. Statistical analysis was performed using generalized linear mixed model in MATLAB with subject and stimuli as random intercepts to account for repeated measures (Baayen, Davidson, & Bates, 2008). As expected, participants had difficulties in finding the target, but showed a good performance on average: success rate of 93.67%. In most cases Waldo was located at the first attempt (86.92%). There was no significant difference on the success rate of finding Waldo at the first attempt between WC (87.93% [84.07, 90.96], square bracket shows 95% confidence intervals) and EA (86.52% [82.43, 89.77], $F(1,38) = 0.326$, $p = .571$). The average search duration for locating Waldo at the first attempt was 42.53s. The WC observers ($M = 37.40$s [21.72, 53.08]) were significantly faster to locate the target than EAs ($M = 59.81$s [44.10, 75.52], $F(1,1041) = 12.94$, $p = .00034$).

4.4.2 Eye Movement Results

Only the trials in which participant gave correct answers at the first attempt were analyzed for eye movements. We did not find any significant difference between the two groups of observers for eye movement descriptive indices. Both groups showed a comparable number of fixations per second (M_{WC} = 3.57 [3.37, 3.77]; M_{EA} = 3.46 [3.26, 3.66]; $F(1,1041) = 0.55$, $p = .458$), similar mean fixation duration (M_{WC} = 244.92ms [233.58, 256.26]; M_{EA} = 245.20ms [233.85, 256.55]; $F(1,1041) = 0.001$, $p = .970$), and comparable mean saccade amplitudes (M_{WC} = 3.36° of visual angle [3.06, 3.66]; M_{EA} = 3.05° [2.75, 3.35]; $F(1,1041) = 2.28$, $p = .131$).

To quantify the effect of task difficulty on oculomotor characteristics, we separated the Waldo stimuli into two levels of difficulty (*easy* or *hard*) independently for each participant. We first sorted the search durations of all the stimuli within one single observer, and then labeled the first 15 stimuli as *easy* and the rest as *hard*. Eye movement characteristics were then modeled as functions of the task difficulty (*easy* or *hard*), culture of the observer (WC or EA), and their interaction. The number of fixations per second and the mean fixation duration were not significantly modulated by the task difficulty, as neither the main effect nor its interaction with the group predictor was significant (Fs < 0.647, $p > .05$). However, both the main effect of the task difficulty ($F(1, 1039) = 49.63$, $p = 3.3699e\text{-}12$) and the task difficulty x group interaction ($F(1, 1039) = 12.09$, $p = 5.2858e\text{-}4$) were significant for mean saccade amplitude. Post hoc comparisons showed that the significant effects were driven by the EA observers, who made significantly smaller saccades during the viewing of hard (M = 2.76° [2.456, 3.072]) than easy (M = 3.27° [2.971, 3.578]) stimuli, whereas the WCs displayed similar mean saccade amplitudes during the viewing of both easy (M = 3.45° [3.149, 3.756]) and hard (M = 3.26° [2.948, 3.562]) stimuli.

4.4.2.1 Analysis on the One-back and Two-back Fixation Distribution

The n-back fixation distribution is represented as a smoothed 2D map of the relative saccade orientation and amplitude for both groups of observers (Figure 29). As shown in Figure 29, the forgoing saccades were not distributed uniformly. Two local maximums are presented in the angular-amplitude map (Figure 29b and 29d). This result indicates that the subsequent saccade performed by human observers was most likely to be either exactly the same as the previous saccade, or directed toward the N-back fixation location. More importantly, the local maximum located around [0°, 0°] clearly shows that there was no strong evidence of inhibition of return. Both WC and EA showed high likelihood to return to the previous fixated location.

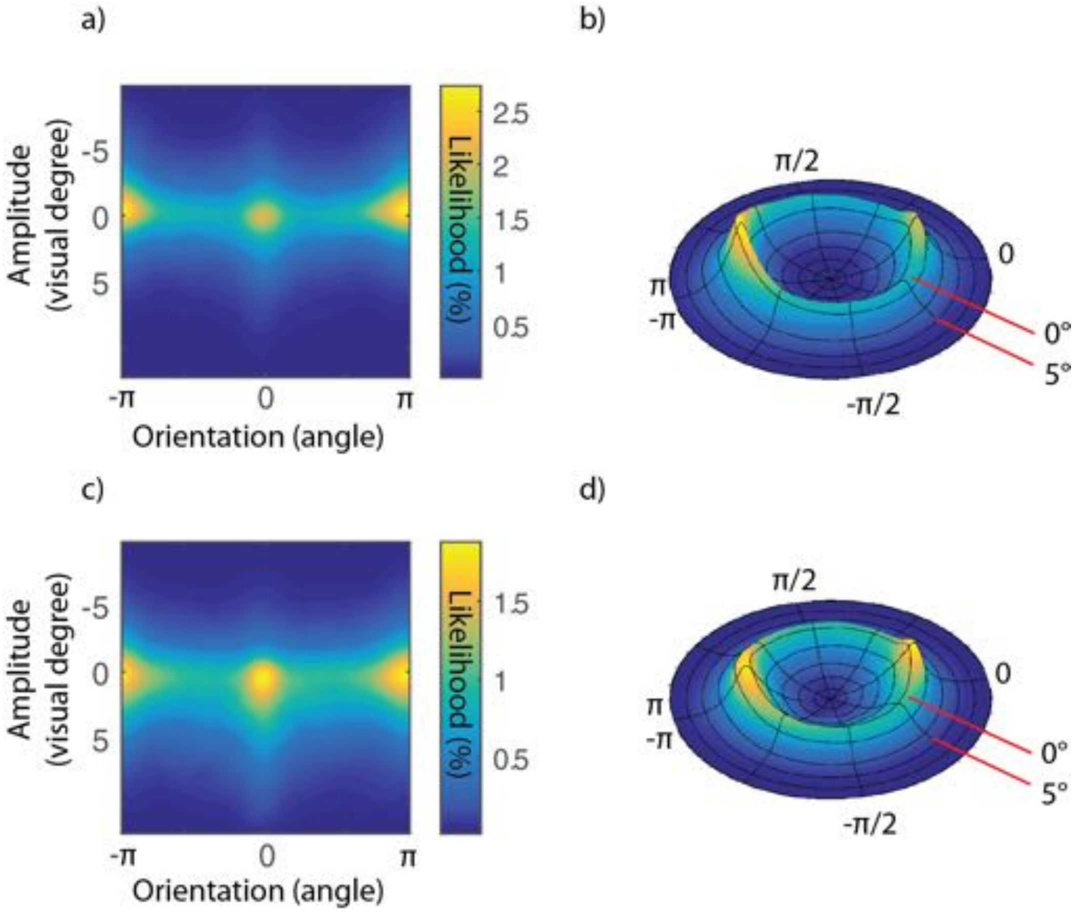

Figure 29. 2D representation of the joint likelihood function of the relative saccade angular and amplitude for 1-back (a & b) and 2-back (c & d) saccades across both groups of observers. In a & c, saccade information is presented in Cartesian coordinate system with the relative orientation on the x-axis and amplitude in degree of visual angle on the y-axis. Importantly, the yellow area in the middle [0°, 0°] shows n-back saccades that deviated at an angle of 0° and an amplitude difference of 0° (a return to the n-back fixated location). b & d are the Polar coordinate representation of a & c. Color map indicates joint likelihood of orientation and amplitude in percentage.

We then performed statistical mapping using *i*Map4 to compare the cultural difference of the 2D angular-amplitude map between WC and EA. The result is shown in Figure 30. For both 1-back and 2-back saccades, significant differences are revealed after non-parametric bootstrap clustering test: EA showed higher saccade likelihood on the [0°, 0°] compare to WC observers, indicating a decreased inhibition of return for EA observers (1-back: maximum F value: $F(1, 38) = 30.23$, $p = .00003$; 2-back: maximum F value: $F(1, 38) = 29.35$, $p = .000004$).

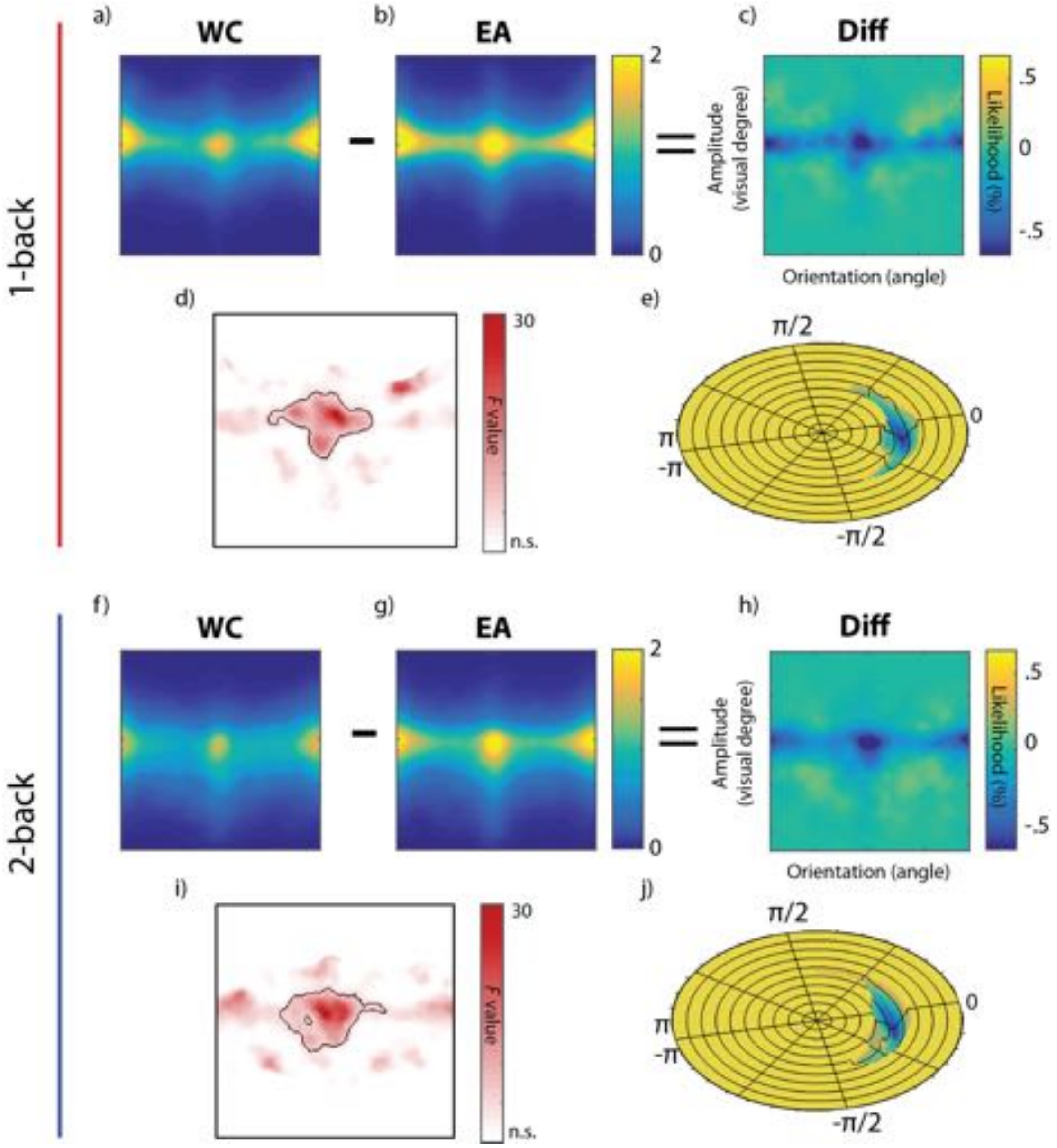

Figure 30. Statistical analyses on the differences between WC and EA on the angular-amplitude joint likelihood map. a) Angular-amplitude map for WC in 1-back condition. b) Angular-amplitude map for

EA in 1-back condition. c) Angular-amplitude differences between WC and EA in 1-back condition (WC minus EA). d) Statistical value map (F-value) for the difference showed in c), black line indicates the significant area. e) The polar representation of the significant different area. f-j) are the result for the 2-back condition.

To further quantify the cultural fixation return bias and explore its relationship with individual visual search performance, we conducted a post hoc analysis within the significant cluster. Using the sum likelihood value within the significant region (i.e., around [0°, 0°]), we estimated that the EA observers were about 4% more likely to saccade to a previously visited fixation location than WC observers (1-back: EA - 19.27% [18.23, 20.31], WC - 15.53% [14.49, 16.56]; 2-back: EA - 19.56% [18.43, 30.68], WC - 15.02% [13.90, 16.14]). Importantly, this returning strategy was positively related to the search performance (Figure 31). The longer it took for an individual to find Waldo, the more likely for the observer to perform a return saccade (1-back: regression coefficient *beta* = 0.0915 [0.0570, 0.1259], *t*(38) = 5.38, *p* = 4.079e-6; 2-back: *beta* = 0.1071 [0.0722, 0.1419], *t*(38) = 6.22, *p* = 2.849e-7).

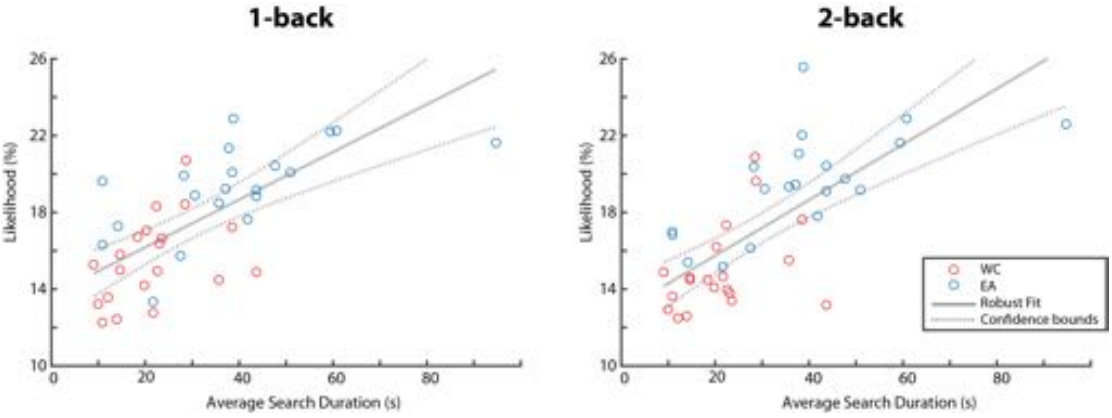

Figure 31. Post-hoc analysis within the significant cluster. The scatter plots show the likelihood to orientate the gaze towards previously fixated locations (sum likelihood within the significant cluster, y-axis) as a function of individual search performance (average search duration, x-axis). A robust linear regression was performed in Matlab using *fitlm* with a Cauchy weight function. Red dot: WC observers; Blue dot: EA observers.

4.5 Discussion

The present study investigated whether culture modulates the oculomotor strategies during the visual search of *Waldo*. We modelled the fixation distribution by quantifying the stochastic differential of the gaze temporal dynamics (1-back and 2-back fixation distributions). We had a particular interest in mapping a potential difference in terms of inhibition of return, an inhibitory process that facilitates eye gazes to novel locations in the visual field. WC and EA observers found *Waldo* with similar accuracy and displayed similar eye movement properties (i.e., fixation duration, saccade length, etc.) and distributions. We also found that both groups of observers did not show any IOR by using a data-driven non-parametric analysis: return fixations occurred very frequently during the search equally for both groups. However, the novelty of the current findings is that EA observers were more likely to gaze toward a previously fixated location compared to WCs. This “double-checking” visual search strategy also correlated with a decrease in performance, as the longer an observer spent on finding *Waldo*, the more return fixations they performed. Overall, our results highlighted this very distinct and time consuming visual search strategy in EA observers, a strategy that might be related to the difficulty of processing visual fine-grained information. Waldo images represent a crowded scene where the dissociation between foreground and background is parametrically hampered. The task of finding Waldo is then straightforward and neutral, unlike judging the appeal of a picture or reporting the content of an image, which could easily be affected by subjective affective decisions like in previous studies (Chua et al., 2005; Goh et al., 2009; Miellet et al., 2010). Importantly, both cultural groups had comparable familiarity with Waldo’s vignettes and the paradigm used here.

In line with Smith and Henderson (2011), our results did not show strong evidence for IOR in either group of observers during the visual search of *Waldo*. Smith and Henderson (2011) argued that such complex visual stimuli necessitate observers to perform return saccades for a second inspection. In the reading literature, the increase in reflexive saccades with increasing text difficulty is well documented (Rayner & Pollatsek, 1989; Vitu, 2005). Interestingly, for this factor we found that EA observers returned more to previously investigated locations than for WC observers for both 1-back and 2-back fixations. Since EA observers have a more *global* distribution of attention relative to WC observers, they might be less efficient in the processing of foveal information (Miellet et al., 2013). This cultural difference in the scan path strategy might thus relate to the encoding of the high-spatial frequency details of the Waldo image and the location of the target. EA observers revisited the previous fixation location more often than WC observers, thus extending the search for Waldo. On the contrary, WC observers were better in encoding *local* information and in asserting the absence of the target in the fixated areas and propagate their eye gaze forward by then locating Waldo faster than EA observers. Such a lower rate of return fixations observed in Westerns engenders a better monitoring of the eye movement scan paths. As detailed before, evidence for a larger perceptual window in EA observers comes from previous studies that used different tasks and visual problems (Boduroglu et al., 2009; Petrova et al., 2013; Miellet et al., 2013). Thus, ultimately, a future study using a gaze-contingent design that parametrically manipulates the quantity of foveal information in this task is necessary (Miellet, et al., 2013) to provide direct evidence for a larger attentional window in the EA observers.

The larger return fixation rate observed in the EA observers increased with task difficulty. EA performed shorter saccades when the task difficulty increased, which could be used as an indicator of the area inspected during a single fixation. However, it is worth noting that in line with previous studies (Evans et al., 2009; Rayner et al., 2007, 2009), we did not observe a significant cultural difference on the global eye-tracking measures. The mean fixation duration and the fixations per second in both groups are comparable and similar even when the difficulty level of the vignettes increased.

4.6 Conclusion

During the last two decades, many cultural differences in diverse perceptual tasks (Nisbett & Masuda, 2003; Nisbett & Miyamoto, 2005) and face processing paradigms (e.g., Blais et al., 2008) have been reported in the literature. East Asian observers tend to sample and process visual information more with a *global* strategy, compared to a *local* processing style for Western Caucasian observers. However, the results reported so far for visual tasks involving the processing of natural images have provided mixed evidence of an effect of culture (Chua et al., 2005; Goh et al., 2009; Masuda et al., 2008). Here, we investigated whether finding *Waldo* would elicit culturally specific eye movement patterns. Our data-driven analyses have clearly shown that visual search strategies are not falling into *universal* rules, with EA observers being slower and having more return fixations compared to WC observers. Future studies are necessary to clarify whether and how the *global/local* cultural perceptual bias observed for face processing contributes to this effect. In fact, the *local* eye movement strategy typical of Western observers could lead to a more profound analysis of the inspected area thus preventing a return fixation. Whereas, on the contrary, the *global* strategy, typical of Eastern observers compensates for a suboptimal foveal sampling, by reprocessing previously visited locations (Findlay & Brown, 2006). In the future, the use of a design with a gaze-contingent technique is necessary for a verification of this hypothesis, as visual information intake can be controlled parametrically. Regardless of these potential explanations, the present data feed the literature by informing culturally-dependent cognitive and visual strategies, and emphasize the necessity to report the observers' cultural background as a crucial variable for the understanding of visual cognition.

5 General Discussion

The main purpose of this thesis was to investigate factors leading to changes in visual processing performance during visual search. In particular, the current thesis focused on developmental, top-down, bottom-up and cultural influences on behavioral measures of attention and eye movements. To directly investigate any modulation of performance, I recorded manual reaction time and oculomotor parameters. The combination of both measures is ideal to reveal any effects along the time course between stimuli presentation up to manual response.

In my first experiment, performance in a standard visual search task across ages from five to 13 years shows acceleration in reaction time with increasing age. Typical search pattern, such as faster responses in target-present trials compared to target-absent trials are stable across all ages with comparable error rates. Thus, the visual search task is ideal for the investigation of children as young as five years of age and shows a development in visual search. Some of the increase in speed can be explained by the mere faster motor execution, as tested in a separate motor task. The remaining variance in reaction time can be accounted for by the ongoing development of the brain due to myelination of the axons of nerve cells. The simultaneous measure of saccade latency confirms the temporal acceleration across the different ages with shorter saccade latencies for increasing age. The overall shorter time of visual processing with increased age, already starts at the level of saccade programming, that is segregation of the search display, and carries on along target selection and manual response. In regard to eye movement frequencies, it is evident in the motor task, that after the age of eight years (4th class), unnecessary eye movements towards the target were inhibited. The task was only to respond to the appearance of any visual display, irrespective of the presence of a target. In line with studies by Schultze-Kraft, Onat and König (2010), top-down influences become more apparent in children at the age of seven to nine years. To summarize, children of specific ages undergo maturation of the brain and behavior leading to advanced performance in a simple visual search task. To the best of my knowledge, this thesis is the first to combine oculomotor and manual measures to investigate visual search along development. Generally, combining manual reaction times and eye movements in a search task with children is a novel approach, which is facilitated by the use of the modern eye tracking systems.

The second experiment continues with a similar methodological setup, namely the visual search paradigm, with recordings of manual and oculomotor responses. While in chapter I the influencing factor came form the observer, in chapter II, the task-set between search conditions is manipulated, making it possible to investigate the impact of top-down information on early visual processes. A well-established beneficial effect of target search within the visual search paradigm, is the redundancy gain (Miller, 1982; Mordkoff & Yantis, 1993). Target singletons differing from distracting singletons in a combination of two dimensions are responded to faster than any response to just uniquely defined target singletons. Such enhancing characteristics coming from the stimulus itself are accordingly referred to as stimulus-driven effects, causing the bottom-up signal to increase and accelerate attentional deployment. The design of the experiment in chapter II used the advantageous fusion of two dimensions to construct conditions that weaken the redundancy effect by making one of the dimensions task irrelevant. In line with previous studies redundancy gains were observed for the baseline condition when there was no interference of any irrelevant dimension (Müller et al., 2003). The redundant signal effect (RSE) could be observed for saccadic and manual reaction time, however, more pronounced for the latter. Detecting the RSE already at the level of saccade programming supports locating it at an early processing stage as put forward by Töllner, Zehetleitner, Krummenacher and

Müller (2010). In a similar experiment by Gurbert, Krummenacher and Eimer (2011), additionally investigating the N2pc component allowed the same conclusion of a pre-attentive locus of the RSE effect. Together with the results of this thesis there is ample evidence supporting the early occurrence of the redundancy gain effect. In the matter of the condition including a task irrelevant dimension, the RSE was attenuated compared to the baseline condition showing the influence of the task-set defining the relevant target dimensions. This can be seen as evidence that top-down (task-specific) knowledge can influence the processing of visual information as early as the generation of its saliency signal. This redundancy diminishing effect even increased its strength along the temporal window of response to a larger suppression on the manual response level. Overall, the findings of chapter II demonstrate that the control of attention and eye movements is prone to top-down information to the level that it can abolish bottom-up effects caused by redundant signal strength.

Taken together, the first two chapters use the visual search paradigm to investigate observers' performance in search for a target among distractors.

Together, the findings of chapter I and II, lists modulating factors for the control of attention and eye movements. Be it on the level of developmental aspects or guidance by bottom-up and top-down effects. Along these lines, chapter III expands both the complexity of the search scene and broadens the experimental manipulation to the cultural origin of observers. In other words, chapter III investigated the cultural influence on complex visual scene search. In particular, exploring the search for Waldo between EA and WC observers as a universal and complex scene search. In contrast to the previous chapters in terms of stimuli this experiment moves form simple search displays of a visual search paradigm towards more realistic scenarios. As differences in cognitive styles between EA and WC are established (Nisbett, 2010), chapter III contributes to the pool of perceptual differences between both groups by investigating the low-level mechanism of inhibition of return (IoR). IoR is a mechanism preventing the reinvestigation of previously visited location. Interestingly, it can be regarded as a low-level mechanism prioritizing novel locations, pushing search towards new locations. The data-driven approach allows having both groups of observers undergo the same task of search with stimuli that should not prefer any cognitive style of the different cultures, but rather represent an objective scene. The analysis of all the saccades up to the localization of Waldo were decomposed into their angle and length, in order to investigate any return to previously visited locations in the 1- or 2-back fixation. Whereas there was no difference between the search strategies between the groups on the general oculomotor parameters they did differ on the lines of returning to previously visited locations. EA returned more often to locations they had already visited on the 1-back or 2-back fixation. EA's more global distribution of attention necessitates them to return for a reinvestigation of the previously fixated area. Thus leading to a longer overall search time, which we found in our results.

All together, my work demonstrates that the control of attention and eye movements can be modulated by factors within the observer and by the external setting. To fully understand how all of these effects contribute to the versatile task of searching for an object among distractors more research is required which will be elaborated in the future directions section.

With this thesis I provided evidence form three different point of views. Chapter I contributed to the developmental aspects of attention and eye movement. Chapter II supported the idea of top-down modulation at an early processing stage for both manual and saccadic reaction time. And chapter III provided yet another cultural difference when observers are searching a complex scene. Incorporated the entire finding from the chapters supplies confirmation that the way we search is a complex process adaptable by internal and external circumstances.

5.1 Implications

Although the research methods used in this thesis are not new, they were combined in a manner that had not been done before. The combination of manual and oculomotor search parameters proved to add insight into the processes underlying search. In all three chapters, the addition of eye movement data allowed for supplementary information. While in chapter I reaction time patterns showed similar patterns between children and adults, the measure of oculomotor patterns revealed a change in control of eye movements. Saccadic reaction times firstly confirmed familiar reaction time pattern by simple acceleration with increasing age. However, eye movement frequency data revealed the emergence of inhibitory control of eye movements after the age of nine years. With the ease of use of today's eye tracking systems, children at early ages can be tested with conventional paradigms while including oculomotor measures. As increasing research focuses on the comparison between healthy and clinical groups in regard to cognitive performances, adding oculomotor parameters reveals underlying search processes that could be effected by certain cognitive dysfunctions (Karatekin, 2007). Also in chapter II, the recording of saccadic reaction times provided temporal evidence for locating the redundancy signal effect (RSE) at an early stage in visual processing. Together with EEG findings from Grubert et al. (2011), my findings proof top-down modulation on the RSE to be at the stage of the saliency signal generation. Further more, demonstrating the RSE early at the level of saccadic reaction time and later at the level of manual reaction time supports the idea of a close link between covert and overt attention (Deubel & Schneider, 1996). The inclusion of eye movement data renders necessary for a deeper understanding into processes occurring before detection and response of stimuli. In chapter III, only the analysis of the oculomotor search pattern revealed a significant difference, otherwise hidden by other means of measurement. In recording return fixations in a complex scene search, my findings add to the pool of cultural differences in cognitive styles. Importantly, the use of universal stimuli and a data-driven approach, allows for highest objectivity in comparing both cultures' search performance. Chapter III provides a significant contribution in understanding how culture influences the search pattern in a complex scene. As suggested by Nisbett et al. (2001), culture determines observer's information processing to be more global for EAs and more local for WCs.

5.2 Future Directions

As briefly mentioned above, children's performance in visual search tasks could be an indicator of any abnormal development. Munoz, Armstrong, Hampton and Moore (1998) compared differences in a pro- and anti-saccade task for healthy children and those diagnosed with ADHD. Differences showed in their oculomotor performance. How these observer groups compare in a visual search task is yet to be tested. With modern tracking devices, it becomes easy to test children at young ages to develop a greater database of typical parameters for each age. It would be interesting to take experiments outside the laboratory and investigate children's oculomotor behavior and judgment in every day situation like crossing a road for example. With the knowledge of better inhibitory control of elderly children, future studies should investigate the underlying mechanism to further our understanding of the oculomotor development.

The benefit of including eye movement data with manual reaction time is a trend in modern research providing deeper insight into underlying search mechanisms. The global effect of eye movement could show the influence a different stimulus has on the saccade accuracy. Investigating the global effect for the redundancy experiment of chapter II, would provide useful information as to the proximity of the competing dimensions of a stimuli. Different manipulations of dimensions, such as motion need to be tested to expand the knowledge on the possible combinations for a redundancy effect within the saccade latency and manual reaction time. My results have certainly provided novel data in the domain of eye movements and mechanisms related to them. In Chapter III, I showed that inhibition of return is culture-dependent and justify the difference due to the global, local difference in perception. To pinpoint this finding to the exact underlying mechanism, gaze-contingent experiments are required. As for many cross-cultural studies, a future investigating needs to test observers who have substituted their native background. Concretely, further experiments should test EAs that have lived in Europe and WC that lived in Asia.

Overall, my finding provide evidence that including oculomotor measurements yield more insight into visual search mechanisms and promise to stimulate new set of experiments testing a variety of dimensions within search.

5.3 Final Remarks

Eye movements can tell us more than just where we look. The aim of this thesis was to investigate modulatory factors of oculomotor performance in different visual search tasks. I explored the effect of development, top-down knowledge and culture on visual processing. Measuring the unseen is the bridge between mind and behavior and by understanding eye movements, we can explain how the environment can shape our behavior.

6 References

Abrams, R. A., & Jonides, J. (1988). Programming saccadic eye movements. *Journal of Experimental Psychology. Human Perception and Performance*, *14*(3), 428–443.

Accardo, A., Pensiero, S., Da Pozzo, S., & Perissutti, P. (1992). Some characteristics of saccadic eye movements in children of primary school age. *Documenta Ophthalmologica*, *80*(2), 189–199. http://doi.org/10.1007/BF00161245

Açık, A., Sarwary, A., Schultze-Kraft, R., Onat, S., & König, P. (2010). Developmental Changes in Natural Viewing Behavior: Bottom-Up and Top-Down Differences between Children, Young Adults and Older Adults. *Frontiers in Psychology*, *1*. http://doi.org/10.3389/fpsyg.2010.00207

Andrews, T. J., & Coppola, D. M. (1999). Idiosyncratic characteristics of saccadic eye movements when viewing different visual environments. *Vision Research*, *39*(17), 2947–2953.

Ansorge, U., Kiss, M., Worschech, F., & Eimer, M. (2011). The initial stage of visual selection is controlled by top-down task set: new ERP evidence. *Attention*. http://doi.org/10.3758/s13414-010-0008-3

Anstis, S. (1998). Picturing peripheral acuity. *Perception*, *27*(7), 817–825.

Aring, E., Grönlund, M. A., Hellström, A., & Ygge, J. (2007). Visual fixation development in children. *Graefe's Archive for Clinical and Experimental Ophthalmology*, *245*(11), 1659–1665. http://doi.org/10.1007/s00417-007-0585-6

Arndt, P. A., & Colonius, H. (2003). Two stages in crossmodal saccadic integration: evidence from a visual-auditory focused attention task. *Experimental Brain Research*. http://doi.org/10.1007/s00221-003-1424-6

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of memory and language*, *59*(4), 390-412.

Blais, C., Jack, R. E., Scheepers, C., Fiset, D., & Caldara, R. (2008). Culture Shapes How We Look at Faces. *Plos One*, *3*(8), e3022–9. http://doi.org/10.1371/journal.pone.0003022

Boduroglu, A., Shah, P., & Nisbett, R. E. (2009). Cultural differences in allocation of attention in visual information processing. *Journal of Cross-Cultural …*. http://doi.org/10.1177/0022022108331005

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*.

Braithwaite, J. J., Humphreys, G. W., & Hulleman, J. (2005). Color-based grouping and inhibition in visual search: Evidence from a probe detection analysis of preview search. *Perception & Psychophysics*, *67*(1), 81–101. http://doi.org/10.3758/BF03195014

Broadbent, D. E. (1954). The role of auditory localization in attention and memory span. *Journal of Experimental Psychology*, *47*(3), 191–196. http://doi.org/10.1037/h0054182

Buswell, G. T. (1935). How people look at pictures: a study of the psychology and perception in art.

Bylinskii, Z., DeGennaro, E. M., Rajalingham, R., Ruda, H., Zhang, J., & Tsotsos, J. K. (2015). Towards the quantitative evaluation of visual attention models. *Vision Research*, *116*(Part B), 258–268. http://doi.org/10.1016/j.visres.2015.04.007

Caldara, R. (2015). Mapping the impact of culture and race in visual processing (pp. XVIII–XVIII). Presented at the 2015 7th International Conference on Knowledge and Smart Technology (KST), IEEE. http://doi.org/10.1109/KST.2015.7051447

Calder, A. J., & Young, A. W. (2005). Understanding the recognition of facial identity and facial expression. *Nature Reviews Neuroscience*, *6*(8), 641–651. http://doi.org/10.1038/nrn1724

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525. http://doi.org/10.1016/j.visres.2011.04.012

Cave, K., & Wolfe, J. M. (1990). Modeling the role of parallel processing in visual search. *Cognitive Psychology*, *22*(2), 225–271.

Chandna, A. (1991). Natural-History of the Development of Visual-Acuity in Infants. *Eye*, *5*, 20–26.

Chua, H. F., Boland, J. E., & Nisbett, R. E. (2005). Cultural variation in eye movements during scene perception. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(35), 12629–12633. http://doi.org/10.1073/pnas.0506162102

Chuk, T., Chan, A. B., & Hsiao, J. H. (2014). Understanding eye movements in face recognition using hidden Markov models. *Journal of Vision*, *14*(11), 8–8. http://doi.org/10.1167/14.11.8

Chun, M. M., & Wolfe, J. M. (1996). Just say no: How are visual searches terminated when there is no target present? *Cognitive Psychology*, *30*(1), 39–78. http://doi.org/10.1006/cogp.1996.0002

Connor, C. E., Egeth, H. E., & Yantis, S. (2004). Visual Attention: Bottom-Up Versus Top-Down. *Current Biology*, *14*(19), R850–R852. http://doi.org/10.1016/j.cub.2004.09.041

Conway, B. R., Hubel, D. H., & Livingstone, M. S. (2002). Color contrast in macaque V1. *Cerebral Cortex*, *12*(9), 915–925.

Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The Eyelink Toolbox: eye tracking with MATLAB and the Psychophysics Toolbox. *Behavior Research Methods, Instruments, & Computers : a Journal of the Psychonomic Society, Inc*, *34*(4), 613–617.

Cramer, E. S., Dusko, M. J., & Rensink, R. A. (2016). Group-level differences in visual search asymmetry. *Attention, Perception, & Psychophysics*, 1–18. http://doi.org/10.3758/s13414-016-1137-0

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: evidence for a common attentional mechanism. *Vision Research*, *36*(12), 1827–1837.

Deutsch, J. A., & Deutsch, D. (1963). Attention - Some Theoretical Considerations. *Psychological Review*, *70*(1), 80–90. http://doi.org/10.1037/h0039515

Donnelly, N., Cave, K., & Greenway, R. (2007). Visual search in children and adults: Top-down and bottom-up mechanisms. *The Quarterly Journal …*. http://doi.org/10.1080/17470210600625362

Duchowski, A. (2013). Eye Tracking Methodology: Theory and Practice. Springer Science & Business Media. http://doi.org/10.1007/978-1-4471-3750-4

Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience*, *20*(8), 1423–1433. http://doi.org/10.1162/jocn.2008.20099

Evans, K., Rotello, C. M., Li, X., & Rayner, K. (2009). Scene perception and memory revealed by eye movements and receiver-operating characteristic analyses: Does a cultural difference truly exist?. *The Quarterly Journal of Experimental Psychology*, *62*(2), 276-285. http://doi.org/10.1080/17470210802373720

Feintuch, U., & Cohen, A. (2002). Visual Attention and Coactivation of Response Decisions for Features from Different Dimensions. *Psychological Science*, *13*(4), 361–369. http://doi.org/10.2307/40063769?ref=no-x-route:dfec9eab0adb9d2ac3ab88a626e0faf4

Findlay, J. M., & Brown, V. (2006). Eye scanning of multi-element displays: I. Scanpath planning. *Vision Research*, *46*(1-2), 179–195. http://doi.org/10.1016/j.visres.2005.06.010

Fioravanti, F., Inchingolo, P., Pensiero, S., & Spanio, M. (1995). Saccadic eye movement conjugation in children. *Vision Research*, *35*(23-24), 3217–3228.

Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a "dimension-weighting“” account. *Perception & Psychophysics*, *58*(1), 88–101. http://doi.org/10.3758/BF03205479

Fukushima, J., Hatta, T., & Fukushima, K. (2000). Development of voluntary control of saccadic eye movements. I. Age-related changes in normal children. *Brain & Development*, *22*(3), 173–180.

Geangu, E., Ichikawa, H., Lao, J., Kanazawa, S., Yamaguchi, M. K., & Caldara, R., & Turati, C. (2016). Culture shapes 7-month-olds perceptual strategies in discriminating facial expressions of emotion. Current Biology, 26, 663–664.

Gerhardstein, P., & Rovee-Collier, C. (2002). The Development of Visual Search in Infants and Very Young Children. *Journal of Experimental Child Psychology*, *81*(2), 194–215. http://doi.org/10.1006/jecp.2001.2649

Gerhardstein, P., Kraebel, K. S., Gillis, J., & Lassiter, S. (2002). Visual search for high-level configural differences as well as low-level critical features is highly efficient early in childhood. *Developmental Psychobiology*, *41*(3), 241–252. http://doi.org/10.1002/dev.10074

Goh, J. O., Tan, J. C., & Park, D. C. (2009). Culture Modulates Eye-Movements to Visual Novelty. *Plos One*, *4*(12), e8238–9.
http://doi.org/10.1371/journal.pone.0008238

Greene, M. R., Liu, T., & Wolfe, J. M. (2012). Reconsidering Yarbus: A failure to predict observers' task from eye movement patterns. *Vision Research*, *62*(C), 1–8. http://doi.org/10.1016/j.visres.2012.03.019

Gregory, R. L. (1978). Eye and Brain. McGraw-Hill Companies.

Grubert, A., Indino, M., & Krummenacher, J. (2014). From features to dimensions: cognitive and motor development in pop-out search in children and young adults. *Frontiers in Psychology*, *5*, 519. http://doi.org/10.3389/fpsyg.2014.00519

Grubert, A., Krummenacher, J., & Eimer, M. (2011). Redundancy gains in pop-out visual search are determined by top-down task set: behavioral and electrophysiological evidence. *Journal of Vision*, *11*(14). http://doi.org/10.1167/11.14.10

Haji-Abolhassani, A., & Clark, J. J. (2014). An inverse Yarbus process: Predicting observers' task from eye movement patterns. *Vision Research*, *103*(C), 127–142. http://doi.org/10.1016/j.visres.2014.08.014

Handford, M. (1987). Where’s Waldo? London: Little Brown.

Handford, M. (2008). Where’s Wally? The solid gold collection. London: Walker Books.

Hendee, W. R., & Wells, P. N. T. (1997). The Perception of Visual Information. Springer Science & Business Media.

Henderson, J. M. (2003). Human gaze control during real-world scene perception. Trends in Cognitive Sciences, 7(11), 498–504. http://doi.org/10.1016/j.tics.2003.09.006

Hoffman, J. E., & Subramaniam, B. (1995). The Role of Visual-Attention in Saccadic Eye-Movements. *Perception & Psychophysics*, *57*(6), 787–795.

Hommel, B., Li, K. Z. H., & Li, S.-C. (2004). Visual Search Across the Life Span. *Developmental Psychology*, *40*(4), 545–558. http://doi.org/10.1037/0012-1649.40.4.545

Hooge, I. T. C., Over, E. A. B., van Wezel, R. J. A., & Frens, M. A. (2005). Inhibition of return is not a foraging facilitator in saccadic search and free viewing. *Vision Research*, *45*(14), 1901–1908. http://doi.org/10.1016/j.visres.2005.01.030

Hopf, J. M., Luck, S. J., Girelli, M., & Hagner, T. (2000). Neural sources of focused attention in visual search. *Cerebral …*. http://doi.org/10.1093/cercor/10.12.1233

Hughes, H. C., Reuter-Lorenz, P. A., Nozawa, G., & Fendrich, R. (1994). Visual-auditory interactions in sensorimotor processing: Saccades versus manual responses. *Journal of Experimental Psychology. Human Perception and Performance*, *20*(1), 131–153. http://doi.org/10.1037/0096-1523.20.1.131

Hunt, A. R., & Kingstone, A. (2003). Covert and overt voluntary attention: linked or independent? *Cognitive Brain Research*, *18*(1), 102–105. http://doi.org/10.1016/j.cogbrainres.2003.08.006

Irving, E. L. (2006). Horizontal Saccade Dynamics across the Human Life Span. *Investigative Ophthalmology & Visual Science*, *47*(6), 2478–2484. http://doi.org/10.1167/iovs.05-1311

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*(3), 194–203. http://doi.org/10.1038/35058500

Itti, L., Koch, C., & Niebur, E. (1998). A model of saliency-based visual attention for rapid scene analysis. *Ieee Transactions on Pattern Analysis and Machine Intelligence*, *20*(11), 1254–1259. http://doi.org/10.1109/34.730558

Jack, R. E., Blais, C., Scheepers, C., Schyns, P. G., & Caldara, R. (2009). Cultural confusions show that facial expressions are not universal. *Current Biology : CB*, *19*(18), 1543–1548. http://doi.org/10.1016/j.cub.2009.07.051

Kanan, C., Bseiso, D. N. F., Ray, N. A., Hsiao, J. H., & Cottrell, G. W. (2015). Humans have idiosyncratic and task-specific scanpaths for judging faces. *Vision Research*, *108*(C), 67–76. http://doi.org/10.1016/j.visres.2015.01.013

Karatekin, C. (2007). Eye tracking studies of normative and atypical development. *Developmental Review*. http://doi.org/10.1016/j.dr.2007.06.006

Kelly, D. J., Liu, S., Rodger, H., Miellet, S., Ge, L., & Caldara, R. (2011). Developing cultural differences in face processing. *Developmental Science*, *14*(5), 1176–1184. http://doi.org/10.1111/j.1467-7687.2011.01067.x

Kelly, D. J., Miellet, S., & Caldara, R. (2010). Culture shapes eye movements for visually homogeneous objects. *Frontiers in Psychology*, *1*, 6. http://doi.org/10.3389/fpsyg.2010.00006

Kiss, M., & Eimer, M. (2010). Attentional capture by size singletons is determined by top-down search goals. *Psychophysiology*, *48*(6), 784–787. http://doi.org/10.1111/j.1469-8986.2010.01145.x

Klein, C. (2001). Developmental functions for saccadic eye movement parameters derived from pro-and antisaccade tasks. *Experimental Brain Research*. http://doi.org/10.1007/s002210100711

Klein, R. M., & MacInnes, W. J. (1999). Inhibition of return is a foraging facilitator in visual search. *Psychological science*, *10*(4), 346-352.

Kowler, E. (2011). Eye movements: The past 25years. *Vision Research*, *51*(13), 1457–1483. http://doi.org/10.1016/j.visres.2010.12.014

Kowler, E., & Martins, A. J. (1982). Eye Movements of Preschool Children. *Science*, *215*(4535), 997–999. http://doi.org/10.2307/1688353?ref=no-x-route:1de4c34d8c7770a627313888a0d9d15f

Krauzlis, R. J. (2008). Eye Movements. In *Fundamental Neuroscience* (pp. 775–792). Academic Press.

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*(5), 901–917.

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*(6), 1303–1322. http://doi.org/10.1037//0096-1523.28.6.1303

Kümmerer, M., Wallis, T. S. A., & Bethge, M. (2015). Information-theoretic model comparison unifies saliency metrics. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(52), 16054–16059. http://doi.org/10.1073/pnas.1510393112

Kümmerer, M., Wallis, T. S., & Bethge, M. (2016). DeepGaze II: Reading fixations from deep features trained on object recognition. *arXiv preprint arXiv:1610.01563*.

Kwon, M., Legge, G. E., & Dubbels, B. R. (2007). Developmental changes in the visual span for reading. *Vision Research*, *47*(22), 2889–2900. http://doi.org/10.1016/j.visres.2007.08.002

Lao, J., Miellet, S., Pernet, C., Sokhn, N., & Caldara, R. (2016). iMap4: An open source toolbox for the statistical fixation mapping of eye movement data with linear mixed modeling. *Behavior Research Methods*, 1–17. http://doi.org/10.3758/s13428-016-0737-x

Lao, J., Vizioli, L., & Caldara, R. (2013). Culture modulates the temporal dynamics of global/local processing. *Culture and Brain*, *1*(2-4), 158–174. http://doi.org/10.1007/s40167-013-0012-2

Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in Cognitive Sciences*, *4*(1), 6–14. http://doi.org/10.1016/S1364-6613(99)01418-7

Livingstone, M. S., Freeman, D. C., & Hubel, D. H. (1996). Visual responses in V1 of freely viewing monkeys. *Cold Spring Harbor Symposia on Quantitative Biology*, *61*, 27–37. http://doi.org/10.1101/SQB.1996.061.01.006

Lobaugh, N. J., Cole, S., & Rovet, J. F. (1998). Visual search for features and conjunctions in development. *Canadian Journal of Experimental Psychology = Revue Canadienne De Psychologie Expérimentale*, *52*(4), 201–212. http://doi.org/10.1037/h0087293

Luna, B., Velanova, K., & Geier, C. F. (2008). Development of eye-movement control. *Brain and Cognition*, *68*(3), 293–308. http://doi.org/10.1016/j.bandc.2008.08.019

Masuda T, Akase M, Radford M, Wang H (2008a) Cross-cultural research on the pattern of eye movement: comparing the level of concentration between Japanese and Western participants. *Japanese Psychological Research,* 79, 35-43

Matsuzawa, M., & Shimojo, S. (1997). Infants' fast saccades in the gap paradigm and development of visual attention. *Infant Behavior and Development*, *20*(4), 449–455. http://doi.org/10.1016/S0163-6383(97)90035-7

Mehoudar, E., Arizpe, J., Baker, C. I., & Yovel, G. (2014). Faces in the eye of the beholder: unique and stable eye scanning patterns of individual observers.

Journal of Vision, *14*(7), 6. http://doi.org/10.1167/14.7.6

Miellet, S., He, L., Zhou, X., Lao, J., & Caldara, R. (2012). When East meets West: gaze-contingent Blindspots abolish cultural diversity in eye movements for faces. *Journal of Eye Movement Research*, *5*(2). http://doi.org/10.16910/jemr.5.2.5

Miellet, S., Vizioli, L., He, L., Zhou, X., & Caldara, R. (2013). Mapping Face Recognition Information Use across Cultures. *Frontiers in Psychology*, *4*, 34. http://doi.org/10.3389/fpsyg.2013.00034

Miellet, S., Zhou, X., He, L., Rodger, H., & Caldara, R. (2010). Investigating cultural diversity for extrafoveal information use in visual scenes. *Journal of Vision*, *10*(6), 21–21. http://doi.org/10.1167/10.6.21

Miller, J. (1982). Divided attention: evidence for coactivation with redundant signals. *Cognitive Psychology*, *14*(2), 247–279.

Mordkoff, J. T., & Yantis, S. (1993). Dividing attention between color and shape: evidence of coactivation. *Perception & Psychophysics*, *53*(4), 357–366.

Motter, B. C., & Belky, E. J. (1998). The guidance of eye movements during active visual search. *Vision Research*, *38*(12), 1805–1815.

Munoz, D. P., Broughton, J. R., Goldring, J. E., & Armstrong, I. T. (1998). Age-related performance of human subjects on saccadic eye movement tasks. *Experimental Brain Research*, *121*(4), 391–400.

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics*, *57*(1), 1–17. http://doi.org/10.3758/BF03211845

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. http://doi.org/10.1037/0096-1523.29.5.1021

Nakayama, K., & Silverman, G. H. (1986). Serial and Parallel Processing of Visual Feature Conjunctions. *Nature*, *320*(6059), 264–265.

Nisbett, R. E. (2010). The Geography of Thought. Simon and Schuster.

Nisbett, R. E., & Masuda, T. (2003). Culture and point of view. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(19), 11163–11170. http://doi.org/10.1073/pnas.1934527100

Nisbett, R. E., & Miyamoto, Y. (2005). The influence of culture: holistic versus analytic perception. *Trends in Cognitive Sciences*, *9*(10), 467–473. http://doi.org/10.1016/j.tics.2005.08.004

Olson, R. (2015, February 3). Here's Waldo: Computing the optimal search strategy for finding Waldo [Web log post]. Retrieved April 23, 2017, from http://www.randalolson.com

Paus, T., Babenko, V., & Radil, T. (1990). Development of an ability to maintain verbally instructed central gaze fixation studied in 8- to 10-year-old children. *International Journal of Psychophysiology*, *10*(1), 53–61.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spatial Vision*, *10*(4), 437–442. http://doi.org/10.1163/156856897X00366

Petrova, K., Wentura, D., & Fu, X. (2013). Cultural influences on oculomotor inhibition of remote distractors: Evidence from saccade trajectories. *Vision Research*. http://doi.org/10.1016/j.visres.2013.03.008

Pinto, Y., van der Leij, A. R., Sligte, I. G., Lamme, V. A. F., & Scholte, H. S. (2013). Bottom-up and top-down attention are independent. *Journal of Vision*, *13*(3), 16–16. http://doi.org/10.1167/13.3.16

Polyak, S. L. (1941). The retina: the anatomy and the histology of the retina in man, ape, and monkey, including the consideration of visual functions, the history of physiological optics, and the histological laboratory technique.

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. http://doi.org/10.1080/00335558008248231

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. *Attention and performance X: Control of language processes*, *32*, 531-556.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, 41, 211–236.

Rayner, K., Castelhano, M. S., & Yang, J. (2009). Eye movements when looking at unusual/weird scenes: Are there cultural differences? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(1), 254–259. http://doi.org/10.1037/a0013508

Rayner, K., Li, X., Williams, C. C., Cave, K. R., & Well, A. D. (2007). Eye movements during information processing tasks: individual differences and cultural effects. *Vision Research*, *47*(21), 2714–2726. http://doi.org/10.1016/j.visres.2007.05.007

Rayner, K., & Pollatsek, A. (1989). *The Psychology of Reading*. Englewood Cliffs, NJ: Prentice Hall.

Remington, R. W. (1980). Attention and saccadic eye movements. *Journal of Experimental Psychology. Human Perception and Performance*, *6*(4), 726–744. http://doi.org/10.1037/0096-1523.6.4.726

Rizzolatti, G., Riggio, L., Dascola, I., & Umiltá, C. (1987). Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention. *Neuropsychologia*.

Rodger, H., Kelly, D. J., Blais, C., & Caldara, R. (2010). Inverting Faces Does Not Abolish Cultural Diversity in Eye Movements. *Perception*, *39*(11), 1491–1503. http://doi.org/10.1068/p6750

Scott, D.W. (1992). "*Multivariate Density Estimation: Theory, Practice, and Visualization*". New York, Chicester: John Wiley & Sons.

Shepherd, M., Findlay, J. M., & Hockey, R. J. (1986). The relationship between eye movements and spatial attention. *The Quarterly Journal of Experimental Psychology Section A*, *38*(3), 475–491. http://doi.org/10.1080/14640748608401609

Smith, T. J., & Henderson, J. M. (2009). Facilitation of return during scene viewing. *Visual Cognition*. http://doi.org/10.1080/13506280802678557

Smith, T. J., & Henderson, J. M. (2011). Looking back at Waldo: Oculomotor inhibition of return does not prevent return fixations. *Journal of Vision*, *11*(1), 3. http://doi.org/10.1167/11.1.3

Tardif, J., Fiset, D., Zhang, Y., Estéphan, A., Cai, Q., Luo, C., et al. (2016). Culture Shapes Spatial Frequency Tuning for Face Identification. *Journal of Experimental Psychology. Human Perception and Performance*, 1–14. http://doi.org/10.1037/xhp0000288

Thompson, L. A., & Massaro, D. W. (1989). Before you see it, you see its parts: evidence for feature encoding and integration in preschool children and adults. *Cognitive Psychology*, *21*(3), 334–362.

Töllner, T., Zehetleitner, M., Gramann, K., & Müller, H. J. (2010). Top-down weighting of visual dimensions: Behavioral and electrophysiological evidence. *Vision Research*, *50*(14), 1372–1381. http://doi.org/10.1016/j.visres.2009.11.009

Töllner, T., Zehetleitner, M., Krummenacher, J., & Müller, H. J. (2011). Perceptual basis of redundancy gains in visual pop-out search. *Journal of Cognitive Neuroscience*, *23*(1), 137–150. http://doi.org/10.1162/jocn.2010.21422

Torralba, A., Oliva, A., Castelhano, M. S., & Henderson, J. M. (2003). Top-down control of visual attention in object detection. *International Conference on Image Processing*, *1*, I–253–6 vol.1. http://doi.org/10.1109/ICIP.2003.1246946

Treisman, A. (1988). Features and objects: the fourteenth Bartlett memorial lecture. *The Quarterly Journal of Experimental Psychology Section A*, *40*(2), 201–237.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.

Trick, L. M., & Enns, J. T. (1998). Lifespan changes in attention: The visual search task. *Cognitive Development*, *13*(3), 369–386. http://doi.org/10.1016/S0885-2014(98)90016-8

Turatto, M., & Betta, E. (2006). Redundant visual signals boost saccade execution. *Psychonomic Bulletin & Review*, *13*(5), 928–932.

Vitu F, McConkie GW. *Regressive saccades and word perception in adult reading*. In: Kennedy A, Radach R, Heller D, Pynte J, editors. Reading as a perceptual process. Elsevier; Oxford, England: 2000. pp. 301–326.

Wade, N., & Tatler, B. W. (2005). The Moving Tablet of the Eye. Oxford University Press.

Wilson, S. J., Glue, P., Ball, D., & Nutt, D. J. (1993). Saccadic eye movement parameters in normal subjects. *Electroencephalography and Clinical Neurophysiology*, *86*(1), 69–74. http://doi.org/10.1016/0013-4694(93)90068-7

Wolfe, J. M. (1994). Guided Search 2.0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238. http://doi.org/10.3758/BF03200774

Wolfe, J. M. (1998). What Can 1 Million Trials Tell Us about Visual Search? *Psychological Science*, *9*(1), 33–39. http://doi.org/10.2307/40063243?ref=no-x-route:f2e1515723cdee5c88ba57a7461645db

Wolfe, J. M. (2007). Guided search 4.0. *Integrated Models of Cognitive Systems*. http://doi.org/10.1525/rep.2014.127.1.83?ref=no-x-route:5a6ee577dcdb76124924bdd4f72d7e88

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience*, *5*(6), 495–501. http://doi.org/10.1038/nrn1411

Yang, Q., Bucci, M. P., & Kapoula, Z. (2002). The latency of saccades, vergence, and combined eye movements in children and in adults. *Investigative Ophthalmology & Visual Science*, *43*(9), 2939–2949.

Yarbus, A. L. (1967). Eye movements and vision. *New York: Plenum Press* (Vol. 160).

Ygge, J. N., Aring, E., Han, Y., Bolzani, R., & Hellström, A. (2006). Fixation Stability in Normal Children. *Annals of the New York Academy of Sciences*, *1039*(1), 480–483. http://doi.org/10.1196/annals.1325.049

Zelinsky, G. J., & Sheinberg, D. L. (1997). Eye movements during parallel-serial visual search. *Journal of Experimental Psychology. Human Perception and Performance*, *23*(1), 244–262.

7 Curriculum Vitae

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Ausbildung

Seit Sep, 2009	Doktorat im Bereich der visuellen Aufmerksamkeit
Sep, 2007-Jul, 2009	Psychologiestudium (Master) Universität Fribourg Titel der Masterarbeit: "To move or not to move: Investigating the relationship between attention and eye movements in popout and compound tasks"
Sep, 2004-Jul, 2007	Psychologiestudium (Bachelor) Universität Fribourg Titel der Bachelorarbeit: "Influences of Cognitive Styles on Humor Processing in Connection to the Asperger Syndrome"
May, 2003	Abitur Deutsche Schule London (Gymnasium)

Berufserfahrung und Praktika

Aug-März, 2016/17	Betreuung von Bachelor- und Projektarbeiten an der Fachhochschule Nordwestschweiz
Okt-Jan, 2016/17	Forschungsprojekt an der Universität Bern im Bereich französischer Linguistik (Studie zu Bilingualismus)
Nov-Dez, 2016	Auswertung von Microsaccaden im Rahmen eines

	Forschungsprojekts der Universität Fribourg
Feb-Aug, 2016	Dozent für Experimentalpraktikum an der Fachhochschule Nordwestschweiz
Jan-Aug, 2016	Betreuung von Bachelor- und Projektarbeiten an der Fachhochschule Nordwestschweiz
Seit Jan, 2016	Praktikum als Kameraassistent bei Filme von Draussen
Sep-Feb, 2014/15	Lehrauftrag an der Universität Fribourg im Bereich computerunterstütztes Experimentieren mit E-prime (auf Französisch)
Jul-Jan, 2014/15	Dozent für biologische Psychologie an der Zürcher Hochschule für angewandte Wissenschaften (ZHAW)
Sep,2013-Jul,2016	Velokurier beim Velokurier Luzern
Mai-Jul, 2013	Lehrperson am Lernforum Ambassador in Solothurn
Sep-Feb, 2012/13	Lehrauftrag an der Universität Fribourg im Bereich der experimentellen Übungen
Sep, 2007-Aug, 2009	Unterassistent im Bereich der kognitiven experimentellen Psychologie
Jun-Aug, 2007	Praktikum beim Marktforschungsinstitut Concept (Zürich)
Sep-Nov, 2006	Praktikum im Bereich der Entscheidungspsychologie
Sep-Feb, 2005	Tutor für Arbeitstechniken

Publikationen und Konferenzbeiträge

- Gygax, P., Schoenhals, L., Lévy, A., Luethold, P. & Gabriel, U., (submitted). Grammatical gender and its influence on pre-school children's perception of the world. Manuscript submitted to *Cognitive Development*
- Schmidt, R., Lüthold, P., Kittel, R., Tetzlaff, A., & Hilbert, A. (2016). Visual attentional bias for food in adolescents with binge-eating disorder. *Journal of Psychiatric Research*, *80*, 22–29. http://doi.org/10.1016/j.jpsychires.2016.05.016
- Lüthold, P. & Krummenacher, J. (2012). "Behavioral and oculomotor reaction time redundancy gains in visual search for feature targets: modulated by top-down task set", Poster am "Third Symposium on Visual Search and Selective Attention", Holzhausen, 20-23 Juli 2012.
- Lüthold, P. & Krummenacher, J. (2011). "Eyes or attention: who is in control of searching visual displays?", Vortrag im Symposium am "12th Congress of the Swiss Psychologigal Society", Fribourg, 12-13 September 2011.
- Lüthold, P. & Krummenacher, J. (2011). "Saliency guides covert and overt attention", Poster am "16th European Conference on Eye Movements", Marseille, 21-25 August 2012.
- Lüthold, P. & Krummenacher, J. (2008). "Bottom-up priming of multiple dimensions in search for redundant targets", Poster am "Second Symposium on Visual Search and Selective Attention", Murten, 16-19 Juli 2008.
- Hegenloh, M, Luethold, P., & Samson, A.C. (2007). "Influences of Cognitive Styles on Humor Processing in Connection to the Asperger Syndrome". Poster am " 6th Gallup International Positive Psychology Summit", Washington, DC, USA, 4-6 Oktober 2007.

Sprachkenntnisse

Deutsch:	Muttersprache
Griechisch:	Muttersprache
Englisch:	Sehr gute Kenntnisse
Französisch:	Gute Kenntnisse

Computerkenntnisse

Windows, OsX (Mac), MS Office, SPSS, Matlab, Photoshop, E-prime, Programmierung und Bedienung eines EyeTracker (SR-Research Eyelink)

Hobbys

Volleyball (2. Liga), Mountain-Bike, Rennrad, Gleitschirmfliegen, Fotographie und Film