Measurements of Kinematics of the Eye in Characterising Cognitive Processes

Author:
Roberts Paeglis

Advisor:
Prof. Ivars Lācis

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF NATURAL SCIENCES IN PHYSICS AND ASTRONOMY, MEDICAL PHYSICS FIELD, AT THE UNIVERSITY OF LATVIA

RIGA
2008

PREFACE

At the onset, this research has been a system of equations with many unknowns. The boundary conditions provided were that Medical Physics is about people and about discovering nature, the latter being done for and by the former.

The first unknown was solved with the assistance of Ivans Ļeonovs. He has shown me the primer with the *iViewX* eye-tracker, and also demonstrated the virtues of coding to present visual stimuli. It was him who introduced me to Ingvars Birznieks, PhD in Biology and PhD in Medicine. Discussions with Dr Birznieks shed light on the current research in the field, which was supported by several "hot" articles from his Australian datamine, the Prince of Wales Medical Research Institute.

"If opportunity doesn't knock, build a door," said Milton Berle. These doors were built by Bachelor students who entrusted me to supervise their research. Kristīne Bagucka, Anda Podniece, Aleksejs Koteļņikovs, Inita Jokste, Irīna Goršanova and Laura Vilkauša added much of flavour to the PhD studies. With Kristīne and Anda, we installed and explored ILAB 3.6.4., a MATLAB based application for eye-tracking data processing. Then the terms "fixations" and "saccades" first appeared on the stage of our research. With a new release of eye-tracking software, *BeGaze* replaced ILAB in the data processing. Four of the students had to discover it with me "on flight".

It was unknown if we would manage to install and master a new piece of equipment, the eye-tracking helmet or HED. The combined eye-tracking system that we now have was possible in principle but never mentioned in any manuals. My reverence goes to the courage of Aleksejs, with whom we journeyed a long path of trials and errors (costly errors at times). I appreciate that Professor Ivars Lācis, my supervisor, was willing to allow us these trials and promoted our creativity even when he was the rector of the University of Latvia. Professor Māris Ozoliņš was the one to light the torch of my interest in research during the first years at the University.

Several of my miscalculations and dead-ends were resolved by the charismatic insight of Dr Vjačeslavs Kaščejevs, or Vyacheslavs Kashcheyevs as he is known from Physical Reviews. Ivo Vīksna with his ultimate IT expertise provided that the University computers would be capable of managing the

menace of the data flow. In turn, my fellow PhD student Romans Krutohvostovs was always available for a coffee-break, should any software questions arise.

When solving the many unknowns, one may occasionally start doubting if the solution exists at all. Therefore my devotion belongs to the family who kept me in good cheer during the years of research.

Riga, 2008 *Roberts Paeglis*

CONTENTS

Part I

THEORIES BEHIND EYE KINEMATICS

1. INTRODUCTION

1.1 Eye movements are tightly linked to cognitive processes

The movements of the eyes are a physically accessible indicator of intangible mental processes. They can be measured non-invasively, with stern data acquisition algorithms applied and statistical analysis made. Eye movements are not only the reflections but also precursors of the processes in brain, this mutual dependance is task-related (Loetscher, Bockisch, & Brugger, 2008). Yet the areas of interest in the eye movement research vary, it is challenging to compare and contrast their targets and methods.

Several classes of large scale eye movements are known. Saccades are the fast shifts in gaze when the information processing is suppressed. Smooth pursuit eye movements are involved in tracing a moving object, whereas vergence eye movements make the lines of gaze of both eyes to converge or diverge to switch between objects at various distances. Apart from these, small-scale eye movements as microsaccades, drifts and nystagmus are known. However, it is reported that "...saccadic eye movements are more relevant in typical information processing tasks" (Rayner, 1998, p. 373). This class of eye movements lends itself to basic detection algorithms and is further analyzed in the present research. Fixations, or periods when the gaze is relatively still, signify the information acquisition. In fact, eyes are never absolutely still, with some tremor and other minor movements involved (Rayner, 1998).

In the thesis, saccadic eye movements and fixations have been explored in three areas, with the primary concern to make the visual tasks as natural as possible. Fixations and saccades are considered to be the main indicators of cognitive processes (Rayner, 1998). Efforts have been made to minimise the influence of laboratory conditions and to avoid abstract stimuli. The reasoning behind this adherence to "real life" situations is further elaborated in the theory part. It has been influenced by the reports that the human visual system has advantages to perform in natural tasks. Seemingly simplifying stimuli may sometimes pose a challenge to vision and do not describe the vision as it is. First, eye movements in sports present a realistic task for the observers, where unconscious strategies of the action perception are deployed. Second, image recognition tasks have been devised to investigate the response of the human visual system to photographs of natural objects. This area is fueled by the questions of what makes the human visual system as efficient as it is and how this knowledge could be transferred to the machines. Third, eye movements in reading textbooks have been recorded. The last task, in addition to fundamental aspects, has stirred considerable interest in the institutions responsible for making education more efficient. Several findings of how people read textbooks have been reported repeatedly to the Latvian Ministry of Education and Science (*Latvijas Republikas Izglītības un zinātnes ministrija, Izglītības satura un eksaminācijas centrs, Valsts jaunatnes iniciatīvu centrs*), Riga City Council (*Rīgas domes Izglītības, jaunatnes un sporta departaments*) and a leading national publishing house *Zvaigzne ABC*.

As varied as they are, all three areas represent different combinations of related cognitive processes. "Cognition includes all processes of consciousness by which knowledge is accumulated, such as perceiving, recognizing, conceiving, and reasoning" (Encyclopaedia Britannica, 2008.) A latest trend in scientific literature encourages the interdisciplinary approach and looking for the common conclusions to be drawn from eye movement research. Thus "...cognitive processes as different as attentional orienting, memorizing, the formation of mental images and numerical processing are all reported to be at least accompanied, if not influenced, by eye movements" (Loetscher, Bockisch, & Brugger, 2008, p. 728).

1.2 Aim and tasks of the thesis

The Aim

The aim of this thesis is to equip and explore the combined video-based eye-tracker available at the University of Latvia and to elaborate methods for eye-tracking of motion scenes, graphical and textual information tasks.

The Tasks

- To instal and explore eye-tracking setup for fixed head and free head eye-tracking; to describe the raw data analysis software and to develop mathematical algorithms for eye movement data analysis under different experimental paradigms.
- To determine the characteristic individual and task-dependant differences in eye movement parameters in motion perception.

- To create methods and algorithms for image classification with eye movements; to develop data processing for large data arrays.
- To detect distinctive eye movement parameters in reading formatted text and to explore statistically the differences for head-fixed and head-free conditions.

2. EYE MOVEMENTS IN COMPLEX ACTION OBSERVATION

Is it the strategy of shifting attention and the information selection that distinguishes successful athletes? Or is the success determined by the functioning of the visual system that is trained just as the muscle and respiratory systems are? Several reports address these questions to clarify what elements should be stressed in the sports exercise, along with the endurance and movement techniques (e.g., Williams, & Grant, 1999; Williams et al., 1994; Oudejans et al., 2002). Both strategic decisions and advantages of the visual system are manifested if an athlete responds to the familiar game in laboratory settings, either watching a video or performing in a simplified game situation.

In contrast, the information selection strategies should not operate in full if an athlete is assessing a situation of unfamiliar sports for the first time. It was surmised that these learning advantages of an athlete over those of a non-athlete may emerge gradually as the situations become more familiar. The possible advantages of the visual system training, on the contrary, should appear from the onset. Therefore basketball players and non-athletes were invited to watch martial arts and Latin dance films, aims of watching were set beforehand. Eye movements of the viewers were recorded and distinguished the gaze parameters that could and could not be voluntarily controlled.

The research hypothesis was that athletes, once sufficiently acquainted with a situation in a sport that they had not practiced before, will tend to implement the gaze shift patterns they use in their field of expertise (Vilkauša, 2007). To test this hypothesis, national level female basketball and volleyball players observed film-based situations in karate. None of the participants has practiced martial arts. Thus individuals trained in a team ball sports were asked to observe individual karate professionals' performance of a learned sequence of movements ('kata') or a non-injury tournament of two ('kumite'). An additional task was a movie of a fast-paced cooperative performance, a Latin dance. The same tasks were given to demographically matched non-athletes that did recreational sports only.

2.1 The observers mirror the actions

Visual skills are generally correlated to a person's performance in sports. This finding is revealed in a wide range of phenomena, ranging from those assessed in a routine visual testing (Jafarzadehpur, Aazami, & Bolouri, 2007) to gaze shift recorded by highly specialised equipment (Vickers, 2006).

Motor skills and gaze behaviour act in concert at various stages of life. Infants acquire new gaze behaviour, which matches the new competences that they develop after the first six months of life (Falck-Ytter, Gredebck, & von Hofsten, 2006). This learning of basic eye and limb coordination is similar to the intricate processes that recur later in the lifetime. Arguably, crawling the first metre and putting a toy into a bucket for an infant matches the challenge of a school child skating to score the first goals in hockey, as far as neuronal computations are concerned. When a teenager joins dance lessons or an adult practices for a driver's licence, motor representations of these complicated actions are formed in the brain. As a new action is learned, a person becomes capable of predicting the goal of similar actions that he observes in others. This has led researchers to describe the mirror neuron system. Both in humans and monkeys, this system responds similarly to actions that are performed by self and observed in others, which is the key to understanding the behaviour of other individuals (Fadiga et al., 1995; Keysers, & Perrett, 2004).

In their experiments, Flanagan and Johansson (2003) demonstrate evidence for the "direct matching hypothesis". Their results witness that visually observed data are indeed mapped as motor representations in the observer's brain. They found that if a person is either moving blocks or observing others doing it, the participants make anticipatory eye movements. On the contrary, if the performer of the move is not visible, the gaze is reactive and lags by approximately 200 ms. In a further research, Falck-Ytter and collaborators (2006) amplify this point by showing that not only adults but also 12 months old infants direct their gaze to the assumed goal of the action, the bucket where a toy will be placed, 200 ms or earlier before the actor's hand arrives there. These predictive eye movements occur only if a part of a human agent, the hand that carries the object, is visible.

In general, gaze was found to precede hand movements also in more complex actions (Vickers, 1992; Vickers, 1996; Land, & McLeod, 2000). Johansson et al. (2001) state that the role of the visual information may serve a feedback role, just as a motor command also programs the expected sensory consequences of a successful action (like certain pressure on the fingertips if an object is successfully grasped). To summarise these findings, in a real sports action the viewer's vision is involved in the task control, partly by monitoring own actions and partly by mirroring and predicting the movements of others. This must not necessarily be done by the central vision, though, yet the foveal vision is essential for tracing small objects (Land, & McLeod, 2000). The central vision may also be slightly impaired, as only myopic blur of at least +3.00 D has caused a significant deterioration of interception in cricket (Mann et al., 2007). As contrasted to everyday occasions, in sports it may be a part of the attacking player's strategy to direct the eyes and the head away from the intended target in order to mislead the defence players.

Tracing an object may also be related to some indirect mirroring of the actions. Even before they have already mastered some motor actions, infants attend the hands of adults that move objects. In this respect, a different hypothesis is voiced in the researches like that of Amato, Kezuka and Yamamoto (2004) and Hayes et al. (2007). The investigators present supportive evidence to the decisive role of the actor's gaze. Thus infants direct their gaze to the objects in the hands of an adult if the adult's gaze is also directed there. Adults report the filmed actions as being easier to perceive if the actors themselves look at the object in their hands. On the other hand, Pierno et al. (2006) have concluded that merely looking at an object activates some of the cortical areas that are then involved in the grasping, and does not engage any "empathy" or "mirror" neurons.

If the above findings are applied to sports, two different neural strategies could be implemented if a player aims to intercept a ball that he has just noticed or to block a power forward's shot. Likewise, a video where a ball is modelled on a screen (Brouwer et al., 2006), or fired by a machine (Land & McLeod, 2000), and a video with a person shooting the ball do not present equivalent information for neural processing. Only the cases with visible actors would activate any "mirror neurons" that are engaged in predicting the goal of action. The automated situations leave only the physical properties of motion for analysis. This may also explain some variations in the results of what are the critical factors to predict the trajectory of a ball, depending on whether the human initiator could be observed before the object motion (McLeod & Dienes, 1996; McLeod, Reed, & Dienes, 2003; Brouwer, Brenner, & Smeets, 2002; McBeath, Shaffer, & Kaiser, 1995).

Brouwer et al. (2006) have pointed out that motion projected on a screen may not provide the observer with every necessary cue that is used in real situations. In the research, they generated the motion of a tennis and a volley-ball and asked the participants to estimate whether the ball will land before or behind the person. They opine that the vertical angular velocity may be used as the main cue, contrary to the results of Oudejans et al. (1997). Because of display limitations, a blank background with no reference objects and screen resolution may deprive the observer of sufficient information about the angular expansion of the approaching object. Moreover, stereopsis can contradict the perception of an approaching object which is in fact drawn on the screen. On the other hand, if the observed motion occurs predominantly in a single plane, more can be said about the sequence of gaze shift and limb movements. Importantly, Johansson and collaborators (2001) could arrive to their exact calculations concerning the timing and sites of gaze direction because the action observed took place in a single plane, with no objects approaching or receding significantly. Similarly, we selected the sports situations that develop mostly in the same plane and proposed to use clustering methods to gaze targets.

2.2 Eye movements are directed to pivotal points in the scene

The time that a person looks at a point with suppressed eye movements is called a fixation and is related to information processing demands, while the shift of a person's gaze, or saccade, is related to task and motivation specific factors (e.g., Leigh, & Kennard, 2004). Unlike in other voluntary movements, the velocity of rapid eye movements, or saccades, cannot be voluntarily controlled. Yet this velocity is correlated to the amplitude of eye movements, the "main sequence" relationship, and some factors, such as alertness or fatigue, can alter it (Snyder et al., 2002). The velocity depends on the cause of saccades, the visually guided ones are faster than memory or audially guided ones (Smit, & Van Gisbergen, 1987; Snyder et al., 2002). The velocity of saccades of certain amplitudes can also be modified by neural processes, Snyder et al. (2002) found that a coordinated arm movement promotes a faster saccade than if the arm and the eyes move in opposite directions.

Hayes and co-workers (2007) define visuomotor action "fluency" as the ease of processing of some observed action. An object whose motion path is not obstructed is generally perceived as "more fluent", with the processing speed being a possible but not the ultimate reflection of this. The familiarity of the object in focus has been reported to influence the ease of the situation's processing, actions on familiar objects are perceived as more fluent. This may be suggestive of the fact that if this object, e.g., a ball, has been a key element in the sports practice of the athletes, it will put them and non-athletes to different perceptual states in the observing of a filmed ball shot. Conversely, if athletes and non-athletes are presented with an action that is novel to all of them, the intrinsic visuomotor differences and adaptation skills could be assessed in both groups.

If an action is not fluent in the sense that some obstacles need to be avoided, the coordination and timing of gaze with respect to other body movements can be monitored. The group of Johansson and colleagues (2001) have found that some sites are always visually attended while others become optional targets as an object is moved. If a bar is carried to touch a switch, the grasping site on the bar and the target switch were always looked at. In the same cases, the participants tended to look at other points, such as the intended trajectory points rather than the most salient parts of the obstacles. Notably, if the central vision and eye movements were not employed in the control experiments, the performance did not deteriorate significantly. In a task that involves a motor action, the gaze is shifted to the points that are relevant for the procedure instead of the points of highest contrast or other remarkable physical features.

In the cases when the main setting involves objects approaching, sports experience is assumed to map one or more variables onto others, like the initial ball velocity and height onto the flight distance and bounce time. Land and McLeod (2000) have explored the gaze of cricket batsmen and found that the ball is not followed throughout its flight. In the first 100 or 150 ms after the ball launch batsmen shift their gaze to the estimated bouncing site. The ball is then traced after the bounce, when the angular expansion of the ball may provide further details necessary to hit it. Right after the launch, the ball is too small and too fast, and empirical mappings rather than calculations from the retinal information yield the estimate of the future bounce point. Experienced batsmen appear to use more of smooth pursuit eye movements in combination with saccades, thus minimising the saccadic suppression of the visual information.

Does this eye velocity and amplitude relationship change if an observed sports situation gets familiar? Do athletes and non-athletes adapt their eye movements to different extent, as the situation becomes "more fluent"? Do the ranges of velocities for the two groups differ significantly? These issues were addressed by exploring the "main sequence" relationships for the films demonstrated.

2.3 Martial arts and dance as "unfamiliar" sports

The ball sports can be contrasted to some sports that lack a clearly defined target of actions, and the exact performance rather than a reached visible goal is important. In karate, like in several other martial arts, mastery is determined in tournaments as well as in individual performance. The individual performance, called "kata" or "forms", consists of a series of pre-defined movements. The athlete's performance is assessed in terms of precision and timing of these movements. Every movement does not last the same time, some key positions or "kime" are accentuated and are followed by a pause of approximately 1 second. Since this performance is self-paced, it involves movements that are not usually possible to perform during a tournament because the opponent would intervene or the rules prohibit such actions as overly dangerous. These movements include intricate jumps, kicks and punches to the side, turns etc. Within one position, the exact sequence of actions is important. For instance, the head must be turned briefly before the trunk turns and a block is made, i.e., an imaginary attack is first recognised and then responded to. Turning the head simultaneously or after the trunk would be considered as an error by the referees. Therefore karate experts spent years in practicing fast and clear movements that are made to the exact location at the exact time. The "kata" are usually highly symmetric, many movements follow in pairs to the opposite sides. As a rule, there is also a central axis along which distinctive movements are made, the symmetry is then observed in the forward and backward movements and the performer ends the "kata" at the place it was started. In fact, "fighting a shadow" involves several imaginary opponents, therefore after performing some action the athlete can abruptly turn around and proceed with the defence and attack to the opposite direction. Some "kata" involve several transitions from slow and gradual changes in position to fast and strong movements.

The tournament, called "kumite" or "sparring", follows the rules of what punches or kicks would score. Thus the goal is not clearly defined, there are various actions that would lead to a victory in a dynamic process. Unlike the basket in basketball, the "target" is never still and is constantly on the move to mislead the opponent. These rules are style-dependent, in some styles hitting the opponent with an elbow or knee is not allowed. Likewise, in more ortodox styles, as in the one we filmed, a punch must be made in a straight line to certain areas of the opponent's body and the hand must be returned back to the waist level to earn a point. Also the space of the tournament is outlined, and the tournament is halted if any of the participants crosses the line. As contrasted to the above two, a Latin dance, being a cooperative rather than a competitive action, follows a certain rhythm but often lacks symmetry. The lack of symmetry means that the moves to the right and to the left may differ, like in the jive, and the gentleman may make movements than cannot be deduced from the lady's part, and vice versa.

3. HUMAN VISUAL SYSTEM IN CLASSIFYING NATURAL OBJECTS

The more complex an image is, the more of computational time the processing takes. This is not always the case with the human visual system, however. Individuals can recognise photographs faster than it could be expected from the research of laboratory stimuli.

3.1 Image Categorization

Two separate lines of research converge in the natural image classification, one dealing with the biological vision and the other with the artificial one. For the latter, machine vision experts look for image features that bring automated image segmenting closer to human performance. Image cues, such as brightness, colour, edges and texture, enable objects to be identified and classified by a computer (Shi, & Malik, 2000; Martin et al., 2004). Grouping images by the colour pixel distribution in a digital photograph has been shown to be a successful approach to rapidly categorise digital images (Greenspan, Goldberger, & Ridel, 2001; Goldberger, Gordon, Greenspan, 2006). This is aimed at the image database search, like data mining (Greenspan, Goldberger, & Eshet, 2001) or medical data analysis (Lehmann et al., 2005). Computer vision is inspired by the findings of the human and animal vision. Thus in the categorisation tasks the nature and limits of the human visual system are explored. It is done under conditions of short image presentation and the demand for a rapid behavioural response (VanRullen, & Thorpe, 2001), increased number of simultaneously presented items (Rousselet et al., 2004), deteriorated image contrast (Mac et al., 2005) and other constraints. It has been long recognised that visual processing of some object categories, for instance, faces, can proceed through highly specialised pathways and elicit responses in the primate superior temporal sulcus as early as in 100 milliseconds (Perrett et al., 1982; Rolls et al., 1994). What types of pictures correspond best to the real world objects in human and animal visual system has also been a matter of detailed study (Bovet, & Vauclair, 2000). It stirs the question of what higher cognitive processes are involved (VanRullen et al., 2002; Evans, & Treisman, 2005).

At rapid sequential visual presentation of images psychophysical responses to classify images have the median reaction time of 445 milliseconds, with the shortest being below 400 milliseconds (Thorpe et al., 1996). In the objective measurements, differential neuromagnetic signal for the first pass starts after 150 ms both for targets and distractors (VanRullen, & Thorpe, 2001), with the following behavioural of high precision (above 80 per cent). This has led to alternative models for the neuronal communication in the visual pathway (Van Rullen et al., 1998), which has been supported by the data from other sensory systems (Johansson, & Birznieks, 2004; VanRullen et al., 2005). Research suggests that the differential neural activity, which is evoked by semantic categorization of objects into groups like natural objects (animals, plants) or man-made objects (furniture, clothing), is not task dependent (Lw et al., 2003). If one compares the time for cortical processes for isolated objects as detected by Lw and collaborators, and that for objects in context (VanRullen et al., 2002; VanRullen, & Thorpe, 2001), it can be argued that the context facilitates classification of object images but is not the decisive factor. The interpretation of diverging electrophysiological activity for distinct image categories is not clear-cut (Kirchner, & Thorpe, 2006; Johnson, & Olshausen, 2003), psychophysical response needs to be correlated to it for describing recognition.

3.2 Eye movements in image classification

In a recent paper, Kirchner and Thorpe (2006) report that eye movements may emerge as a faster way to respond in a classification task. With the minimum reliable saccade response time of 120 milliseconds, this is even faster than the differences in the ERP (Thorpe, Fize, & Marlot, 1996) and has inspired possibilities that each pass of image processing actually uses a different neuronal path. Previous research points out that two images can be visually processed as fast as one (Rousselet et al., 2002). Repeated presentation of the same images does not improve their recognition speed or accuracy, no image specific learning has been found (Kirchner, & Thorpe, 2006). The same researchers also report that no hemisphere-specific effects could be found in healthy participants.

The proposition of Kirchner and Thorpe (2006) was followed to use eye movements to categorise images. Since piloting research hinted that no differences between response and the image presentation side, all images were presented on the right side only as then the eye-tracker adjustment was more reliable for wider faces.

Together with the analysis of the psychophysical response, the nature of small fixational eye movements before it was explored. Hypothetically, the image recognition and classification could act as an internal cue for the gaze stability before a conscious and voluntary action is performed. It was also the research question how rapid is the categorization process if it is not facilitated by the alternative forced choice paradigm and less trained by the number of images presented in sequence. We term a saccade towards the side of image presentation a pro-saccade, whereas an opposite movement an anti-saccade. Both of them are in fact voluntary saccades (Leigh, & Kennard, 2004; Munoz, & Everling, 2004), with a memory guided component. Upon image presentation a reflexive response must be suspended until a hypothesis concerning the object reaches conscience. Since animal category form a perceptually distinct group, a movement towards the site of target presentation can require less conscious effort with practice.

The hypothesis was probed that the saccade response times of 120 ms may not be universally found in image classification tasks (Podniece, 2006). Specifically, we expect longer response times if the series of images is shorter and only one image is seen on the screen in each trial. The "forced choice" thus is not of choosing one image or the other, but respond with a saccade to a target image, and with an anti-saccade otherwise. We also hypothesize that the time it takes for the cognitive image processing and oculo-motor response may be reflected in the following saccade. Some signs of recognition decision could be observed in the stability of fixation before the launch of the response to categorise.

4. RESEARCH OF READING

Last few decades have produced more textual information than the centuries before. The increase in the information spurs the need of efficiency in text selection. Equally beneficial it is for a person to make the most of their reading skills. Family and schools are guiding the formation of reading abilities, yet the impact of the individual factors must be borne in mind (Byrne et al., 2007). The role of an institution of higher education also should not be neglected. Therefore several types of reading research have been undertaken within the present research and the bachelor thesis supervised by the author (Bagucka, 2006; Goršanova, 2007; Jokste, 2007).

4.1 Eye movements in reading

Eye movements have been extensively used in reading research (Sovik, Arntzen, & Samuelstuen, 2000; Rayner, 1997; Rayner, 1998; Starr, & Rayner, 2004). They yield a quantitative description of human behaviour, even though the relationship between reading rate and eye movements is not clearly delineated (Starr, & Rayner, 2004; Rayner, & Juhaz, 2004). On one hand, the re-positioning of gaze while reading a text is known to be an indicator of a shift in visual attention (Sovik et al., 2000). On the other hand, models have been developed about word parameters in a text and their impact on eye movements (Reichle, Rayner, & Pollatsek, 1999; Lehtimaki, & Reilly, 2005). Words in a text may be skipped in a non-accidental manner, word omission without losing the meaning in silent reading is related to word frequency, contextual clues and peripheral processing (Drieghe, Rayner, & Pollatsek, 2005).

The variables of eye movements that research may be aimed at are fixations, saccades and regressions (regressive saccades). While reading, the gazes progresses over the text in a series of jumps Fig. 4.1)Fixations are the periods when gaze is relatively stable. In reading, it is a time of 200 to 300 milliseconds when the visual information is being processed and a move to the next site of interest is being prepared. Of that time, a reader needs at least 50 milliseconds for the word to be passed to the visual cortex (Rayner, 1998). The longer the fixation, the more cognitive processing was needed before reading can proceed. Word length, frequency, context and other textual clues contribute to variations in the duration, for a single text fixations can last from 100 to 500 milliseconds.

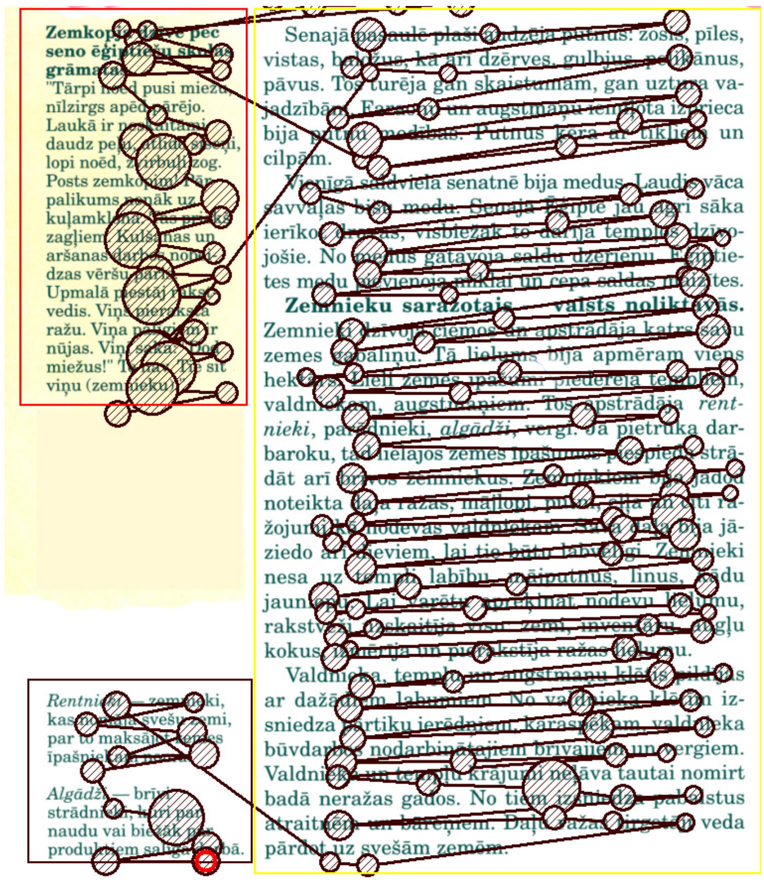


Fig. 4.1: Gaze in reading is a pattern of fixations (shown by hatched circles) and saccades (connecting lines) In a textbook page, several areas of interest (AOI) can be defined, and gaze can be analysed for the main text and side columns separately.

No evidence exists that any information is acquired during saccadic eye movements themselves. Upon completion of a fixation the eyes are redirected, this type of targeted eye movements is referred to as saccades if performed in the direction of reading (left to right for Latin or Cyrillic based texts) or regressions if the gaze returns to a previously read fragment. Ten to 15 per cent of the reading time is spent for returning to previous passages. Saccades cover six to nine letters in English texts and take 20 to 40 milliseconds on average. For the same text, saccades as short as one character or as long as 15 characters can be found (Rayner, 1997; Rayner, 1998; Starr, & Rayner, 2004; Lehtimaki, & Reilly, 2005). The more letters a reader covers per saccade, the faster she progresses through the text.

4.2 Binocular interactions and parafoveal influence

The issues pertaining to the binocular coordination may affect the calculations of eye movements. It has been investigated that for an adult reader horizontal and vertical movements of both eyes are in tune. This process in adults is more precise, resulting in the difference of saccade size of 7% for both eyes as compared to 18% in children (Bucci, & Kapoula, 2006; Engbert, & Kliegel, 2004a), other indicators being less affected. Binocular eye tracking is the option of choice over the dominant or non dominant eye tracking, whenever it is technically possible. As a process that involves eyes and many brain areas in whole, reading nevertheless is tightly bound to the central visual acuity. Moving one's eyes becomes necessary since the visual acuity, and thus the capability to recognize characters, drops rapidly off the centre. A saccade is launched to bring into focus a text fragment that was not clearly visible. The highest visual acuity is found in the foveal region of the human retina that horizontally spreads 1 degree to both sides from the point of regard. Longer words are projected outside this area onto the parafoveal region that stretches approximately 5 degrees from the point of regard. Parafoveal region facilitates word processing and is instrumental in word skipping. This region corresponds closely to the perceptual span, for a reader of Latin based texts it consists of 15 characters or so to the right and three characters to the left from the point of regard at a single fixation. Perceptual span may be smaller in less skilled readers (Starr, & Rayner, 2004), the parafoveal information seems to be extracted less effectively and hence shorter saccades need to be made. Word identification span is smaller than the perception span and usually reaches out to eight letters from the fixated point (Enbert, & Kliegel, 2004b; Drieghe, Brysbaert, & Desment, 2005; Drieghe et al., 2005b; Rayner, Liversedge, & White, 2006; Rayner, 1998).

According to the current research in the field, the information that is extracted from the text on parafoveal regions is the length of the forthcoming word, recognition of short words and partial processing of longer words. A saccade is targeted when the lengths of the next words are detected. Short word recognition before foveating them allows for word skipping, whereas partial processing of longer words promotes reading by reducing recognition times on fixation (Rayner, 1997; Starr, & Rayner, 2004). If the surrounding words are masked and no useful information is available from parafoveal areas, reading is slowed down (Rayner, & Juhaz, 2004; Drieghe, Brysbaert, & Desment, 2005;Drieghe, Rayner, & Pollatsek, 2005). Eye Movements and Word Skipping During Reading Revisited. Journal of Experimental Psychology: Human Perception and Performance, 31 (5), pp. 945-969.). Word skipping and regressions may be thought of as two opposing forces modifying the speed of reading. Regressions cause the reading speed to drop. In contrast, a skilled reader omits inferred words and thus gains the speed since approximately 30 per cent of words in a text may be skipped, contextual clues and word length are the principal determiners of word skipping probability (Rayner, & Juhaz, 2004; Drieghe, Rayner, & Pollatsek, 2005). The skipped words are at least partially available for cognitive processing, recognition by peripheral vision or an 'educated guess' of shorter words may be the mechanisms that leave the reader content (Drieghe, Rayner, & Pollatsek, 2005; Radach, & Kennedy, 2004). Lower level oculo-motor processes slightly deflect the saccade landing positions away from the optimum (Lehtimaki, & Reilly, 2005). For English texts, a reader is tended to land the saccades in between the beginning and the centre of words. It remains to be clarified whether the optimal viewing position is similar for the languages like Latvian where the word endings matter.

4.3 Text understanding and reading speed

Since teenage years, when optimal ocular coordination has been achieved, the reading speed may change little. It depends not only on the reader's skill but also on the type of the text. A person with an average of 250 words per minute may read a particular text with a speed between 100 and 500 words per minute depending on the purpose, interest, text difficulty and reader's vocabulary in the selected area (Sabatini et al., 1995). Intelligence and early reading training may prime a child for becoming a fast reader, as may be inferred from existing research (Jacobson, & Lundberg, 2000). Reading speed or fluency is descriptive if the degree of text acquisition is also provided. Auxiliary knowledge aids text comprehension, for instance, so does language mastery, general world knowledge and knowledge of the topic described. Some readers may be skilled because they are better in making use of their existing knowledge.

The validity of any reading experiment would be undermined without the means to control comprehension. For oral reading there is straightforward way to evaluate whether the text has been read in its entirety. Silent reading should be accompanied by some kind of additional tasks during reading itself or by posterior assessment, for instance, through multiple choice questions or filling in the blanks. As a rule, reading training that demand the comprehension level of at least 75 per cent do not report any reading speed improvement beyond 600 words per minute (Calef, Pieper, & Coffy, 1999). Comprehension is determined by three types of factors. First, the short term and working memory is involved in manipulating the freshly acquired information, whereas the long term memory is essential for vocabulary and general knowledge. Second, brain areas responsible for phonological word processing are crucial for silent text reading as well. Third, skilled readers appear to be better at decoding the sentence structure and anticipating the following words (Lesaux, & Lipka, 2006).

There is no unequivocal explanation of the link between text comprehension and reading speed. A controversy still exists, since people who are skilled readers before training seem to comprehend text better than their counterparts who have reached the same reading speed through training. If a mature person is trained in reading, the improvement of the speed comes at the expense of comprehension and retention of the meaning (Dyson, & Haselgrove, 2001). This issue brings the educator to the question if the screening of reading skills and training should only be initiated as early as possible or if there is sufficient motivation to train adult population with low reading skills.

4.4 Detection of gaze shift and gaze holding

How does eye movement research in reading may improve textbooks, provided that the eye-tracking devices and algorithms differ? Could laboratory conditions, such as head stabilizing or the eye-tracker's helmet, modify the results of cognitive tasks to various extents? The results of fixation and saccade detection were contrasted, those recorded by two video-based eye-trackers, one with a chin-rest and the other being helmet-mounted. The detection algorithms and text difficulty were the same in both cases, whereas the data sampling frequency and participants' position differed. The latter two vary considerably in the eye movement research reports, with the eye position sampling rates ranging from 100 Hz or less (Oommen, Smith, & Stahl, 2004; Pelz, Hayhoe, & Loeber, 2001; Svik, Oddvar, & Samuelstuen, 2000) to 1000 Hz and eventually more than that (Nuthmann et al., 2007; Rayner, Liversedge, & White, 2006; Ditterich, Eggert, & Straube, 2000). Some research situations impose strict limitations on the equipment to be involved, the one used in infant vision research or vision in sports action sampled the signal only 30 times per second (Martell, & Vickers, 2004).

Notably, in the entire range of digitizing rates not only fixations, but also gaze shift parameters, like saccade timings and velocities, are obtained (Leff et al., 2000; Pelz, Hayhoe, & Loeber, 2001; cf. Proudlock, Shekhar, & Gottlob, 2003; Ditterich, Eggert, & Straube, 2000). Given that the temporal precision alone in the reported results differs by an order of magnitude, it was substantiated to explore which parameters may indeed be treated as equal irrespective of the apparatus. This research compares the results of infra-red eye-trackers that calculate eye position from the centroids of corneal reflection and pupil area. Yet suffice it to mention that a broad spectrum of implementations is represented also in other eye-tracking techniques, for instance, the magnetic coil (Pelz J., Hayhoe M., & Loeber R., 2001; Stahl, 1999; Stahl, 2001; cf. McDonald, 2006; Seo, & Lee, 2002) and Dual Purkinje Image (Schnitzer, & Kowler, 2006; Ashby J., Rayner K., & Clifton C., Jr., 2005; Blythe et al., 2006). Comparison of video-based and other eye-tracking methods is done elsewhere (e.g., van der Geest, & Frens, 2002). High data precision has mostly been achieved through fixed-head protocols (Blythe et al., 2006; Vitu et al., 2006), more mobility for a participant as a rule is traded for precision of the data (Oommen, Smith, & Stahl, 2004). Reportedly, recent developments allow the video-based oculographs to achieve the same precision in the head-free condition as is in head-fixed (Proudlock, Shekhar, & Gottlob, 2003). In essence, the two setups that we used were representative of two trends in technology development, namely higher precision or more of participant's mobility. One of them (iViewX Hi-Speed, SensoMotoric Instruments) is capable of compensating small head movements, and a participant's head is stabilised on a chin-rest instead of being fixed by a bit-bar, similar to the one used by Rayner et al. (2007). The second one (iViewX HED) is mounted to a light-weight helmet and its precision is close to other unrestricted head setups (Oomen, Smith, & Stahl, 2004).

4.5 The impact of text formatting

From the previous research in the field one could expect that gaze shift parameters are task dependent and thus could indeed vary among the stabilised and free head conditions. Even though saccades were shown to contribute for about 95% to the gaze shift in reading either horizontally or vertically aligned Korean text (Seo, & Lee, 2002), their dynamics diverged in both cases. Thus the peak velocities of gaze saccades were shown to be higher for reading horizontally aligned texts, as reflected in the 'main sequence' plots. The lower velocities in vertical reading were accompanied by a stronger eye-head coupling in the reading of the same texts that were aligned vertically.

In the research of Seo and Lee saccades were found to have smaller amplitudes in the vertical direction, with the mean of 3.4 degrees as contrasted to 4.4 degrees for the horizontal text reading. This finding, along with longer regressing and fixations, is thought to justify the 24% lower reading speed in the vertical reading. In their paradigm Seo and Lee analyzed the data of six participants. Reportedly, both horizontal and vertical alignment of text is common for the contemporary Korean language, therefore neither of the reading conditions is essentially novel for the native speakers that volunteered to Seo and Lee's research. In spite of the fact that the duration of fixations in total was mentioned to contribute to the discrepancy in the reading speeds, their difference in fact was not statistically different. Moreover, their means, namely, 242 and 233 ms, were even witnessing to slightly larger durations in the horizontal reading condition. In fact, reading research indicates that gaze holding is controlled by cognitive factors independently from the gaze shift conditions (Starr, & Rayner, 2004; Rayner, 1998; Rayner, & Pollatsek, 1981), so a change in one of them must not be necessarily accompanied by a change in the other.

The outcome that eye and head coordination can be flexibly coordinated has also been shown for reading Latin based texts (Proudlock, Shekhar, & Gottlob, 2003). The researchers have compared reading of text printed on A4 size pages and bent sheets extending 90 degrees. They found that horizontal head movements play a minor role in reading a standard page, accounting only for 4.3% of the gaze shift. In contrast, approximately 40.3% of the horizontal gaze shift was due to head rotation in reading spatially extended text. Proudlock and colleagues conclude that eye-head coordination can show a large degree of adaptation depending on conditions imposed by a task or otherwise. They also have investigated the issue of vertical eye and head coordination during reading and found that approximately half a distance that the gaze traverses during reading, i.e., from one line to the next one, is accomplished by head movements. It has also been demonstrated that head movement propensity was smaller in reading than in simple saccadic task. This has lead to the conclusion that head movements are suppressed in standard reading conditions in order to achieve more stable fixations. This is also consistent with the research of Epelboim (1998) concerning image stability and smaller head movement amplitudes. Another finding of Proudlock, Shekhar, & Gottlob (2003) that pertains to this research is that the gaze velocity is larger in repeated reading of the same text. They report that this increase is due to a larger velocity of head rotation. Hence in repeated head-free experiments using the same text can produce different results from the onset, probably texts of similar difficulty level would rather be used. On the other hand, multiple readings of the same text do not produce observable differences if the task involves change detection. For the head-fixed condition this has been reported in a longitudinal research of Schnitzer and Kowler (2006).

4.6 Tracing changes in eye movements

Reading performance of a person is not a static phenomenon. Text parameters, such as word predictability and frequency, interact with the reading skill to produce differential effects at repeated measurements (Ashby, Rayner, & Clifton, 2005). In addition to that, a person's reading skill can improve over time, this is to be expected during schooling. Yet the robustness of an eye-tracking system may mask the statistical (and practical) changes in reading by the same person, though two readers may be easily told apart. That is to say that even if two eye-tracker sets may suggest equal conclusions about the current state of the reading skill, they may be not be equally sensitive to trace changes. Has a student improved her reading skill? Is the new textbook easier to read than the former? We introduced the training factor to our research. After a month of pre-defined reading training, six volunteers returned to read different pages from the same textbook (see Methods).

A helmet-mounted eye-tracker, albeit using a light-weight and less precise infra-red camera, allows one to contrast and compare silent and oral reading. It also allows a reader to assume casual position with a book in hands. On the contrary, devices that ensure high precision of the eye movement data, as referred to above, usually require a person's head to be immobilised in front of a screen. Hence they are efficient for silent reading research, leaving oral reading to more descriptive methods (Svik, Oddvar, & Samuelstuen, 2000). We took the advantage of the head-free measurements and introduced an oral reading task. Presumably the proportions of reading speeds and eye movement parameters could testify to possible missing or miscalculated data. Gaze holding (namely, fixations) and gaze shifts (saccades but not micro-saccades) for two silent reading tasks (head fixed and head free) and an oral reading task were calculated and compared. In the task where the head was stabilised, the volunteers read two columns from a scanned page. In the free head measurements, the participants read a column from a page silently, then switched to oral reading of the second column. All three tasks were repeated after the reading training.

Part II

METHODS

5. RECORDING OF EYE MOVEMENTS

In the spectrum of techniques that can register eye position the *iViewX* eye-trackers represent the infrared recording equipment. More specifically, this type of eye-trackers are the video-oculography (VOG) devices (Collewijn, 1998). This means that the device analyzes the eye image (in two dimensions) nearly in the real-time. Possible delays (in milliseconds) are due to computational time. However, during an experiment, the PC is dedicated solely to eye-tracking, with many system processes disabled. The advantage of real-time analysis and visualization is that the experimenter can make any detection threshold adjustments, if necessary, without losing the data or the experiment being repeated. The infra-red recording techniques are based on the fact that the radius of cornea is nearly 8 mm, while the distance from the corneal surface to the axis of ocular rotation is about 13.5 mm (Collewijn, 1998). Therefore an eye movement is accompanied by a displacement of the reflection relative to the cornea.

The *iViewX* eye-trackers analyze the centroids of the reflection from the human cornea and the dark image of the pupil. By tracking these two parameters, the device can compensate for translational head movements. It is possible since the reflection from the 1st corneal surface, or the 1st Purkinje image, is nearly the sine of the angle of eye movement, whereas the center of the pupil moves twice faster (Collewijn, 1998). The setup is further classified as a 'dark-pupil' device, which means that, unlike in some ophthalmic instruments, the incident and reflected light beams are not collinear. The ocular media are transparent to visible light but absorb the infrared wavelengths (Ober, 1994). Thus the pupil area is the darkest region analyzed, whereas the 1st Purkinje image is the brightest region seen. Suffice it to say that the eye image seen on the experimenter's screen in the infra-red image converted to a black and white visible video. In fact, the participant does not sense that her eye is monitored.

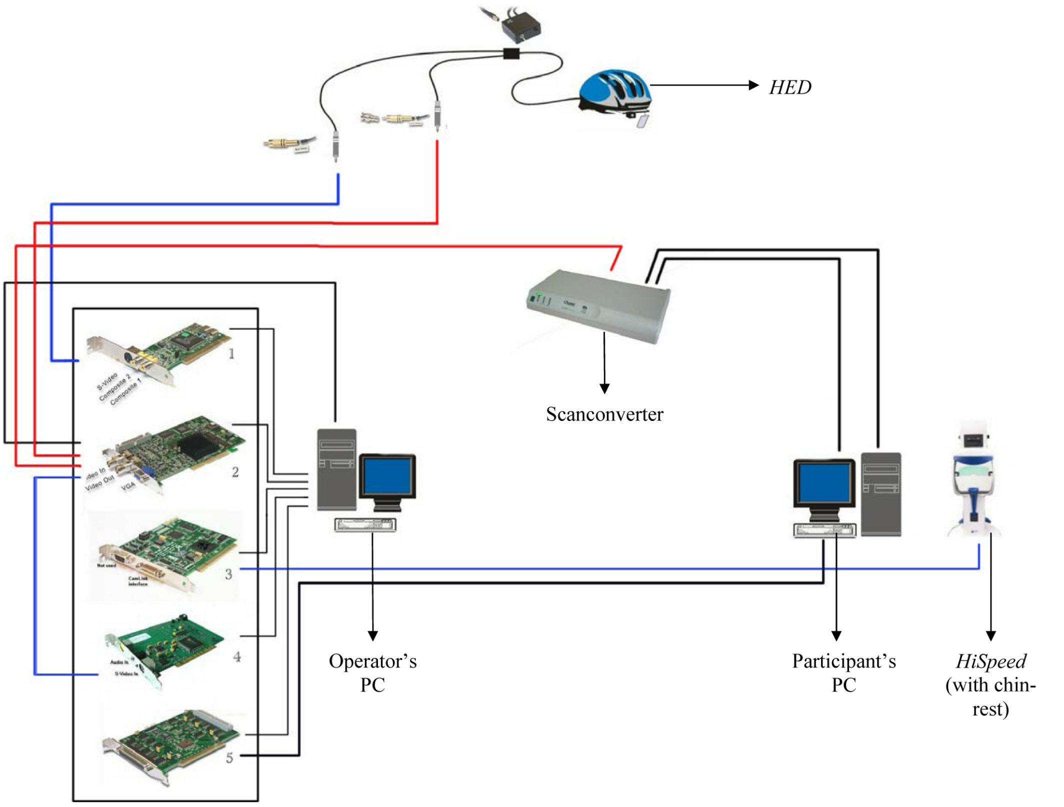
Being non-invasive, the VOG technique is favoured over the magnetic coil by some scientists because the measurements can be set up faster and do not require special medical skills from the experimenter, neither does it require preparing the participants(Ober, 1994; Collewijn, 1998).

For the further discussion, a distinction pinpointed by Collewijn (1998) is observed. Thus if the eye position is recorded relative to the head, it is referred to as the *eye position* (gaze-in-head). In contrast, *gaze* is the eye position relative to the surroundings. In the case of fixed head recording both coincide, while only eye-in-head measurements are possible for the helmet-mounted device since no head-tracking has been implemented.

5.1 *The* iViewX *Eye-Trackers at the University of Latvia*

Movements of the right eye during experiments were tracked by an *iViewX* system (SensoMotoric Instruments, Germany). The system has the option of either the tracking column or the helmet-mounted videooculograph to be powered (Fig. 5.1). The eye-tracker with the chin-rest is referred to as Hi-Speed, whereas the helmet-mounted apparatus is the HED (for the Helmet-mounted Eye-tracking Device). Both devices calculate the eye position from the pupil and the 1st Purkinje reflection at the cornea, as monitored in the infra-red light. The data were stored on the operator's PC, Pentium 4 with MS Windows 2000 that ran *iViewX* software. For the Hi-Speed experiments, images or films were displayed on the participant's PC, Pentium 4, *MS Window XP*, with a 17 inch LCD screen (Hyundai ImageQuest L72D, 1280 by 1024 pixels, horizontal refresh rate 60 Hz). The participant's and operator's computers were connected through the serial port for calibration. We used a 13 point calibration process for higher accuracy. Thus we report the data with the spatial precision of 0.04 degrees and eye position accuracy of 0.2 degrees for the *Hi-Speed*. The device records eye position at the frequency of 240 Hz, i.e., with 4.2 milliseconds of temporal resolution. For the HED version, the spatial precision of 0.1 degree and 1.0 degree accuracy is typical, the data are sampled at 50 Hz, i.e., every 20 ms.

The eye position was expressed in pixels, where the resolution for the infra-red camera of the Hi-Speed corresponded to that of the calibration screen, namely 1280 by 1024 pixels. The resolution for the HED was 768 by 576 pixels, because the calibration is done over the area viewed by the "scene video" CCD with the above resolution. This camera stores the scene seen by a participant into a MPEG file and maps a circle overlay of the eye-in-head position. The same video recording is available for the Hi-Speed eye-tracker, and it was used to monitor if the corneal reflection is clearly visible and is not obstructed by eyelids or lashes. To calibrate eye-tracking with the Hi-Speed, we asked each participant to follow through a series of pre-defined points on the screen of their PC. These points were shown randomly by the iViewX software, the points changed if a stable corneal reflection was recorded for at least 500 ms. The calibration for the HED was done by asking the par-



1 – *Falcon* board, 2 – *Matrox* / *CurVid* board, 3 – *CamLink* board, 4 – *MPEG* board, 5 – LPT port.

Fig. 5.1: The combined *iViewX* eye-tracker at the University of Latvia (adapted from Kotelnikovs, 2007).

ticipants to fixate a laser point on a wall at the approximate experiment distance. These points followed in a constant order and were visible to the experimenters on their PC. The software reported when the corneal reflection could be clearly found for at least 500 ms, and the calibration at every point was confirmed by the experimenters. In general, adjustments of the HED before an experiment were more laborious to reduce helmet slipping during head movements. Since the infra-red image of a participant's eye reaches the tracker's camera after reflecting from a semi-transparent beam-splitter, presence of the corneal reflection after changes in eyelid and head position was verified for the HED.

Saccades and fixations were identified by separate algorithms implemented in *BeGaze*, software provided by the eye-trackers' manufacturer (*SensoMo-*

toric Instruments, Germany). The letter size was calculated in pixels for every text and considered fixations on two neighbouring letters as a single fixation. As a sequence, all groups of data were obtained by the same eye position detection and movement calculation algorithms, leaving all the variation to tasks or hardware limitations. Further statistical analyses were done in Origin 8.0 or SPSS 15.0 and 16.0 for the level of significance of 0.05, if not stated otherwise.

6. TASKS FOR COMPLEX ACTION OBSERVATION

6.1 Participants

Two groups of female volunteers, 13 athletes and 13 non-athletes, participated in the research. All participants were young adults, the average age of the athlete group was 18.5 years and that of the non-athletes was 19.8 years. The athletes participated were members of the Latvian National level basketball teams and students of the Latvian Academy of Sports Education. They were training 3 to 4 hours 4 to 5 days per week (in total at least 12 hours a week). The level of their training corresponds to international standards, this is illustrated by the fact that the Latvian team skipper was recently named the best female basketball player in Europe. The non-athletes participated in recreational sports 3 to 4 times a month. Neither ocular nor neural disease had been recorded to any of the participants, and they had normal or corrected to normal vision.

The experimental protocol was in accordance with the Declaration of Helsinki. The participants joined the research voluntarily and provided written informed consent after the procedure was explained to them.

6.2 Gaze data recording and processing

The possibility to mark gaze direction as a circle in the demonstrated video was crucial in this series of experiments. A scancovertor translated the participant's screen to the operator PC, and the gaze indicator was mapped there as a circle corresponding to 1 degree on the retina. Simultaneously with the numerical data of gaze coordinates the eye tracker recorded the gaze video. The results were saved at a resolution of 768 by 576 pixels. It enables to estimate which body parts (shoulder, elbow, hand etc.) were looked at when we watched through the recorded films after the experiment.

Saccades and fixations were identified by separate algorithms implemented in BeGaze, software provided by the eye-trackers' manufacturer (SensoMotoric Instruments, Germany). A saccade was calculated when the eye movement exceeded the velocity threshold (35 degrees per second), while a fixation was detected when the eye position remained within a defined area (criterion based on dispersion of the position). As a sequence, all groups of data were obtained by the same eye position detection and movement calculation algorithms, leaving all the variation to tasks or minor measurement errors. Further statistical analyses were done in SPSS 15.0 for the level of significance of 0.05, if not stated otherwise. This package was also used to perform the hierarchical and K-Means clustering.

6.3 Procedure

The participant positioned her head on the chin-rest, any minor head movements were compensated by the eye-tracking software. The participants were seated 40 cm from the demonstration screen, thus the effective visible area of the films did not exceed 40 degrees (horizontal). Before the start of every trial the calibration was performed, when a participant looked at a series of pre-defined points. We used a 13 point calibration process for higher accuracy. Further, the colours and contrast of the calibration screen was matched to every task separately, so that the participant's pupil would not change substantially during an experiment, which could lead to eye-tracking errors.

Upon successful calibration, a short (about 30 second) film was shown to the volunteer. The participants had no prior knowledge of how long will the movie be. The instructions were given so that the athletes would have no clearly training-specific advantages, we did not ask any questions as 'count the number of left hand movements'. Every participant would decide herself on the criteria to evaluate. The films also had implicit clues to the answer, like the well known colour of the performer's belt (black) or score on the screen. It was also interesting to find if these 'environmental' clues are grasped along with the task at hand.

In the first three tasks, identical films were demonstrated (top illustration in Fig. 6.1), but every time with different instructions. The film was the karate 'kata' performance by an individual. At first, the participants were asked to watch the video in order to assess the level of the performer (Is he a professional or novice? What level competitions could he take part in?). In the second task, the participants were asked to memorize the sequence of movements to compare to the next film. The third task was a 'change detection' task - were there any differences, compared to the previous film? The particular scene we selected was a fragment of the "kata" named "Unsu" and was performed by a young expert who participated in the international competitions. The fragment included slow leg movements (motion to the side relative to the observer), accompanied by slow and rapid arm movements (parrying an attack and punching the imaginary opponent or ”shadow”). The sequence of slow or rapid movements was not known to the observers and could not in principle be predicted.

Fig. 6.1: Snapshots of the films on the participant’s screen in Tasks 1 to 3 (top), Task 4 (middle) and Task 5 (bottom).

The fourth video was a karate tournament (middle snapshot in Fig. 6.1) where participants performed several attacks, whereas the opponent launched counter-attacks. The task was, judging from the seen situations, to estimate who of the two is more likely to win. We left the room for arbitrary criteria selection of what will lead to scoring, i.e., we did not recite the rules of the tournament, to allow the participants to structure the problem. Thus it was intended to discover any strategic differences in the two groups. A referee and the expert panel but no spectators were seen in the background of the scene. In the real-time preview on the operator's PC we found that participants ignored the background during the dynamic foreground action. We filmed tournaments, or "kumite", at the National Finals. We selected a half-contact scene, which means that punches and kicks were marked but not performed at full strength. The camera angle was such that the episodes of 'kata' and 'kumite' involved movements predominantly in one plane, no remarkable approaching to or receding from the observer occurred.

The fifth task was a scene from salsa, a Latin dance (bottom image in Fig. 6.1). Similarly as in the first task, the participants were invited to estimate the level of the dancers (taking part in national competitions?). As contrasted to karate "forms", the timing of the movements in a Latin dance can be predicted as it follows the same rhythm. The scene selected featured the partners facing the camera and included also a spin, where the lady turns towards the gentleman and further turns out to previous position.

In all the selected films the action was mostly in a single plane, therefore changes in the angular size of the performer would not hinder further data processing of where the viewers looked.

We did not warn the participants that the type of sports will change. The first three films demonstrated an individual's performance, the fourth and the fifth film demonstrated competitive or cooperative performance of two. The first four films featured national level athletes who went on to the international level, while intermediate level dancers were seen in the fifth film. We were interested in finding whether this sudden change in the type of the scene and level of performers would lead to any detectable changes in the eye movements of the two viewer groups. The answers to the instruction questions were asked to maintain the attention of the participants but were not used for further analysis, since no measurable criteria for the answers were set.

In addition, the basketball players were shown a video of free shots by other female athletes. Their task thus was to guess and indicate if the shot will score. This task was devised to provide a reference level for the athletes, i.e., their eye movements in watching the sport of expertise. No such reference level could be defined for the non-athlete group with distinct recreational sports.

7. IMAGE RECOGNITION EXPERIMENTS

7.1 Participants

Twelve healthy volunteers (age 21 to 24) contributed to the research, having normal or corrected to normal near vision. The research was conducted in accordance to the ethical standards of the local committee. All participants provided informed consent concerning the procedure but were naive to the purpose of the research. They were assured that the experiments would be terminated, should they feel any inconvenience during the task.

7.2 Procedure and images

A participant was seated at the eye tracking column, the person's head was stabilised on a chinrest. The demonstration screen was located 40 centimetres from the person's eye. The person fixated the gaze on a white central fixation point on a neutral grey screen. For the overlap paradigm, the central fixation point was on the screen during the entire procedure (Fig. 7.1, A). Two symmetric white fixation points were seen, the image replaced one of them for approximately 330 milliseconds. For the gap paradigm, 200 milliseconds before an image was presented the central fixation point disappeared (Fig. 7.1, B). After a bitmap had disappeared, two symmetric auxiliary fixation points appeared for 200 milliseconds. As soon as they vanished, the central fixation point re-appeared for 4 to 6 seconds. Ten participants watched 30 practice images, after a break a session of 30 test images was presented in the overlap paradigm. To two participants a 90 image sequence was shown to two participants after 30 + 30 image training, the overlap paradigm was used for one and the gap paradigm for the other. After a week the experiments were performed in the gap paradigm. The same images were used, but randomized, thus potentially allowing for a faster recognition. The same mistakes were possible, though, since no feedback was provided in the previous demonstrations. A participant responded to a displayed image by a saccade, i.e., looking at the image if it was a target. If it was a distracter (not an animal in our case), the person was asked to make an anti-saccade, or look away.

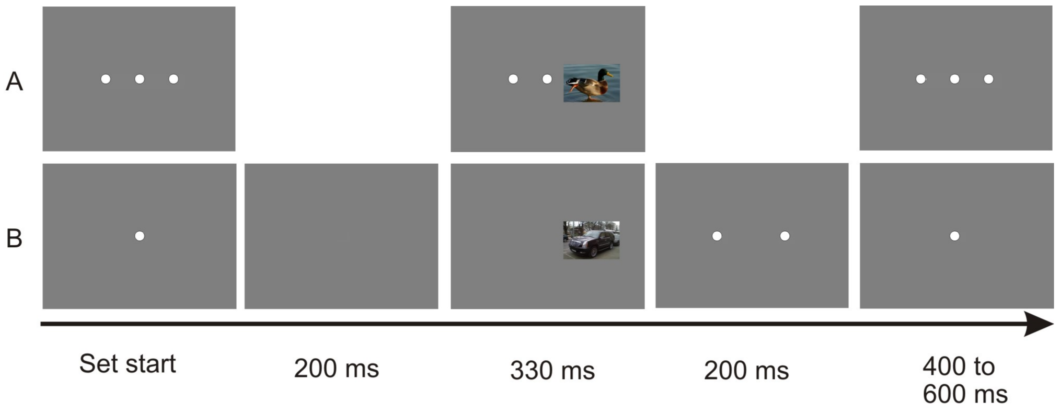


Fig. 7.1: Participant's screen in a single set of the overlap (A) and the gap (B) trials.

The images were 300 pixels wide and 225 pixels high. The exact angle a person saw these images at depends on the facial features, primarily on the interpupillary distance. Thus, for the interpupillary distance of 64 millimetres the images subtended 12 by 9 degrees, their left edge being located 7 degrees from the central fixation point. Since the eyes converge to the central fixation point, a saccade and an anti-saccade for the same tracked eye in fact are not symmetric. Thus, if the image is displayed on the right side, the right eye covers 13 degrees to the right auxilliary fixation point (a pro-saccade) but 10 degrees to the left auxiliary fixation point (an anti-saccade). The opposite is true for the other eye.

In the data analysis, the data flow was as follows. Raw data were recorded by the eye-tracker (*iViewX*, real time), it contained the position of the pupil (in pixels relative to the screen) and corneal reflection. These data were fed into the *BeGaze* software that calculated fixations, i.e., the time intervals when the gaze did not leave a defined area (for instance, 10 by 8 pixels). In a separate run we calculated saccades, the gaze velocity threshold was used to these ends. Further the list of fixations and saccades were parsed in MS Excel, SPSS 15.0 and Origin 8.0 (MicroCal). Conditional operators selected the first saccades of every set and classified them in four categories: correct saccades (towards a target image), erroneous saccades (towards a distracter image, visual grasp reflex), correct anti-saccades (away from a distracter image) and erroneous anti-saccades (away from a target image).

The test images were selected from a collection of *Corel* image base and resized according to the experimental needs. The selection has been made so as to avoid any ambiguity, i.e., only one category has been represented in each. Thus images of animals contained only one animal species, no technical object, buildings, food or suchlike was visible at any part of the image. Images of animals in their natural habitats (e.g., a bird on a tree or a killer-whale in the water) were selected as the targets, which corresponds to the published approach (Kirchner, & Thorpe, 2006). No preference was made for the creature's location in the scene. No image contained a human being or more than one species of animals. The distracters were various unanimated objects, such as food, vehicles, constructions or landscapes. Ambiguous images (a cat on a car) were not included in the collection. Custom code has been made in Visual Basic to display test images. It used an algorithm that selected and inserted a random image into the background screen which was made visible in the next set. This operation was implemented so that the photograph appeared on the screen all at once (within one frame). The image name was simultaneously recorded in the protocol file. This file was later used to classify eye movements in correct and erroneous.

7.3 Data analysis

Saccades and fixations were calculated separately by the *BeGaze* software provided by the manufacturer of the eye-tracker. Any saccades with the response time less than 100 milliseconds after the stimulus onset were excluded from consideration.

The gaze position for a fixed time after the stimulus onset was extracted from the raw data by custom-made MATLAB 7.4 code. Statistical data processing was done in MATLAB, SPSS 15.0 and Origin 8.0 with alpha levels 0.01 if not specified otherwise.

8. READING EXPLORATION

8.1 Participants

Six volunteers read selected textbook pages both with their heads stabilised on a chin-rest and their heads free (with a helmet-mounted eye-tracker). Six of them practiced reading training for a month. The number of reading trainees was chosen as to equip each of them with different textbooks of the same difficulty level. All participants were science students of the University of Latvia, aged 21 to 25. They had normal or corrected to normal near vision. Spectacle vision correction was used during the eye-tracking. The participants were informed of the experimental procedures and provided written informed consent. The tests were conducted in accordance with the tenets of the Declaration of Helsinki.

8.2 Materials

The history text series contained seven books by Andris Rubenis of the same formatting. Six of the books were handed out as reading practice tools. The seventh was available only to the experimenters, texts for eye tracking experiments were selected from it. Every page was divided into two columns, two lines 65 characters each. Books were written in Latvian, the language of studies for all the participants. None of the participants had read them before, neither had they read the experimenters' book during the reading practice.

8.3 Procedures

Since bitmap resolution on the screen (in pixels per inch) is considerably smaller than the resolution (in points per inch) of the printed text, we adjusted the distances for the reading and tracking comfort rather than letter size equality. Participants were seated 40 centimetres from the screen when their head was stabilised on the chin-rest. During the head-free trials, we measured the distances the participants held the book at in order to calculate angular parameters, the distance being approximately 50 centimetres. For this distance the angular size of the letters on the PC screen was 1.4 times larger than on the printed pages. As with the HED eye-tracker the participant was free to change posture during reading, this distance varied and introduced a 10% uncertainty to the angular size of letters. The eye movement parameters were calculated for a page of text (170 words) for the on-screen reading (head stabilised), half a page for silent reading and half a page for oral reading (head free).

Six participants volunteered to consciously monitor their reading and improve its efficiency. They spent at least half an hour three times a week reading the history textbooks provided by the experimenters. The written instructions to the participants contained advice like "Check if you do not move your lips while reading", "Make sure you do not hear the words in your mind", "Do not return to the lines you have already read", "Try to start reading a new line from the second word and end with the one before the last." These were supplemented by online tutorials. The time dedicated to reading practice, number of pages read, main contents and average reading speed were reported on a weekly basis. After a month they returned for repeated eye-tracking experiments. These were performed as before, with new test pages selected from the experimenters' textbook.

Saccades and fixations were identified by separate algorithms implemented in *BeGaze*, software provided by the eye-trackers' manufacturer (*SensoMotoric Instruments*, Germany). In the tradition of reading research, gaze within two neighbouring characters was considered as a single fixation (Rayner, 1998). As a sequence, all groups of data were obtained by the same eye position detection and movement calculation algorithms, leaving all the variation to tasks or hardware limitations. Further statistical analysis was done in SPSS 15.0 for the level of significance of 0.05, if not stated otherwise. Statistical tests were applied according to existing practice in reading research.

Part III

RESULTS AND DISCUSSION

9. GENERAL CONCLUSIONS

In this research, the same eye-tracking equipment has been exploited in three groups of experiments that usually are carried out in specialised laboratories. Thus, apart from the immediate results, further lines of research, and possible pitfalls, were outlined. The rapidly presented image recognition and sports vision research were enabled by the video boards of Fig. 5.1 that have been installed during this research. The possibility to see the participant's screen on the operator's PC, through the scanconverter, allows for online control of data quality. The recorded video files (MPEG) can further be analyzed, as has been done in estimating what parts of a performer's body are followed in sports situations. The PC boards are also mandatory for the helmet-mounted oculograph in free head reading research.

The same line of reasoning has been followed in all three experimental parts when the data were considered. The questions of whether the variables, like the duration of fixations, are normally distributed and their variances are equal, along with the understanding of the independence of the data points, were to be answered before claiming the aid of a statistical test. The 'main sequence' analysis, the fact that the amplitude is linked to the velocities of the saccades up to 20 degrees, has been applied in both sports and reading research.

A major challenge behind the image classification task was operating with large sets of data. Eye movements were recorded in up to 92 sets, 90 experimental and one non-informative set for the start and the end of every session, respectively. Selecting the first 800 ms of every experimental set, averaging them and looking for the correlations of the horizontal and vertical gaze coordinates in every of them required genuine algorithms that could be implemented by custom-made codes. Noteworthy, the methods to analyze raw gaze data were developed besides using the indicators obtained by the manufacturer's software, namely, the saccade response time (start time). The experiment could be introduced only because another custom software selected images randomly and sent a trigger signal through the parallel port from the participant's PC to the operator's PC. In this way, every time a new image appeared on the participant's screen, a new set was started in the recorded data (within 1 ms).

Finally, the statistical tests only lend credence to some conclusions. What are these conclusions, and how are they applicable in the present and future research at the University? In addition to the conclusions described in the following chapters, several other outcomes could be generalized. From the sports research, the method for presenting and analyzing video films has been devised. This was supplemented by the facility to synchronize the two computers, a scheme first introduced by Ivans Ļeonovs, and applying it to a research with large data sets. Free head eye-tracking has been explored and compared to the better known fixed head *HiSpeed* findings, and its applicability to silent reading was proposed.

10. ATHLETES USE TWO EYE MOVEMENT STRATEGIES

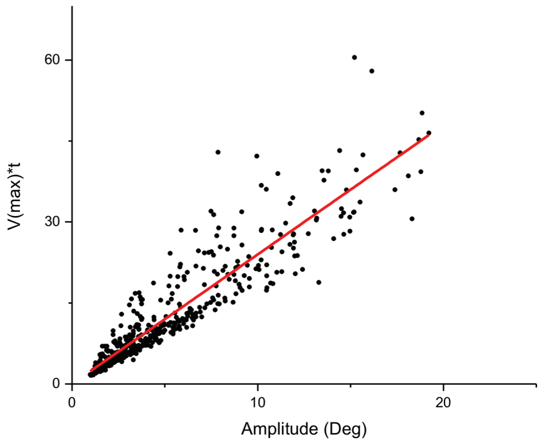
Three questions were tackled to explore the way the participants respond to unfamiliar sport situations. Is an athlete's visual system faster to explore novel motions? To answer this, we calculated eye velocities and compared the confidence intervals for the basketball players and non-athletes groups. Do the groups spend different time to trace human movements? We then compared the distributions of gaze fixations and checked them for any significant difference. Where do the participants look? The fact was used that the visible actions occurred mostly in a single plane and applied clustering algorithms to fixation coordinates. By reviewing the recorded eye movement videos we also could estimate whether the participants made predictive eye movements, or they made only reactive ones.

10.1 Do the athletes make faster eye movements?

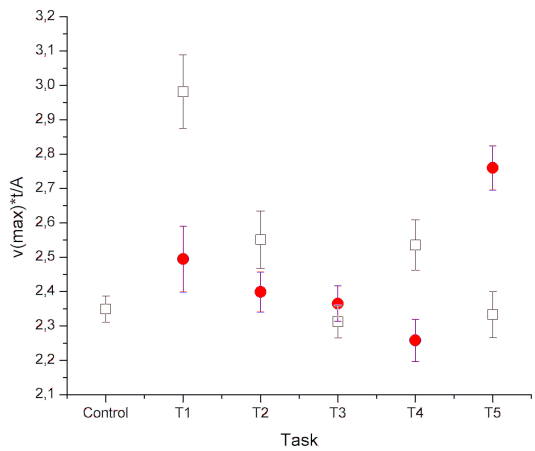
Saccade velocities depend on its amplitude, i.e., the larger the gaze shift is, the faster the eyes move. If the saccades were made to a target at a defined range of distances, the saccade velocities of the participants could be compared directly. Since the viewers explored a real action and the research intended to record their 'natural', unrestricted eye movements, a different route of the data processing was chosen. The 'main sequence' analysis relates the peak velocity of an eye movement to its amplitude over duration, or the average speed. Thus in the 'main sequence' plot saccades of different amplitudes and peak velocities align to a line, the slope of this line is denoted by Q. This linear relationship is observed for the amplitudes of up to 20 degrees, the range where saccades fall in this experiment.

We obtained the values of the maximum velocities of saccades times their duration and plotted them on the Y axis, whereas the X axis contained the corresponding saccade amplitudes. These points aligned to lines whose slope values, or Q values, and their standard errors were further calculated. The 'main sequence' slopes were compared for the 26 participants and calculated the average and the 95% confidence intervals for each group in every task

(Fig. 10.1). In addition, what is also reported are these statistics for a control task, free shots in basketball. They were viewed as a reference by the basketball players only.



(a)



(b)

Fig. 10.1: The "main sequence" plot for the athletes in Task 2 (a). Y axis, the maximum velocity times duration of the saccades; X, the amplitude of the saccades. The mean values of the 'main sequence' slopes for the athletes (empty squares) and non-athletes (full circles) by task are plotted in **??**. The bars denote 95% confidence intervals.

In watching unfamiliar sport situations, the group of athletes can indeed be distinguished from the non-athletes, based on the eye velocity criteria. The same films were shown to the volunteers but with different instructions (estimate, memorize, compare) in the first three tasks (T1 through T3). In the first two tasks, the peak velocity over the average velocity ratio of the two groups differed significantly. Within the confidence intervals, the non-athletes did not respond significantly different in the first three tasks. On the other hand, the eye kinematics of the athletes was significantly different in these tasks. By task three, the Q values for the athletes have converged to 'the baseline' or the control situation of the basketball shots. Task 4 was a karate tournament, again a novel situation. The Q value for the athletes increased, whereas that of the non-athletes decreased.

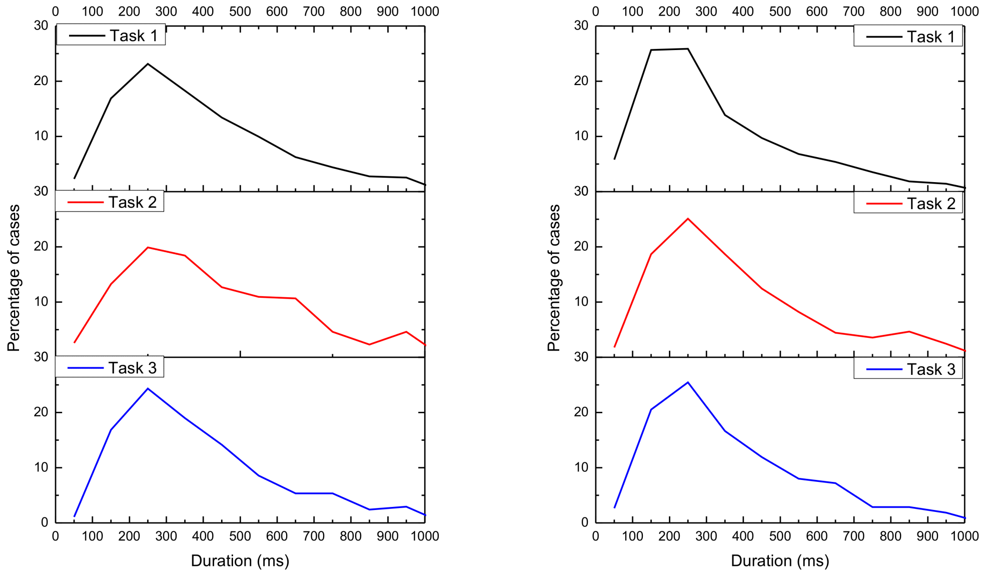
Task 5, the Latin dance, elicited the peak response in the non-athletes group, which was lower only than the Task 1 response in the athletes. On the contrary, the response of the athletes within the confidence intervals matched their 'baseline'.

10.2 Fixations to explore unfamiliar sport actions

The first two tasks witnessed to high differences in the way eyes were accelerated, moreover, significant differences in gaze fixations were also found in these cases (Fig. **??**). The distribution of fixations did not match the normality criteria (Miller, & Miller, 2004, pp. 210-219). This was supported by Kolmogorov-Smirnov normality test, for the fixation durations of the athletes it yielded D=0.099 in Task 1 and D=0.094, Task 2, in both cases $p < 0.01$. For the non-athletes it was found that D=0.132 and 0.121 for Tasks 1 and 2 respectively, in both $p << 0.01$. Therefore a non-parametric test (Miller, & Miller, 2004, pp. 529-523) was applied to compare the distribution of fixations. In the mastery estimation task (No. 1) the group of the athletes made 432 fixations (median 332 milliseconds), the non-athletes made 483 fixations (median 265 ms). The fixations were significantly different (Mann-Whitney U=122985, $p < 0.01$). In Task 2 (memorize the sequence of movements) the athletes made 347 fixations (median value 374 ms) and the non-athletes 450 (median value 315 ms). The groups were also significantly different (U=87915, p=0.02).

These findings, along with the upper two rows in Fig. 10.2, substantiate the conclusion that the athletes made fewer fixations, but their fixations were longer than those of the non-athletes.

For the Tasks 3 to 5 no significant difference was found among the distributions (Mann-Whitney test, $p > 0.05$). In Task 5 (Fig. 10.3), the total



(a) (b)

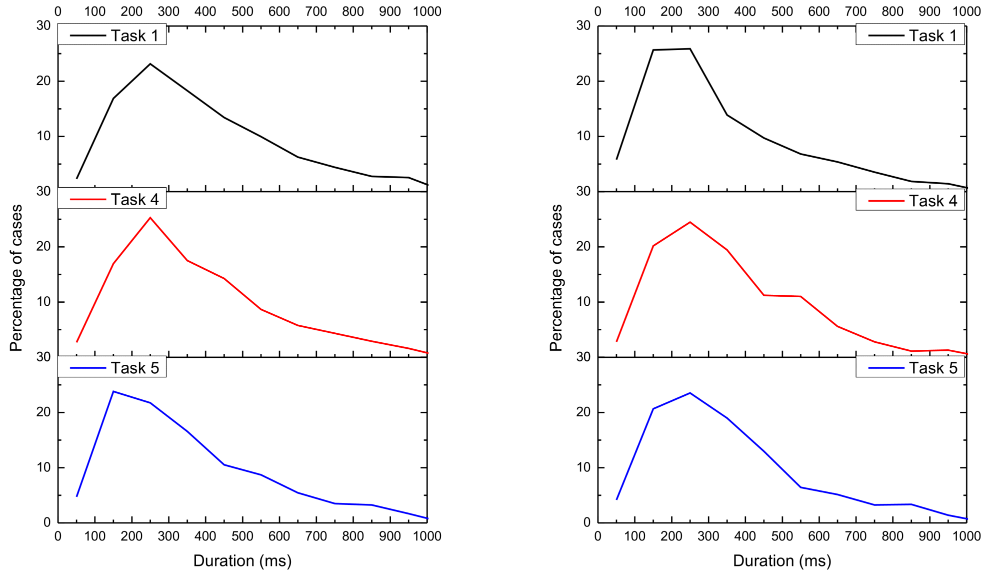
Fig. 10.2: Distributions of the duration of fixations for the group of athletes (a) and non-athletes (b) in the first three tasks. Statistically significant differences were found in Tasks 1 and 2.

time of calculated fixations was 25% higher in the non-athletes than in athletes groups, while in other tasks this difference was within 10% limits. This finding suggests that the athletes used more smooth pursuit eye movements than saccades and fixations in observing the Latin dance.

10.3 The sites that attract the gaze

Once it became known what eye movements the participants launch, it is worth asking where the participants look. The differences between the groups, if there are any, could be correlated to the observed differences in the speed and timing of the gaze. This is not a necessary condition, though, thus it is desirable to use objective algorithms or 'blind' methods in deciding where the participants looked to more frequently.

The filmed actions were seen mostly in a single plane in the prepared sports video films, hence the performers were seen as equidistant from the observer. As a sequel, two-dimensional clustering algorithms were applied to the horizontal and vertical fixation coordinates, the outcome pointed to what



(a) (b)

Fig. 10.3: Distributions of the duration of fixations for the group of athletes (a) and non-athletes (b) in the first three tasks. In contrast to Task 1 (upper curves), differences between the groups in Tasks 4 and 5 were not significant.

regions were attended the most. First the hierarchical clustering was applied and it was found that the best balance between the new information and computational costs is obtained when 12 regions are defined. This number also makes sense from the physiological point of view. In the case of one performer (Tasks 1 through 3), two regions can be defined for each hand and leg, two for the trunk and two for the head. These points could potentially outline the start and end points of right to left motion visible on the screen. On the other hand, six regions could be detected for both performers in Tasks 4 and 5. This number was fed into the K-means clustering algorithm (MacQueen, 1967; Kanungo et al., 2002). The K-means clustering groups the points into K clusters (in our case it is motivated to define K=12) so that the geometrical distances from all the fixation points in a cluster to the cluster centre are the smallest. It is noteworthy that the K-means clustering does not yield the exact point that every person had been looking at, e.g., the right wrist, since the performer is in motion. The points obtained by clustering algorithms mark the centres of the regions where fixations are scattered around. These points can be compared to what was visible on the participant's screen (Fig. 6.1).

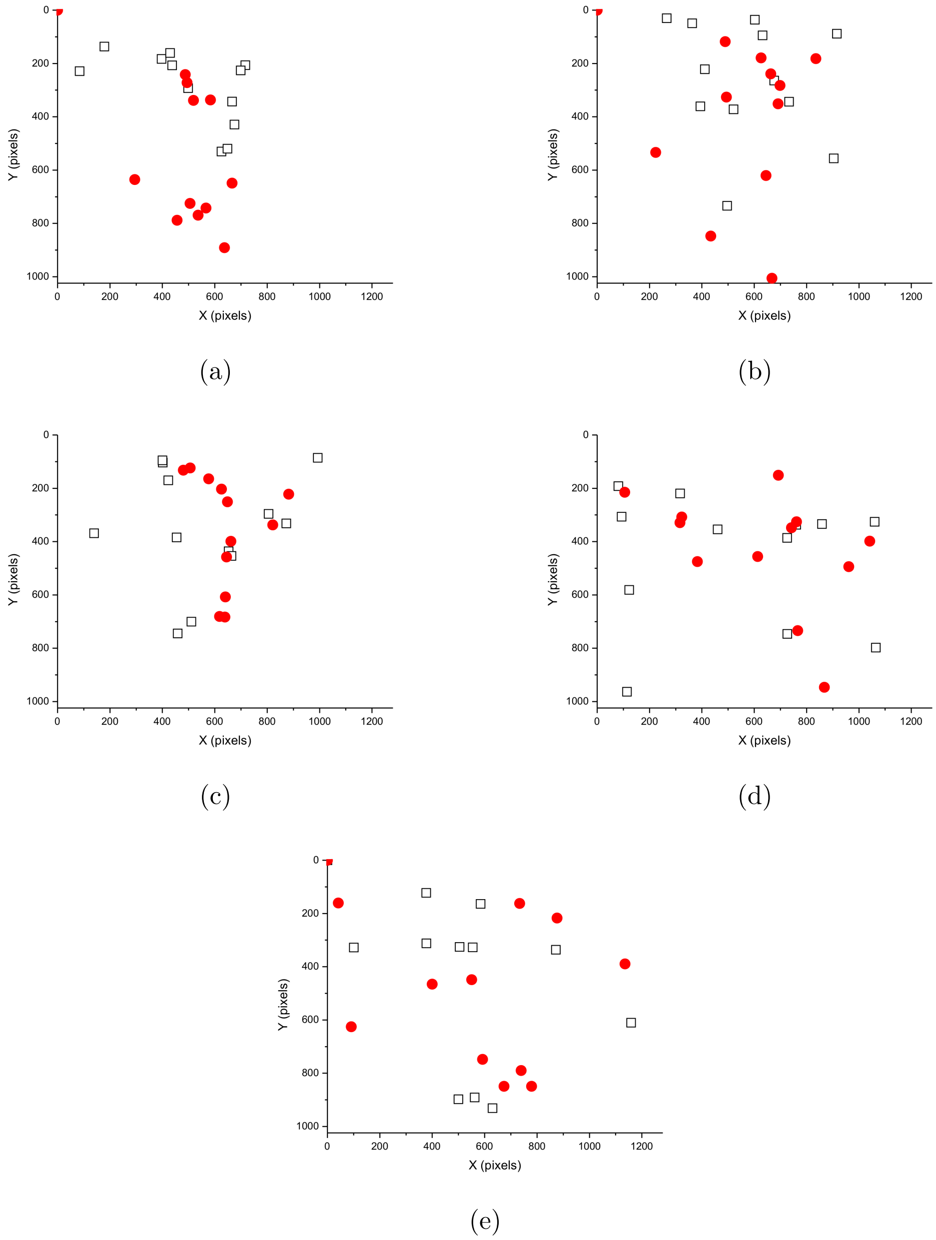


Fig. 10.4: Centres of fixation clusters for the athletes (empty squares) and the non-athletes (filled circles) mark the regions were the fixations were scattered around. Results for Tasks 1 through 5 are presented in (a) to (e).

In Task 1 (Fig. 10.4a), the main distinction that were recognised between the groups was that they looked to either fast or slow moving body parts in estimating the performer's expertise. The non-athletes fixated more the lower part of the body, the slow leg motion. The athletes in general spent more time looking at horizontal and vertical arm movements. They also were prone to examine the scene in general, picking up a possible clues of mastery, such as the belt colours. The non-athletes commenced tracing actions with few fixations to the action setting. When the participants were asked to memorize the sequence of movements (Task 2, Fig. 10.4b), the athletes aimed at fixating the endpoints of punches and blocks. The non-athletes relied more on observing the launch sites of movements, hence the cluster centres group on the person's trunk. This finding is supported by the picture of cluster centres in Task 3 (Fig. 10.4c, compare to the previous film - change detection). Both groups screened through the entire body of the 'kata' performer as he moved. Although the most fixated regions do not differ considerably here, the athletes tended to gaze more to the left, the direction of the performer's expected motion.

In the Task 4 (Fig. 10.4d), the tournament of two opponents, the gaze of the viewers was scattered throughout the scene. In contrast, the rhythmical dance movements of Task 5 (Fig. 10.4e) were followed in a structured manner by the two viewer groups. The clusters group at the arms and shoulders, the upper clusters corresponding to the underarm turns, and the feet of the two dancers. Knees were rarely looked at, in the beginning some fixations were made on the faces of the dancers.

10.4 Are the differences in eye movements apparent?

If there are indeed any qualitative differences between two groups, it would be possible to classify an arbitrary gaze video as belonging to a participant of one or the other group based on some features. We indeed found a qualitative difference that hinted to the viewer's sports experience. The athletes picked up a 'favourite', which was monitored through an action, and restricted the number of the selected sites. By a 'favourite' we denote a body part, like an arm or a leg, which was the target of observation. When a movement was launched, the athletes scanned this part repeatedly, e.g., they looked at the joints of an arm from the shoulder to the wrist several times.

Interestingly, they attended the 'favourite' even when it when the main action was made by other body parts, yet they also shifted from one selection to another. This selection strategy was especially apparent in the first two tasks. In the fourth and fifth task, the athletes preferred to follow one performer, while the non-athletes frequently switched their gaze between the two. Since the 'favourites' differed, the clusters of Fig. 10.4d and 10.4e are evenly spread for the entire group of the athletes. The athletes also had a restricted number of sites they fixated, for instance, they fixated the shoulder, the elbow and the wrist of the karate performer. The non-athletes fixated also the parts that were not instrumental for the action, e.g., the neck or the upper-arm. We also observed in the eye movement videos that the athletes rely on the slow pursuit movements rather than jump-like saccades in watching the films.

The athletes and non-athletes witnessed to no considerable differences in the 'when?' part of the gaze strategies. In our experimental paradigm, we could not detect any significant differences in the saccade latency. Albeit the eye movements were mostly reactive even in repeated exposure tasks, the non-athletes were capable of making as fast responses to new movements on the screen as the athletes were.

10.5 The athletes' eye movements are not always faster

We conclude that the visual system advantages exist in athletes when a real situation is viewed. It was not obvious from the onset that eye kinematics of the athletes and non-athletes would form two distinct groups in any task. It could be equally well expected that the 'main sequence' lines would form one diffuse family. Since the two groups were age and gender matched, we are inclined to assume that it is the adjustment of the visual system, rather than genetic factors or cognitive strategies, primarily explain for the differences between the groups. To answer the posed hypothesis, we indeed observed relatively higher eye movement velocities when the basketball players first observed the karate scenes. At further exposures, the "main sequence" relationship converged to that of watching basketball shorts and the confidence intervals of the two groups overlapped.

The velocities of eye movements thus do not distinguish athletes and non-athletes. The eye velocities of the non-athletes were relatively higher than those of the athletes in Task 5. Possibly dance scenes are easier to perceive for the female group in consideration, for they may have been more accustomed to this sort of action through the everyday experience (television or other). Moreover, the Q values of the non-athletes in Task 5 exceeded the performance of the athletes in other 3 tasks (2nd to 4th). Even though the highest group average was calculated for the athletes in Task 1, it appears that the athletes rarely use "the full power" of their visual system. In addition, the largest differences in the eye velocities within both groups (i.e., the largest confidence intervals) were found in the same task (Fig. 10.1). It probably deserves further research if these eye velocity differences in the response to a novel situation may be a reflection of the sports mastery or potential. Could the level of an athlete be predicted based on this criterion?

Our findings are in part contrary to the findings of Babu and colleagues (2005) who found no significant differences in the kinematics of saccades between the athletes and non-athletes. There is no reason to assume that the type of sports of the athletes, the racquet sports or basketball, was the decisive factor. Possibly here we face a problem that is encountered in other types of eye movement research, namely, the human visual system tends to behave more efficiently on the natural rather than laboratory stimuli (Thorpe et al., 1996, Peters et al., 2003). The performance advantages of the athletes may not be fully revealed in computer-generated abstract forms but appear whenever real situations are viewed. We also refer back to the "direct matching hypothesis", the support to which was provided by Flanagan and Johansson (2003). According to it, the participants of our research mapped the observed movements of human actors to their motor cortex. The generated eye movements corresponded to their efforts to predict or reproduce the observed actions. The participants with a better trained kinaesthetic memory did it with significantly different saccades and fixations.

The above reasoning leaves unanswered the question of why does the kinematics of the athletes' eye movements in novel sports situations converge to the performance in their familiar basketball shots (Fig. 2). We hypothesize that athletes are also better accustomed to distinguish the situations that risk a failure and those that do not. An athlete is trained to use brief moments of the game to relax and restore performance. A non-familiar sports display, and non-customary task of watching videos at a scientific laboratory, could initially mobilize the athletes for tougher performance. Likewise, a decisive sports situation would cause much arousal. On the other hand, recorded basketball video, and dance that may not be perceived as 'a real sport' by the invited athletes, has been classified as 'non-threatening' by the athletes.

10.6 Athletes use fewer but longer fixations

Comparing Tasks 1 and 2, the athletes use a smaller number of fixations that are longer than those of the non-athletes. Remarkably, at repeated exposure both groups watched the same video with relatively longer fixations. Thus the extent but not the nature of changes differed in both groups. In other words, the quantity and not the quality are of importance when an unfamiliar sport scene is tackled. No differences in fixations were found in the other 3 tasks, even though the last two differed significantly in eye kinematics. Furthermore, the unexpected shift in Task 5, where the non-athletes witnessed to relatively higher eye velocities times their duration, was not accompanied by any significant changes in the duration of fixations. This is not surprising since saccades and fixations are programmed independently and saccades alone can be used as a research tool (Leigh, & Kennard, 2004).

A limitation of eye movement research in sports is that the fixations mark only the foveal vision. As shown by Hassan and co-workers (2007), the field of view of up to 32 degrees is necessary for an efficient navigation if the contrast is sufficiently low. Before getting to fixate the target milliseconds before a shot, the player must traverse the playgrounds in a dynamic setting of team-mates and opponent players (Martell, & Vickers, 2004; Oudejans et al, 1997). The success of navigation determines if the 'quiet eye' (Vickers, 1996) will be used at all, hence the rating of a player is determined by the entire course of action. Are there as yet incompletely described skills that must accompany the 'quiet eye' of a successful player? It may be further researched what preliminary information of the para-foveal vision is processed before the player gets to the 'ready position'.

10.7 Clusters of fixations

The athletes mobilize for "risky" novel situations, but their performance is not distinguishable from that of the non-athletes if the target is known or not challenging enough. This probably needs to be borne in mind if the athletes and non-athletes are compared in laboratory settings. The case when an unfamiliar sports situation was seen for the first time (Task 1) yielded considerable differences in "how fast" and "how long" do the participants explore it. Additionally, there were differences in "where" do the participants mostly look to. The clustering algorithms revealed the trend that the athletes traced the fast arm movements to assess the mastery of the performer, whereas the non-athletes focused more on the slow leg movements (Fig. 10.4a). These differences decreased when the video was watched repeatedly with the instruction to memorize the sequence of movements (Fig. 10.4b). The significant differences in the "main sequence" relationship of eye velocities and the duration of fixations, the locations of fixations clustered around the upper body of the actor. The athletes tended to direct their fixations more to the endpoints of the movements, hence the cluster centres are further apart. The third demonstration of the same video (to be compared to the previous) was accompanied by no considerable differences in either "how fast", "how long" or where did the participants look (Fig. 10.4c), which accentuates the role of the initial exposure to a situation.

The karate scene with two opponents witness that the athletes are better at finding task-relevant clues. This video has again stirred relatively faster responses in the athletes' eye movements. Both groups focused on the upper body of the two participants (Fig. 10.4d). Yet the athletes attended other clues in the environment to predict the winner. Therefore two cluster centres were found at the left side of the scene (in the middle and at the lower part). These centres correspond to gaze at the score on the board and the referee's flag that appeared twice at the lower left.

As mentioned before, the athletes seem to implement different strategies, one with high arousal and the other similar to the non-athletes', depending on the "risk" of the situation at hand. Novel and competitive situations lead to considerable differences in the attended areas by both groups, whereas a cooperative scene of a fast Latin dance does not. Fixations are aligned along three lines at the dance observation (Fig. 10.4e) and correspond to the feet, the arms and shoulders and lifted arms in underarm turns. The location of the cluster centres is very close for both groups in this case, similarly like in accustomed Task 3 with one performer.

10.8 What is selected in the scenes?

The finding that the athletes chose a 'favourite' part or performer to trace could be explained by target-focusing in sports. In the ball sports, the players divide the attention among the target (e.g., the basket), the opponents and team-mates, essentially suppressing the rest of the visual information (like advertisement banners or spectators). In the case of undefined criteria for the task, the method we used, they defined a target for themselves and focused on it. Recalling previous findings (e.g., Babu et al., 2005), the athletes and non-athletes must not necessary differ in their eye movement timings. Therefore it is not surprising that our qualitative analysis found no apparent differences in how fast were the participants to react to an action.

As compared to the martial arts, even a fast-paced Latin dance leaves more possibilities for slow pursuit movements instead of saccades. The 'main sequence' analysis involves only the saccades, the fast eye movements when the vision is temporary suppressed. Indeed, it is virtually impossible to track a punch, while one may follow through a spin in a dance. If the group of athletes use faster saccades, they may also perform better in tracking the dance. The qualitative analysis of the recoded gaze video supports our claim.

What sets training in professional and recreational sports apart? One element that is likely to be trained is focusing on a target. This target, or "favourite", may be arbitrarily defined and followed dynamically and rapidly changed. Thus targeting and following a karate performer's arm and then switching to the leg is similar to following a ball that travels from one player to another. Possibly, the years in sports exercise on a professional level (hours of training per week) is an indicator that permits one to compare different researches (Babu et al., 2005; Oudejans et al., 2002). By definition, the 'elite' athletes available to a research are but a few. Therefore the criteria for selecting 'elite' athletes are somewhat arbitrary, those ranked as 'elite' in one research would score as 'near-elite' or otherwise in another (Martell, & Vickers, 2004; Panchuk, & Vickers, 2006). Classifying the players as professionals and good or week amateurs is rewarding for some sports research (Land, & McLeod, 2000), but should be used with caution, or conflicts with the official designations will appear. An 'amateur contest' dancer probably spends more hours in training than a skier who is called 'an amateur'.

What is behind a talent in sports? Babu et al. (2005) revisit the "nature" versus "nurture" problem in sport. Does an athlete possess some superior motor skills because she trains intensively, or was she selected for the team training because she had early demonstrated some outstanding potential? We have found that straightforward differences exist in the visual system, but these are modified by higher cognitive processes if the tasks are compared.

10.9 Summary

We have found that exposure to unfamiliar sports situations reveal eye velocity advantages that exist in the athletes. The athletes are also better at alternating between higher performance and more relaxed modalities, and at selecting and following instrumental body parts of a performer. They initially use longer but fewer fixations than the non-athletes, both groups tend to use longer fixations at repeated exposures.

11. EYE VELOCITY IS CORRELATED TO NATURAL OBJECT RECOGNITION TIME

11.1 Saccading to short series of images

Ten volunteers observed a series of 30 images appearing to the right from the central fixation point. The saccades calculated under ILAB software (Gitelman, 2002) were further classified into correct responses (either a saccade to an animal image or an anti-saccade otherwise) and erroneous responses. The sets where a participant failed to make an eye movement response in 1000 ms or made an eye movement sooner than 100 ms after the image appearance were excluded from consideration. With these cases excluded, we obtained the mean saccade response time 455 ± 164.8 ms for the correct responses, and 362 ± 228.9 ms for the movements to a wrong direction. Since the distributions of the response times in both groups were normal (Kolmogorov-Smirnov $D(284) = 0.063 > 0.207$) but their variances were significantly different (Levene's test, $F = 13.019, p < 0.001$) it was found that the correct and erroneous response times are different significantly by the Independent samples t-test assuming unequal variances, $t(57, 317) = 2.311, p = 0.024$. The erroneous responses were sooner on average, at the same time, higher standard deviation was found in this group (Fig. 11.1). The erroneous responses are positively skewed, i.e., the values above the median are more dispersed than the values below it. This finding motivated us to make an experiment where saccades and anti-saccades could be distinguished in the correct and erroneous response groups.

11.2 Saccade response times

Another eye movement calculation program, *BeGaze*, was used and the data analysis was modified so that it was possible to classify the responses into correct saccades, correct anti-saccades, erroneous saccades and erroneous anti-saccades. The average response times for pro-saccades and anti-saccades are summarized in Table 11.1. Participant AK responded to the series in overlap paradigm, whereas participant LV did it for the gap paradigm. A series of 90

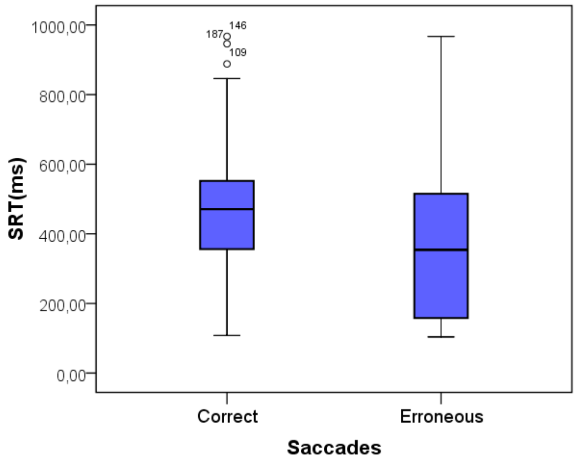


Fig. 11.1: Box-plot of correct and erroneous saccade response times. Horizontal lines are the median values, 50% of values are contained in the box-part, 25% of values are marked by every whisker. Outliers are shown as circles.

randomly selected images was shown to the two participants. A correct pro-saccade is a movement of the eyes toward an image of an animal, a correct anti-saccade is a correct move away from an image of a distracter. Before averaging of the data 5% of the outliers were removed.

Tab. 11.1: Saccade response times (milliseconds) in the overlap paradigm and the gap paradigm. CS, correct saccades; CA, correct anti-saccades; ES, erroneous saccades; EA, erroneous anti-saccades

	Gap			
(ms)	CS	CA	ES	EA
Average (SD)	460(73)	460(88)	370(114)	450(81)
Minimum	117	285	121	357
Maximum	550	722	525	609
	Overlap			
(ms)	CS	CA	ES	EA
Average (SD)	440(30)	420(42)	420(15)	390(34)
Minimum	395	365	407	331
Maximum	584	521	848	458

11.3 Case studies of gaze stability

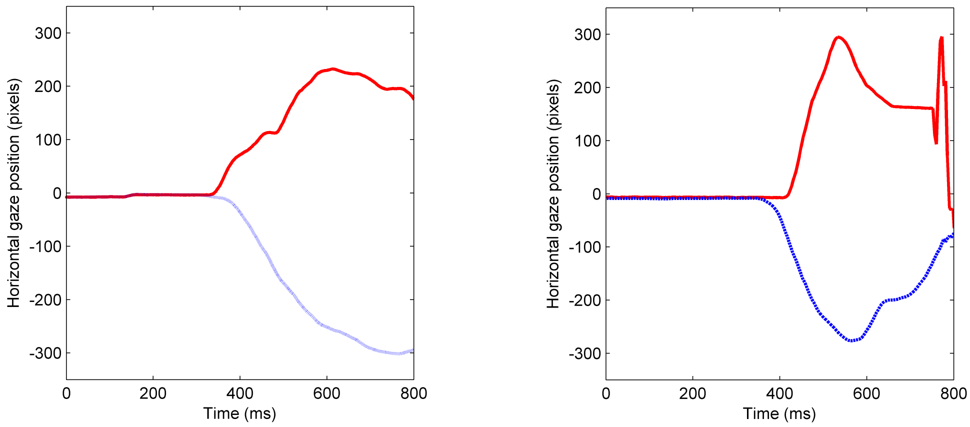
The maximum velocity of eye movements were correlated to its amplitude, Spearman's $\rho = 0.549$ for the overlap paradigm and $\rho = 0.751$ for the gap paradigm, $p < 0.01$ in both cases. The larger is the eye movement, the larger will its maximum velocity be. This finding is predicted by the "main sequence" relationship (Leigh, & Kennard, 2004) and lends support to the data validity. The other correlation, which was surmised at the beginning, is that the maximum velocity is correlated to the response time. Contrary to the predictions, this correlation is negative, i.e., the longer it takes to process an image and respond, the slower the response will be. Thus Spearman's $\rho = -0.652$ ($p < 0.01$) for the overlap paradigm and $\rho = -0.733$ for the gap paradigm ($p < 0.05$).

Saccade dynamics were searched for any potential correlations to the saccade response times. Statistically significant correlations were found among the saccade response time and its peak speed ($\rho = 0.613$), average speed (0.723) and duration (0.849) for the overlap paradigm, and the responose times and peak speed ($\rho = 0.788$) and duration (0.511) for the gap paradigm. Correlation at a 0.05 level of significance among the response time and the speed parameters (at least 0.433) was recorded for all erroneous saccades in the overlap paradigm. No such significant correlation could be found for the gap paradigm data. Saccade response times and the dispersion of the preceding fixation (in pixels) yielded a significant correlation of $\rho = 0.304$ for the overlap paradigm, which encouraged us to undertake a more detailed analysis of the gaze behaviour during a fixation before a categorization response.

No trend was observed concerning changes in response times for the first 30 images and the following (0.05 level of significance, the determinacy coefficients R^2 for saccade and anti-saccade responses over time were essentially zero).

No consistency was found in correlating the horizontal and the vertical gaze position at 0.05 level of significance, as could be expected from the task. Even though the shift of gaze from the central fixation point to any of the sides would demand a purely horizontal movement of the eye, as a rule some vertical displacement is also involved and a correlation exists for approximately 10% of saccades. As an exception, for the participant LV (gap paradigm) 160 milliseconds before launching the saccades the small horizontal and vertical gaze shifts around the centre were correlated in 18% but this percentage vanished to zero in the 160 millisecond period of saccading. Notably the onset of anti-saccades here precedes the onset of pro-saccades (Fig. 11.2b).

Another case that was brought into focus is the participant AK. We ob-

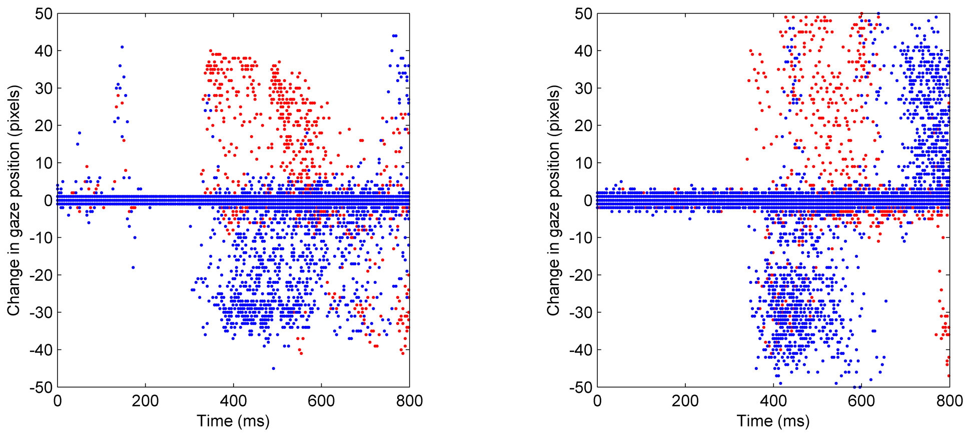


(a) Overlap (b) Gap

Fig. 11.2: Averaged horizontal gaze direction (pixels on screen) in the gap (a) and overlap (b) paradigm. Red solid lines, saccades; blue dashed lines, anti-saccades

served the horizontal gaze position component changed its nature approximately 160 milliseconds after an image was presented (and thus was still on the screen). Alongside with small gaze displacements towards the demonstrated image (positive values in the Fig. 11.3), which are candidates for the visual grasp reflex, after this period fixation becomes more stable. The derivative of the horizontal gaze component remains more confined to zero. The large positive and negative value of the derivative 400 milliseconds from start reflects the pro-saccades (positive values) and anti-saccades. This observation was found only in the case of the overlap demonstrations, gap paradigm presents overall more fluctuations as no central fixation point is visible before the saccades.

The response times of the voluntary (memory guided) saccades was not found to differ significantly, apart from one case, and a bias of classifying an uncertain case as a target image has been noted. Since the four groups of saccade response times were uneven in size after the classification algorithms were implemented, Shapiro-Wilk normality test (small samples) was used. The normality tests witness that a sample conforms with the normality if the probability of obtaining the test statistic (W-statistic for Shapiro-Wilk, D-statistic for Kolmogorov-Smirnov) is larger than 0.05. The calculated $W(88) = 0.958$, $p = 0.006$, for the overlap paradigm and $W(91) = 0.777$, $p < 0.001$, for the gap paradigm. In both cases normality tests suggest



(a) Overlap (b) Gap

Fig. 11.3: Average values of the derivative of the horizontal eye position in the gap (a) and overlap (b) paradigm. Red dots, saccades; blue dots, anti-saccades

non-Gaussian distribution of saccade response times warrant the use of non-parametric tests. Of them, Kruskal-Wallis ANOVA was applied to compare all four groups of saccade response times and for the participant AK found no difference between the saccades towards and away from the displayed image ($t^2(3)= 5.728$, $p = 0.126 > 0.05$). For the participant LV, however, we found significant differences ($t^2(3)= 17.488$, $p < 0.001$) due to erroneous saccades. Half of the erroneous saccades were launched considerably more than 400 ms after the image display by this individual (Fig. 11.3). Since the actual image presence on the screen was 330 ms on average, one may conclude that the entire display time has been used for recognition of images harder to interpret, whereas the time of around 100 ms after image disappearance and the saccade launch has been used for saccade preparation. Interestingly, the image was more likely to be classified as the target in doubtful cases. This class of erroneous saccades was not the visual grasp reflex, since the relatively long response time puts them into memory-guided group of saccades. To conclude, if the alternatives in our forced choice task (2AFC) were not of choosing one of two images but choosing one of two responses to a single image, relatively uniform response times of over than 420 ms were found (median times in four saccade groups 422 ± 22; 447 ± 14; 453 ± 12; 429 ± 6 ms respectively).

11.4 Limits of ultra-rapid responses

The finding of response times above 400 ms conforms to the results in the button-press or release experiments. It invites further research into the conditions when an eye movement responses as fast as 120 ms are dominant. Possibly, the alternative visual information processing route suggested by Kirchner and Thorpe (2006) may be used under specific "fight or flight" circumstances and is not descriptive of the human visual system in general.

A statistically significant link was found between the saccade response time and its speed. Seemingly the visual system should compensate for longer processing with a faster response. In our experiment this effect was reverse, the more effort the processing takes, the slower or less decisive the response will be. In this way, both parameters reflect the uncertainty of the responder. It was also calculated that the longer it takes to respond to an image, the more dispersed is the fixation preceding the response. This dispersion is typical for the first 160 milliseconds after the image presentation, but a more detailed exploration of the phenomenon invites a better eye-tracker's spatial resolution of down to 0.01 degrees (Laubrock, et al., 2005). The findings that saccade amplitudes are significantly correlated to the duration, peak speed and average speed (which is the amplitude divided by the duration) is a reflection of the main sequence relations (Leigh, & Kennard 2004). It is noted that there is some variability in the dynamics of saccades, which is linked to the participant's alertness and experimental conditions (Leigh, & Kennard 2004; Munoz, & Everling 2004).

What we did not anticipate is the fact that when outliers were removed and hardware delays taken into account, pro-saccades and anti-saccades as a rule were not launched during the image exposition. Rather it takes about 100 milliseconds after the image has been erased from the screen to launch a saccade, which is close to the express saccade response time (Leigh, & Kennard 2004; Kirchner, & Thorpe 2006). Provided that the verbal instructions introduce a trade-off between response times and accuracy in a saccade task (Mosimann et al., 2004), we chose a longer image presentation time, 330 milliseconds as compared to 20 milliseconds used in other protocols (Rousselet et al., 2004; vanRullen, & Thorpe 2001). Then we motivated the volunteers to "try to move the eyes while the image is still on screen, even if you are not sure of it." In our experiments saccade start has been measured from the moment (within 1 millisecond) the image appeared on the computer screen. If the measurement had started from the moment the image disappeared, one could test the possibility if this event may serve as a trigger for eye movements in a categorisation task. In addition, the image in our case was not flashed and remained on the screen for a comparably long time. This places higher demands on the dorsolateral prefrontal cortex to inhibit reflexive pro-saccades (Mri et al., 1998). Alternative forced choice methods may reduce this load and shift the task more to the frontal eye fields, which could account for the longer response times than reported elsewhere (Kirchner, & Thorpe, 2006).

The case of AK (Fig. 11.2a) echoes the research on cueing effects on microsaccade inhibition of Laubrock and colleagues (Laubrock et al., 2005). The stimulus recognition may serve as an endogenous cue that changes the rate of fixational eye movements. These changes occur at times close to the differential category-specific activity in the visual cortex, as recorded by electrophysiological methods (Lw et al., 2003; vanRullen, & Thorpe, 2001). This internally guided response may be governed by the supplementary eye fields (Mri, 1998). For the person LV, on the contrary, no change in the fixation patterns could be found by the current experimental setup. This participant tended to make anti-saccades sooner than the pro-saccades. Probably at a higher resolution of eye-tracking similar modulations in fixations would become vivid for other participants as well.

11.5 Devising natural tasks for natural image recognition

Colour images were the option of choice in the experiments as they contain enhanced texture cues for recognition and further classification. Even though we agree to the arguments that natural images are a means to explore the limits of the human visual system, we are cautious to call the task itself "natural." One may assume that the increase of the number of the images presented, besides increasing the power of the statistical tests, introduces learning effects that deserve further exploration. If the number of photographs presented is comparable to the number of stimuli in other saccade tasks, the response times in the image categorisation task are no better than those measured in the button press or release experiments (van Rullen et al., 2002). If a tenfold increase in the number of images presented may yield significantly decreased response times, new experiments could be devised to enhance the inherent capabilities of the visual system, which are latent in everyday tasks. This plasticity probably is best revealed if the task is confined to the oculo-motor system itself, with alternative neural processing routes having a say (Kirchner, & Thorpe, 2006). Alternatively, the forced choice paradigm and shorter demonstration times may expose the participants to faster routes to respond.

It has been stressed repeatedly that the photographs of natural objects reveal the capabilities of the visual system that do not become evident with abstract or simplified stimuli (Bovet, & Vauclair, 2000; vanRullen, & Thorpe, 2001; van der Linde et al., 2005). With the images presented on one side only, we deliberately introduced a task that required an inhibition of the primary response and voluntary production of saccades of two kinds. According to the current opinion (Leigh, & Kennard, 2004; Mri et al., 1998), this redistributes the roles of the dorsolateral prefrontal cortex and the frontal eye fields as compared to a task with target selection and pro-saccades (Kirchner, & Thorpe, 2006). Since what we termed pro-saccades and anti-saccades both involve visual grasp inhibition and a voluntary response, absence of statistical difference in the response times of the correct saccades was to be expected. For this relatively demanding cognitive task the overlap and the gap paradigms, apart from the fixation stability, produced similar results.

Since the central fixation point is not located in front of the tracked eye, the initial position of the gaze is not the primary position. Presumably, the amplitudes for the overlap paradigm could be expected to differ as the fixation point for the anti-saccade is visible all the time, while the attractor for the saccade could be the remembered fixation point position, a salient image feature or the left edge of the image. For the gap paradigm, no fixation points are visible while an image is presented and response is planned. In our case the opposite is true. We screened the MPEG files that were recorded during eye-tracking. We found that in the overlap paradigm, the participants were generally more conscious to reach and fixate the anti-saccade fixation point. When the individuals repeated the task with the gap paradigm, they tended to make hypometric saccades towards the left fixation point and to return to the center before the central fixation point re-appears. Possibly, if we had instructed the volunteers for choosing response precision over its speed, this effect would be eliminated in the gap paradigm.

11.6 Summary

To summarise, several differences in the experimental protocol may account for the fact that saccade response times are not much shorter than the manual response times published before (Kirchner, & Thorpe, 2006). First, we used by angular extent smaller and more peripheral images than other research, yet they were not seen longer (Bovet, & Vauclair 2004; Kirchner, & Thorpe 2006). Second, we observed the performance for one 90 image set instead of 10 sets by 80 images (for different conditions), although same images were presented after a week. Third, we tested both the overlap and gap paradigms and found no difference in response times. Next, and possibly the most influential difference is that we tested single side presentation instead of the alternative forced choice. Saccade response times are close to those of manual responses when single images are presented centrally (Thorpe et al., 1996). This leaves us with the question of the possible mechanisms that can selectively activate the hypothesized faster image processing and response, like V4 to the superior colliculus (Kirchner, & Thorpe, 2006)? They then bypass the typical processing routes for some but not other experimental conditions. It is worth noting that the saccade velocities are negatively correlated to their response times in our image classification task.

12. FACTORS THAT IMPACT MOVEMENTS OF THE EYES IN READING

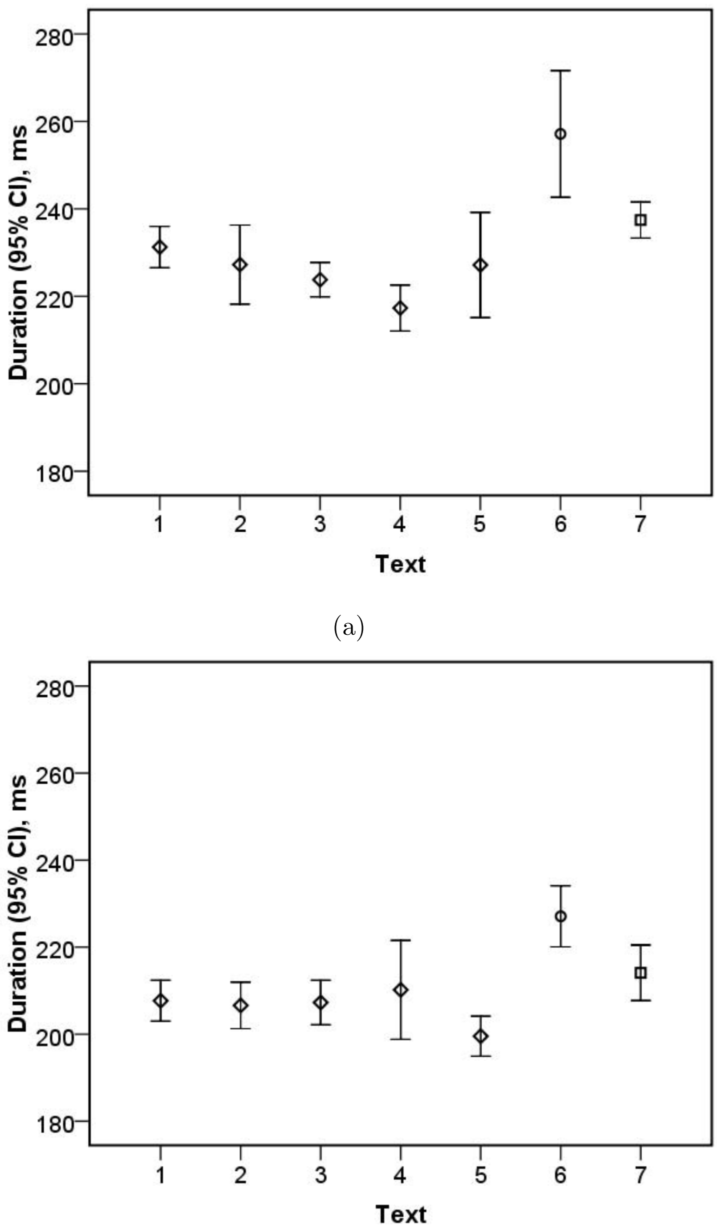
12.1 Eye movements in reading Latvian

The duration of fixations for 10 average readers and 10 skilled readers are summarized in Fig. 12.1. It has been shown that five students are as fluent in reading as six book editors have been joined to the skilled reader group. The duration of fixations in reading Latvian correspond to the results reported for English and German (Rayner, 1998). The texts were selected from magazines and are shorter that the following research of history textbook. The durations of fixations for the skilled readers generally are shorter than that of the student group. The longest fixations are for the text in Russian that is a fragment from a novel.

12.2 Task-specific considerations

Eye movements in three situations have been compared: for silent reading with a participant's head fixed (Task 1) and head free (Task 2), as well as for oral reading (Task 3) when the reader is wearing the eye-tracking helmet. Comparison of the first two measurements describes primarily the influence of different measurement conditions on reading data. Comparing the third condition to the first two may delineate the correspondence between the movements of the eyes in oral and silent reading. This comparison also reveals the limitations introduced by lower data sampling frequency. The helmet-mounted system records eye position every 20 milliseconds, which means that only two or three points are sampled during shorter saccades, while saccades to refixations are entirely omitted. Altogether it complicates saccade detection that is velocity-based. This also means a larger uncertainty for the starts and ends of fixations. Since calculations of fixations are done by using their spatial dispersion, lower temporal precision of the HED eye-tracker plays a lesser role here. Some distortions in detection of closely spaced fixations still occur for the 50 Hz data sampling in Tasks 2 and 3.

The reading speed is lower for an academic textbook, while fixations are



(a)

(b)

Fig. 12.1: Average duration of fixations in reading five Latvian texts (diamonds), a text in Russian (circle) and a text in English (square). The general group of students (a) and skilled readers (b) witness to the duration of fixations Russian, the second language, elicits longer fixations on average than the third language, English.

longer than 250 ms usually reported for adapted texts (Rayner, 1998). Reading speed is measured independently of the eye-tracking and testified that the demands of the two reading conditions are similar.Whe words 'reading speed' and 'reading rate' are used interchangeably here. Reading speeds for the participants before reading training were 158±67 (Task 1), 136±42 (Task 2) and 99 ± 22 (Task 3) WPM, ranging from 94 to 314 in silent reading and from 92 to 133 in the oral part. The slowest reader was a student who was not a native Latvian speaker. The words read per minute were significantly different, $F(24, 2) = 3.600$, $p = 0.040$, One-Way ANOVA. Post hoc analysis (Bonferroni) revealed that the differences could be found between the silent reading, head-fixed, and the oral reading speeds. At the same time, both measurements of the silent reading speed were not significantly different but were correlated ($r = 0.730$, $p < 0.050$), head-free oral reading speed was also strongly correlated to silent reading speed while head was free ($r = 0.880$, $p < 0.010$) and stabilised ($p = 0.850$, $p < 0.010$). Taken together, these findings suggest that the experimental conditions do not introduce selective distractions to participants. In addition, individuals who perform better in silent reading also do so in oral reading.

In accordance with previous findings (Proudlock, Shekhar, & Gottlob, 2003), it was observed that the readers, when have the option, move their heads from top lines of text to the bottom. As calculated from the text size and eye positions, eye movements contributed from 28 to 51 percent for the vertical gaze shift, the rest was done by head movements. To a lesser extent, horizontal head movements while reading a line were also observed, their contribution did not exceed 5 percent. It also means that without head tracking one could calculate the total number of fixations and their duration, yet classifying those into progressive fixations, refixations and regressive fixations cannot be done reliably. Therefore fixations per 100 words were calculated. This measure then can be used to compare reading of onscreen and printed texts that are of different lengths.

No evidence was supplied by tests that the duration of fixations differs in the three tasks. According to the Hi-Speed data in reading from the screen, the mean duration of fixations for six participants was 237 ms (standard error 9.3 ms). The mean in silent reading from a book was 268 (21.7) ms and 237 (14.1) ms in oral reading, as calculated from the HED measurements. The means do not differ significantly (ANOVA, F(2, 15)=1.267, $p = 0.310 > 0.050$). The current opinion in the reading research favours reporting ANOVA results for the mean fixation duration (Rayner, 1998), albeit in the case just mentioned the variances were not homogeneous, Levene's L(2,15)=2.144, $p = 0.152 > 0.050$. The number of fixations per 100 words in the oral reading part differs from the other two according to Bonferroni post hoc test. Their number was 119 (17.2) in Task 1, 121 (12.4) in Task 2 and 170 (8.4) in Task 3. This difference was significant (ANOVA, F(2,15)=4.647, p=0.027).

12.3 Tracing changes in reading

After practising more efficient reading, an improvement in the silent reading speed was observed (Fig. 12.2). The six participants returned for repeated reading tasks after a month of training. They read other pages from the same textbook and re-told the contents. As noted before, the reading speed is the variable calculated independently from the eye movement data and was therefore the first to be explored. From the data of the six volunteers that participated in the first session, we selected the data for the six volunteers that trained their reading skills. Therefore group averages differ insignificantly from the ones reported in the previous section. The volunteers improved their performance from 172±75 to 243±73 words per minute as found in the Task 1 (onscreen text), as well as from 136 ± 44 to 217 ± 75 WPM for the Task 2 (printed text). The increase in the reading speed was significant for both silent reading tasks, Paired-Samples T-Test yielding $t(5) = -5.242$, $p = 0.003$ for Task 1 and $t(5) = -3.588$, $p = 0.016$ for Task 2. For the group of six readers silent reading practise has left no significant impact on the oral reading, the change from 100 ± 17 to 110 ± 17 WPM being insignificant, $t(5) = -1.601$, $p = 0.170$, and is possibly explained by minor differences in the contents of the pages.

After a month of reading a text similar to the ones used in tests, the adult readers changed their pattern of fixation duration and number, but this change was not observed equally in all tasks. Thus the mean duration reported in Hi-Speed results decreased from 236 to 202 ms, which was significant (Paired-Samples T-test, t(5)=8.387, p¡0.001). Essentially no change was observed in the silent reading from a book (237 to 244 ms, t(5)=-0.476, p=0.654). In oral reading, the change from 237 ms to 222 ms also was not significant (t(5)=1.415, p=0.216).

The number of fixations has decreased after reading practice according to the Hi-Speed measurements. The change of the mean from 119 to 82 fixations per 100 words was significant (t(5)=4.682, p=0.005). The change from 121 to 99 fixations in the silent reading did not reach statistical significance (t(5)=1.700, p=0.150), neither did their number in oral reading (t(5)=-0.211, p=0.841).

Notably, only the Hi-Speed measurements before and after reading practice were significantly correlated, r=0.901, p=0.014 for the duration and

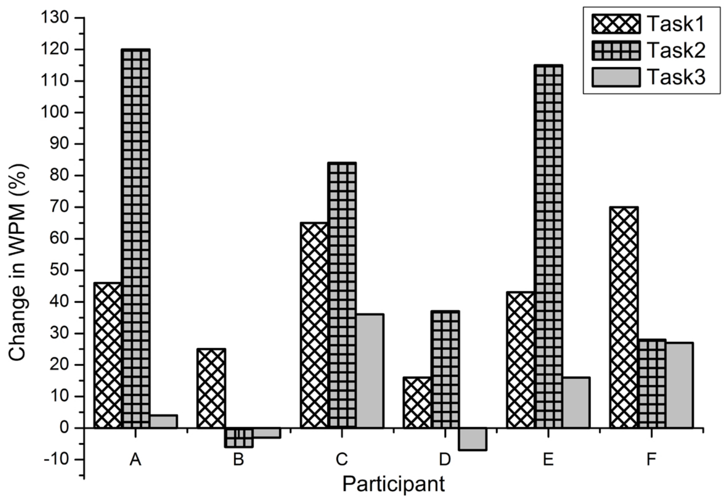
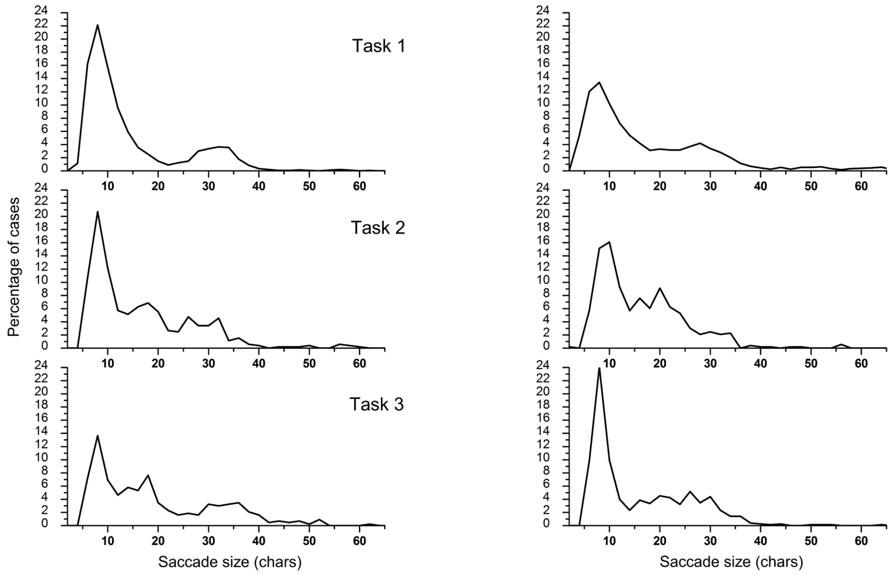


Fig. 12.2: Changes in reading speeds (words per minute).

r=0.887, p=0.018 for the number of fixations respectively.

12.4 Saccade detection

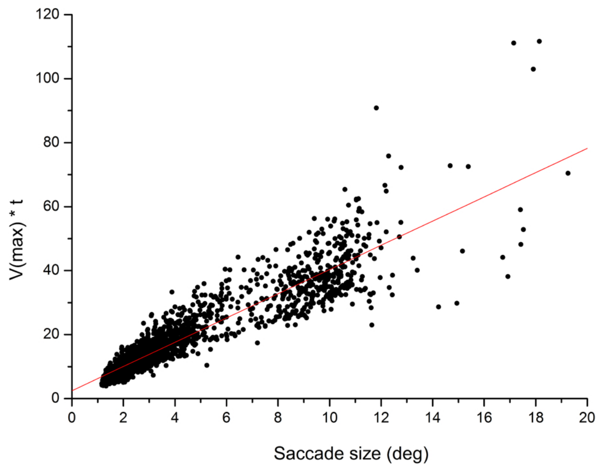
In silent reading, both head-fixed and head-free recordings lead to similar conclusions concerning saccade size distribution and changes in it despite the differences in precision. If the saccade amplitudes (sizes) are binned by two characters, their non-Gaussian distribution becomes apparent (Fig. 12.3). The first maximum consists mainly of progressive saccades, further follow regressive saccades and sweeps to a new line (Tasks 2 and 3). Notwithstanding the differences in the angular subtense of letters and in the data sampling, the first maxima of every task were located at the same place in terms of characters (six to eight characters), evidently a property of the reading process. The differences in the shapes of distributions after the main maximum emerge due to head recruitment in Tasks 2 and 3. It is important to note that the changes in reading are depicted in the same way, namely, the percentage of saccades up to 10 characters long decrease, while the longer saccades increase in number. Importantly, no vivid shifts in maxima is observable in the Fig. 12.3, their relative role redistributes though. Pronouncing a word aloud (Task 3) would require narrowly spaced fixations. Therefore it leaves the question of the large percentage of saccades longer than 10 characters in Task 3, which possibly addresses the issue of the detection algorithm that pools short saccades together. The results were obtained after saccade amplitudes had been filtered for artefacts, only those calculated saccades were left that did not exceed column widths (65 chars).



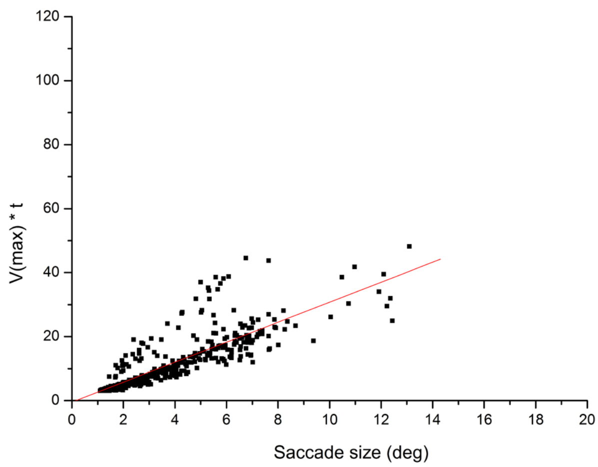
(a) (b)

Fig. 12.3: Percentage of saccades by their sizes (in characters) before reading training (a) and after the training (b).

The duration and amplitudes of saccades are linked by the main sequence relationship that can be modified by the task (Leigh, & Kennard, 2004). Therefore similarities in the two silent reading tasks were anticipated (Fig. 12.4, before training). Yet the limitations imposed by the equipment could in principle produce differences in the short saccade detection, and the option to coordinate both eyes and head may set a temporary movement pattern in reading. Unexpectedly, saccade detection at 50 Hz yielded strong correlations for the saccade main sequence analysis. At the level of significance < 0.01 we found that the saccade size and its maximum speed times duration are strongly correlated, $R = 0.922$ for Task 1 and 0.853 for Task 2. The fourfold difference in the number of points in Fig. 12.4a and ref3fig4b is partly because of shorter text read and saccades missed by the detection algorithm for Task 2.



(a)



(b)

Fig. 12.4: The main sequence plot for Task 1 (a) and Task 2 (b). X axis, saccade size in degrees, Y axis, the maximum speed of saccade times its duration.

A change in saccade amplitudes after reading training was reported in all three tasks. Saccade amplitudes while reading, apart from one case, did not comply with the normality criterion (Shapiro-Wilk, $W < 0.950$, $p < 0.010$). Hence no parametric tests could be applied to disclose significant changes in them. For the six readers, the saccade amplitudes while reading from the monitor (Task 1) before training (n=1898) and after them (n=2025) were significantly different by approximately one character (Mann-Whitney, $U = 1710376$, $p < 0.001$). Likewise the helmet-mounted device recordings testified to this difference (Task 2: n=581 before and n=680 the after training, $U = 123254$, $p = 0.050$; Task 3: n=581 and n=680, $U = 179547$, $p = 0.005$). However, the significant change in the oral reading was a decrease rather than an increase. The smaller numbers of saccades in the latter two tasks are due to, firstly, shorter passages read and, secondly, some number of saccades obviously missed by the HED. The change in the saccade size was accompanied by a statistically insignificant change in the number of fixations, as reported above. A change by one character does not ensure significantly fewer fixations, this outcome is partly due to large interpersonal differences.

12.5 *Changes in eye movements are traced by* Hi-Speed

The lack of significant correlation in the HED data testifies to the result variability due to measurement technique. This warns against HED measurement of reading in the cases where tracking slight changes is relevant. However, this does not preclude HED measurements of eye movements in book reading, since the calculated mean duration of fixations in the three tasks was not different, the pattern of fixations is known to be relatively stable in different tasks throughout the life (Rayner, 1998). The larger number of fixations in oral reading also renders a reason. If head movements are not restricted, further research would possibly benefit from optimizing the fixation detection window to compensate for the gaze shifts due to head rather than eye-in-head movements.

Contrary to results published elsewhere (Rayner, 1998), we found that not only the number of fixations may decrease after reading practice, but so does also the mean duration of fixations.

The rate that the eye position data have been sampled at and processing algorithms differ among researches (Svik, Oddvar, & Samuelstuen, 2000; Seo, & Lee, 2002; Proudlock, Shekhar, & Gottlob, 2003; Vitu et al., 2006; Rayner, 1998) and in principle may lead to diverging results where in fact no difference exists.

As anticipated, the texts were read at approximately the same rate from a printed page and a scanned page on a screen. In addition to that, the reading rates were correlated by participants, none had a vivid preference to printed or onscreen texts. At the relatively robust level of words per minute, two experimental conditions have had no detectable discrepancy. This is in spite of the fact that the letter sizes and resolution were not the same, which can be justified as the optimal letter size has an interval that has been reported (Krischer, & Zangemeister, 2007). The option of choice was the convenience to volunteers, that is to say, reducing angular size of letters on the LCD screen would lead to text graininess, and increasing the distance to it would also deteriorate legibility. In the process of inviting participants, we aimed at having a possibly large spread in reading speeds (90 to 300 WPM), partly due to their varied experience and former interest in history texts. This would presumably present a wider range of fixation durations and saccade sizes for individual comparisons.

From the developmental point of view, suffices it to note that oral reading is strongly correlated to silent reading. This observation has been made before (Sovik et al., 2001) and may also be a reflection of subvocalizing habits. Indeed, the less skilled of the readers had in essence the same reading rate in the silent (93 WPM) and oral (91) part. Since it takes longer to pronounce words, a larger number of fixations in oral reading task was expected. Similarities in the number of fixations per 100 words in the silent reading tasks are characterised both by their number and strong correlation. In general, this affirms that both eye-trackers are similarly efficient in detecting fixations in reading. The silent reading tasks themselves also do not pose different demands on the cognition, despite their difference in the person's mobility and text presentation (print or screen). Since the head position was not monitored, the fixations could not be further classified as progressive or regressive in the head-free reading, therefore this variable could not be used for comparisons.

The more fixations a person makes in reading, the larger share of the reading time is occupied by gaze-shifting saccades, as the results have shown. We have found that the fixations up to one second constitute the same share of time for slower readers, i.e., fixations shorter than that were found by both eye-trackers to occupy the same percentage of time. Since a less skilled reader covers fewer characters by a saccade (Ashby, Rayner, & Clifton, 2005), two closely spaced fixations may appear indistinguishable to a tracking setup. That a faster reader proceeds through the text with shorter fixations and larger size saccades has repeatedly been supported by research (Rayner, 1998; Ashby, Rayner, & Clifton, 2005). Then the fixations are more widely spaced, and less likely to be merged together due to an eye-tracking system. Why then the faster readers are found to spend 90 percent of time in fixating up to 1000 ms in the Hi-Speed data and only 70 percent in the HED data? Possibly the answer is sooner to be found in the tracking conditions rather than the data processing. If the participant's head is free to move, a larger gap between two fixations can be covered by some head moves. Thus in the eye-in-head coordinate system two successive fixations may be closely spaced, even though they are remote in terms of characters. We hypothesize that some words, depending on their meaning, location or length, may involve head movements more than other words do. Do the horizontal head movements have inter-personal variations, or do they vary for the same person depending on semantic cues in the text? For a cognitive exercise like reading, which involves top-down regulation, the eye and head movement coupling may in fact alternate within one task, which is consistent with published research (Pelz, Hayhoe, & Loeber, 2001; Seo, & Lee, 2002; Stahl, 2001; Oommen, Smith, & Stahl, 2004).

A larger number of fixations in the oral reading task was accompanied by them taking statistically different in duration from those in silent reading. The fact that the oral reading fixations were detected to be shorter than others apparently presents the limitations of 50 Hz eye-tracking. Articulating words may demand fixational eye movements, like microsaccades. Due to their short amplitude and duration these movements could not be properly detected by the eye-trackers and would also require a custom detection code to be implemented. Nevertheless, the small eye movements could play a role in fixation detection, and a single long fixation could be interpreted as two or more shorter ones, which, however, does not explain for the strong correlations in the fixation numbers. The possibility that it is the duration of fixations that becomes improperly identified in oral reading is supported also by the lack of correlation between the duration and the reading speed. In silent reading, fewer words read per minute are at least partially explained for by a greater number and longer duration of fixations.

12.6 Detected saccades are similarly distributed

Saccade amplitudes in both silent reading tasks have distributions with corresponding first maxima (Fig. 12.3). In terms of letter sizes, the first maximum occurs at six to eight characters. This finding for the Latvian language agrees with the reading data for other European languages, like English or German (Rayner, 1998). The second maximum is closer to the line length, as texts were formatted in two columns, each 65 characters wide. This bimodality of saccade amplitudes in reading warrants non-parametric tests, which further asks for a comparatively large number of detected saccades to perform a rank test. After reading training, saccade amplitudes have retained the bimodal distribution but means increased by approximately one character in Tasks 1 and 2.

Longer saccades in oral reading may witness to detection failures, which also go in line with the findings that the duration of fixations in Task 3, contrary to the expected, were found to be shorter. The option of having a participant's head free to move advocates a larger spatial and temporal resolution of the tracker in the experiments of oral reading or tasks that involve facial expressions.

Possibly changes in facial mimics while articulating words ask for slight fixational eye movements that are interpreted as the ends of fixations by the software. The times it takes to complete a saccade have similar distributions if they are binned by 20 ms. Though this resolution is sufficient to find correspondences in saccade amplitudes by both eye-trackers, caution needs to be exercised in eye movement research that involves eye speed or acceleration measures or "main-sequence" analysis described elsewhere (Leigh, & Kennard, 2004; Seo, & Lee, 2002). Probably rounding up of timings at lower data digitizing rates is capable of distorting speed plots and can occasionally cause large fluctuations in repeated measurements.

Strong correlations in the main sequence analysis were found in the data of both setups. However, the experiment does not explain the difference in the two slopes. On one hand, it may be purely due to the behaviour of the oculomotor system in the two settings. On the other hand, the bifurcation observable in Fig. 12.3b may hint at some cumulative effects of the saccade duration rounding up if the digitizing rate is below a certain limit.

The participants were aware of the fact that they will re-take the reading tasks. This alertness itself, as well as reading practice, could have lead to more precise fixation landing positions, i.e., less oculomotor errors that are common in reading a contingent text (Nuthmann, Engbert, & Kliegl, 2007). An issue questioned by Nuthmann, Engbert, & Kliegl (2007) is also that of attention during reading under experimental conditions. Repeated experimental situations can mobilize the reader to avoid mind wandering, which is different from mindless reading of one character strings.

12.7 Summary

We measured eye movement parameters in reading and their changes after practise with the aid of two eye trackers. The setups with the participant's head free and stabilised and different precision related to that are often implicitly considered to be equal in terms of the yielded data. The research has revealed that the results of fixation detection are basically comparable. When saccade detection is concerned, one reaches the same conclusions on their size distribution and its changes. However, the more complex analysis that involves saccade dynamics, like the main sequence analysis, invites a further investigation. The outcomes of oral reading research, possibly because of slight head movements during word articulation, hint at possible task-specific detection failures both of saccades and fixations at lower digitizing rates.

13. CONCLUSIONS FOR DEFENCE

1. Athletes assess an unfamiliar sports situation with a smaller number of fixations that are longer, as compared to non-athletes. The result is in accordance with the familiar sports research.

2. Upon repeated exposure to sports situations, the changes in fixations are corresponding in both groups. Athletes change the eye movement strategies between novel or critical situations and less demanding action observation.

3. Gaze holding and gaze shift change independently. Significant differences in one parameter do not imply significant differences in the other.

4. Correct classification responses in a single natural image demonstration start on average after 420 ms. The velocity of the following movements depends on the recognition time.

5. Images that are easier to recognize and classify evoke eye movements with larger velocities.

6. Ultra-rapid classification response as small as 120 ms may be specific to an experimental protocol, with large image sets and alternative choice made.

7. Not only the number of fixations may decrease after reading practice, but so does also the mean duration of fixations. Their duration corresponds to the published values in reading English.

8. In silent reading, the saccade sizes, their distribution and changes are referred similarly by both setups and are close to the values in reading English.

9. The lack of significant correlation in the helmet-mounted eye-tracking device data before and after reading training testifies to the result variability due to measurement technique and warns against *HED* measurements where detecting small changes are relevant.

10. *HED* measurements of eye movements could still be used in reading formatted pages and assessing their layout, for instance, text-books, for the calculated mean duration of fixations by the setups with 240 Hz and 50 Hz data sampling frequency were not significantly different.

14. PUBLICATIONS

14.1 Proceedings

1. **Paeglis, R.**, Bagucka, K., Sjakste, N., Lacis, I. (2006). Maximizing reading: pattern analysis to describe points of gaze. Proc. of SPIE, Vol. 6315, 63150, doi: 10.1117/12.687470.

2. **Paeglis, R.**, Spunde, A., Klavinsh, A., Vilkausha, L., Lacis, I. (2008). Eye Kinematics of Athletes in Non-Familiar Sports Situations. (Alexei Katashev, Yuri Dekhtyar, Janis Spigulis, Eds.), NBC 2008 Proceedings, 20, , Springer, ISBN 978-3-540-69366-6, pp. 146149.

3. **Paeglis, R.**, Kotelnikovs, A., Podniece, A., Lacis, I. (2008). What Conclusions does Rapid Image Classification by Eye Movements Provide for Machine Vision? (Alexei Katashev, Yuri Dekhtyar, Janis Spigulis, Eds.), NBC 2008 Proceedings, 20, Springer, ISBN 978-3-540-69366-6, pp. 299302.

4. **Paeglis, R.**, Jokste, I., Bagucka, K., Lacis, I. (2008). Eye movements during silent and oral reading with stabilised versus free head movement and different eye-trackers. AOMD-6, In Press.

5. **Paeglis, R.**, Gorshanova, I., Bagucka, K., Lacis, I. (2008). Latvian and Russian textbooks: eye movements in reading text formatted in two columns. AOMD-6, In Press.

14.2 Conferences and Reports

1. **Paeglis, R.**, Lacis, I., Sjakste, N. (2005). Speed Matters: Grasping Rapid Vision by Saccadic Eye Movements and Event Related Potentials. Development in Optics and Photonics 2005, p. 5.

2. Lacis, I., **Paeglis, R.**, Bagucka, K. (2006). No average reader: Professional readers employ a different fixational strategy. Perception, 35, p. 80.

3. **Paeglis, R.**, Podniece, A., Pikulins, A., Lacis, I. (2006). Perception, 35, p. 87.

4. **Paeglis, R.**, Bagucka, K., Sjakste, N., Lacis, I. (2006). Acu kustības kā sarežģītu ainu uztveres pētnieciskais instruments. LU 64. zinātniskā konference, pp. 14.-15.

5. Bagucka, K., **Paeglis, R.**, Lacis, I. (2006). Efficiency of eye movements at different reading speeds. Developments in Optics and Communications 2006, pp. 13.-15.

6. **Paeglis, R.**, Bagucka, K., Goršanova, I., Jokste, I., Lācis, I. (2007). Mācību literatūras lasāmība: acu kustību pieraksts. International Scientific Conference "Didactics of Science Today and Tomorrow", p. 26.

7. Vilkauša, L., **Paeglis, R.**, Birznieks, I., Lācis, I. (2007). Skata trajektorija, novērojot sarežģītas ķermeņa kustības. International Scientific Conference "Didactics of Science Today and Tomorrow", p. 37.

8. Kotelnikov, A., **Paeglis, R.**, Lacis, I. (2007). Billiard Simulator as Stimulus in Infra-red Eye Tracking. Developments in Optics and Communications 2007, p. 5.

9. Gorshanova, I., **Paeglis, R.**, Lacis, I. (2007) Eye Movement Parameters of Bilingual People in Reading Latvian and Russian. Developments in Optics and Communications 2007, p. 6.

10. **Paeglis, R.** (2007). Mācību grāmatu lasāmības matemātika (Mathematics of text-book readability), Rīgas dome, Izglītības, jaunatnes un sporta departaments (Riga City Council).

11. **Paeglis, R.**, Jokste, I., Goršanova, I., & Lācis, I. (2007). Valsts izglītības standartiem atbilstošas mācību literatūras veidošana un izvērtēšana. LR IZM Izglītības satura un eksaminācijas centrs. 3. un 4. janvārī. (Latvian Ministry of Education and Science.)

12. **Paeglis, R.**, Jokste, I., Goršanova, I., & Lācis, I. (2007). Kas ir acu kustību videopieraksts? Ko tas dod Apgāda veidoto mācību grāmatu satura uztveramības pilnveidei? (What is video-based eye-tracking? How it may help to improve published text-books?) Apgāds Zvaigzne ABC (Publishing house Zvaigzne ABC).

13. **Paeglis, R.**, Jokste, I., Goršanova, I., & Lācis, I. (2007). Valsts izglītības standartiem atbilstošas mācību literatūras veidošana un izvērtēšana:

aktualitātes un problēmjautājumi. LR IZM Izglītības satura un eksaminācijas centrs. 18. aprīlī. (Latvian Ministry of Education and Science.)

14. **Paeglis, R.** (2007) Vai mācībās un sportā mēs skatāmies līdzīgi? Zinātnes kafejnīca 12. septembrī (Do we look similarly in studying and doing sports? Science Fair).

15. Lācis, I., **Paeglis, R.**, & Vilkauša, L. (2008). Redzes stimuli un acu kustības. LU 66. zinātniskā konference.

16. **Paeglis, R.** (2008). Valsts vispārējās izglītības standartiem atbilstošas mācību literatūras veidošana un vērtēšana. LR IZM Izglītības satura un eksaminācijas centrs (programmas kods: A-9014320040). 26. martā. (Latvian Ministry of Education and Science.)

17. **Paeglis, R.** (2008). Mācību grāmatu lasāmība. Jaunāko pētījumu atziņas. (Readability of text-book. Recent developments.) Apgāds Zvaigzne ABC (Publishing house Zvaigzne ABC).

18. **Paeglis, R.**, Gorshanova, I., Bagucka, K., & Lacis, I. (2008). Formatting of Pages Needs to be Considered in the Eye Movement Research of Reading. Developments in Optics and Communications 2008, pp. 6-7.

19. **Paeglis, R.**, Kotelnikovs, A., Podniece, A., & Lacis, I. (2008). What Conclusions does Rapid Image Classification by Eye Movements Provide for Machine Vision? OSA Latvian Student Chapter Conference, June 15th, Ratnieki, Latvia.

ACKNOWLEDGEMENTS

Research has been supported by the European Social Fund.

The author has been motivated by participating in the University of Latvia SPIE Student Chapter and the OSA Latvian Student Chapter, as well as stimulated by joining the Latvian Young Scientists' Association (LJZA).

The author thanks karate trainer Žanna Vasiļjeva (4th Dan) and dance instructor Ivars Bācis.

REFERENCES

Amano, S., Kezuka, E., & Yamamoto, A. (2004). Infant shifting attention from an adult's face to an adult's hand: A precursor of joint attention. Infant Behaviour & Development, 27, pp. 64-80.

Ashby, J., Rayner, K., & Clifton, C., Jr. (2005) Eye movements of highly skilledand average readers: Differential effects of frequency and predictability. The Quarterly Journal of Experimental Psychology, 58A (6), 1065-1086.

Babu, R. J., Lillakas, L., & Irving, E. (2005). Dynamics of Saccadic Adaptation: Differences Between Athletes and Nonathletes. Optometry and Vision Science, 82 (12), pp. 1060-1065.

Bagucka, K. (2006). Efficiency of eye movements at different reading speeds (Acu kustību efektivitāte dažādiem lasīšanas ātrumiem), University of Latvia: Bachelor Thesis (supervisor Paeglis, R.).

Blythe, H., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., Findlay, J. M., & Rayner, K. (2006) The binocular coordination of eye movements during reading in children and adults. Vision Research, 46, pp. 3898-3908.

Bovet, D., Vauclair, J. (2000). Picture recognition n animals and humans, Behavioural Brain Research, 109, pp. 143-163.

Brouwer, A., Brenner, E., & Smeets, J. B. J. (2002). Perception of acceleration with short presentation times: Can acceleration be used in interception? Perception & Psychophysics, 64, pp. 1160-1168.

Brouwer, A.-M., Lpez-Moliner, J., Brenner, E., & Smeets, J. B. J. (2006). Determining whether a ball will land behind or in front of you: Not just a combination of expansion and angular velocity. Vision Research, 46, pp 382-391.

Bucci, M. P., & Kapoula, Z. (2006). Binocular coordination of saccades in 7 years old children in single word reading and target fixation. Vision Research, 46, pp. 457-466.

Byrne, B., Samuelsson, S., Wads-Worth, S., Hulslander, J., Corley, R., Defries, J. C., Quain, P., Willcutt, E. G., & Olson R. K. (2007). Longitudinal twin study of early literacy development: Preschool through Grade 1. Reading and Writing, 20, pp. 77-102.

Calef, T., Pieper, M., & Coffy, B. (1999). Comparisons of eye movements before and after a speed-reading course. Journal of the American Optometric Association, 70 (3), pp. 171-181.

Collewijn, H. (1998). Eye movement recording. In: Vision Research. A Practical Guide to Laboratory Methods. Eds. Carpenter, R. H. S. & Robson, J. G.

Oxford, pp. 245-285.

Ditterich, J., Eggert, T., & Straube, A. (2000) Relation Between the Metrics of the Presaccadic Attention Shift and of the Saccade Before and After Saccadic Adaptation, Journal of Neurophysiology, 84, pp. 1809-1813.

Drieghe, D., Brysbaert, M., & Desment, T. (2005). Parafoveal-on-foveal effects on eye movements in text reading: Does extra space make a difference? Vision Research, 45, pp. 1693-1706.

Drieghe, D., Rayner, K., & Pollatsek, A. (2005). Eye Movements and Word Skipping During Reading Revisited. Journal of Experimental Psychology: Human Perception and Performance, 31 (5), pp. 945-969.

Dyson, M. C., & Haselgrove, M. (2001). The influence of reading speed and line length on the effectiveness of reading from screen, International Journal of Human-Computer Studies, 54, pp. 585-612.

Encyclopaedia Britannica, Cognition. URL: http://search.eb.com/eb/article-9024661, Accessed on 17.03.2008.

Engbert, R., & Kliegel, R. (2004a). Microsaccades Keep the Eyes' Balance During Fixation. Psychological Science, 15 (6), pp. 431-435.

Engbert, R., Kliegel, R. (2004b). Complexity of eye movements in reading. International Journal of Bifurcation and Chaos, 14 (2), pp. 493-503.

Epelboim, J. (1998) Gaze and retinal-image-stability in two kinds of sequential looking tasks. Vision Research, 38, pp. 3773-3784.

Evans, K. K., & Treisman, A. (2005). Perception of Objects in Natural Scenes Is It Really Attention Free? Journal of Experimental Psychology, Human Perception and Performance, 31 (6), pp. 1476-1492.

Fadiga, L., Fogassi, L., Pavesi, G., & Rizzolatti, G. (1995). Journal of Neurophysiology, 73, pp. 2608-2611.

Falck-Ytter, T., Gredebck, G., & von Hofsten, C. (2006). Infants predict other people action goals. Nature Neuroscience, 9 (7), pp. 878-879.

Flanagan, J. R., & Johansson, R. S. (2003). Action plans used in action observation. Nature, 424, pp. 769-761.

Gitelman, D. R. (2002). ILAB: A program for postexperimental eye movement analysis. Behavior Research Methods, Instruments, & Computers, 34 (4), pp. 605-612.

Goldberger, J., Gordon, Sh., Greenspan, H. (2006). Unsupervised image-set clustering using an information theoretic framework, IEEE Trans. on Image Processing, 15(2), pp. 449-458.

Goossens, H. H., & Van Opstal, A. J. (1997) Human eye-head coordination in two dimensions under different sensorimotor conditioons. Experimental Brain Research, 114, pp. 542-560.

Goršanova, I. (2007). Characteristic eye movement parameters in reading texts in two languages (Raksturīgie acu kustību parametri, lasot tekstus divās valodās), University of Latvia: Bachelor Thesis (supervisor Paeglis, R.).

Greenspan, H., Goldberger, J., & Eshet, I. (2001a). Mixture model for face

- color modeling and segmentation. Pattern Recognitions Letters, 22, pp. 1525-1536.

Greenspan, H., Goldberger, J., & Ridel, L. (2001b). A continuous probabilistic framework for image representation and matching. Journal of Computer Vision an Image Understanding, Dec., 84, pp. 384-406.

Harwood, M.R., Mezey, L.E., & Harris, C.M. (1999). The Spectral Main Sequence of Human Saccades, Journal of Neuroscience, 19 (20), October 15, pp. 9098-9106.

Hassan, S. E., Hicks, J. C., Lei, H., & Turano, K. A. (2007). What is the minimum field of view required for efficient navigation? Vision Research, 47, pp. 2115-2123.

Hayes, A. E., Paul, M. A., Beuger, B., & Tipper, S. P. (2007). Self produced and observed actions influence emotion: the roles of action fluency and eye gaze. Psychological Research, DOI: 10.1007/s00426-007-0125-3.

Herst, A. N., Epelboim, J., & Steinman, R. M. (2001) Temporal coordination of the human head and eye during a natural sequential tapping task. Vision Research, 41, pp. 3307-3319.

Jacobson, C., & Lundberg, I. (2000). Early prediction of individual growth in reading. Reading and Writing, 13, pp. 273-296.

Jafarzadehpur, E., Aazami, N., & Bolouri, B. (2007). Comparison of saccadic eye movements and facility of ocular accommodation in female volleyball players and non-players. Scandinavian Journal of Medicine & Science in Sports, 17, pp. 186-190.

Johansson R. S., Birznieks I. (2004) First spikes in ensembles of human tactile afferents code complex spatial fingertip events, Nature Neurosci., 7 (2), February, pp. 170-177.

Johansson, R. S., Westling, G., Bckstrm, A., & Flanagan, J. R. (2001). Eye-Hand Coordination in Object Manipulation. The Journal of Neuroscience, 21 (17), pp. 6917-6932.

Johnson, J.S., & Olshausen, B.A. (2003). Timecourse of neural signatures of object recognition. Journal of Vision, 2(7), pp. 1-13.

Jokste, I. (2007). Efficiency of reading with free head and fixed head (Lasīšanas efektivitāte brīvas un fiksētas galvas gadījumā), University of Latvia: Bachelor Thesis (supervisor Paeglis, R.).

Kanungo, T., Mount, D. M., Netanyahu, N., Piatko, C., Silverman,R., & Wu, A. Y. (2002). An efficient k-means clustering algorithm: Analysis and implementation. IEEE Transactions on Pattern Analysis and Machine Intelligence, 24, pp. 881-892.

Keysers, C. & Perrett, D.I. (2004). Demystifying social cognitions and mirror neurons A Hebbian circuit. Trends in Cognitive Science 8, pp. 501-507.

Kirchner, H., & Thorpe, S. (2006). Ultra-rapid object detection with saccadic eye movements: Visual processing speed revisited, Vis. Res., 46, pp. 1762-1776.

Koteļņikovs, A. (2007). *Acu kustību videopieraksta priekšrocības un trūkumi*

(Advantages and drawbacks of video-recording in eye-tracking). University of Latvia: Bachelor Thesis, p.25.

Krischer, C. C., & Zangemeister, W. H. (2007). Scanpaths in reading and picture viewing: Computer-assisted optimization of display conditions. Computers in Biology and Medicine, 37 (7), pp. 947-956.

Land, M. F., McLeod, P. (2000). From eye movements to actions: how batsmen hit the ball. Nature neuroscience, 3, pp. 1340-1345.

Laubrock, J., Engbert, R., & Kliegl, R. (2005). Microsaccade dynamics during covert attention. Vis. Res., 45, pp. 721-739.

Lee, C. (1999) Eye and head coordination in reading: roleasof head movement and cognitive control. Vision Research, 39, pp. 3761-3768.

Leff, A. P, Scott, S. K., Rothwel, J. C, & Wise, R. J. S. (2000) The Planning and Guiding of Reading Saccades: a Repetitive Transcranial Magnetic Simulation Study, Cerebral Cortex, 11, pp. 918-923.

Lehmann, T.M., Gld, M.O., Deselaers, T., Keysers, D., Schubert, H., Spitzer, K., Ney, H., & Wein, B.B. (2005). Automatic categorization of medical images for content-based retrieval and data mining, Comp. Med. Imag., 29, pp. 143-155.

Lehtimaki, T. M., & Reilly R. G. (2005) Improving Eye Movement Control Readers. Artificial Intelligence Review, 24, pp. 477-488.

Leigh, R. J., & Kennard, C. (2004) Using saccades as a research tool in the clinical neurosciences. Brain, 127, pp. 460-477.

Lesaux, N. K., & Lipka, O. (2006). Investigating cognitive and linguistic abilities that influence the reading comprehension skills of children from diverse linguistic backgrounds. Reading and Writing, 19, pp. 99-131.

Loetscher, T., Bockisch, C. J., & Brugger, P. (2008). Looking for the answer: the mind's eye in number space. Neuroscience, 151, pp. 725-729.

Lw, A., Bentin, Sh., Rockstroh, B., Silberman, Y., Gomolla, A., Cohen, R., & Elbert, T. (2003). Semantic Categorization in the Human Brain: Spatiotemporal Dynamics Revealed by Magnetoencephalography, Psychoogical Science, 14 (4), July, pp. 367-372 . Mac, M. J.-M., Thorpe, S.J., Fabre-Thorpe, M. (2005). Rapid categorization of achromatic natural scenes: how robust at very low contrasts? European Journal of Neuroscience, 21, pp. 2007-2018.

MacQueen, J. B. (1967). Some Methods for Classification and Analysis of Multivariate Observations, Proceedings of 5th Berkeley Symposium on Mathematical Statistics and Probability, Berkeley: University of California Press, 1, pp. 281-297.

Mann, D. L., Ho, N., Y., De Souza, N. J., Watson, D. R., & Taylor, S. J. (2007). Is optimal vision required for successful execution of an interceptive task? Human Movement Science, 26, pp. 343-356.

Martell, S. G., & Vickers, J. N. (2004). Gaze characteristics of elite and near-elite athletes in ice hockey defensive tactics. Human Movement Science, 22, pp. 689-712.

Martin, D.R., Fowlkes, C.C., & Malik, J. (2004). Learning to Detect Natural Image Boundaries Using Local Brightness, Color and Texture Cues. IEEE

Transactions on Pattern Analysis and Machine Intelligence 26 (5): 530-549.

McBeath, M. K., Shaffer, D. M., & Kaiser, M. K. (1995). How baseball outfielders determine where to run to catch fly balls. Science, 268, pp. 569-573.

McDonald, S. A. (2006) Parafoveal preview benefit in reading is only obtained from saccade goal. Vision Research, 46, pp. 4416-4424.

McLeod, P., & Dienes, Z. (1996). Do fielders know where to go to catch the ball or only how to get there? Journal of Experimental Psychology: Human Perception and Performance. 22, pp. 531-543.

McLeod, P., Reed, N., & Dienes, Z. (2003). How fielders arrive in time to catch the ball. Nature, 426, pp. 244-245.

Miller, I., & Miller, M. (2004). John E. Freund's Mathematical Statistics with Applications (7th Ed.), New Jersey: Pearson Prentice Hall.

Mosimann, U.P., Felblinger, J., Colloby, S.J., & Mri, R.M. (2004). Verbal instructions and top-down saccade control, Exp. Brain Res., 159, pp. 263-267.

Müri, R.M., Heid, O., Nirkko, A.C., Ozdoba, C., Felblinger, J., Schroth, G., & Hess, C.W. (1998). Functional organisation of saccades and antisaccades in the frontal lobe in humans: a study with echo planar functional magnetic resonance imaging. J. Neurol. Neurosurg. Psychiatry, 65, pp. 374-377.

Nuthmann, A., Engbert, R., & Kliegl, R. (2007) The IOVP effect in mindless reading: Experiment and modelling. Vision Research, 47, pp. 990-1002.

Ober, J. (1994). Infra-Red Reflection Technique. In: Eye Movements in Reading. Eds. Ygge, J. & Lennerstrand, G. Elsevier Science, pp. 9-20.

Oommen, B. S., Smith, R. M., Stahl, J. S. (2004) The influence of future gaze orientation upon eye-head coupling during saccades. Experimental Brain Research, 155, pp. 9-18.

Oudejans, R. R. D., Michaels, C. F., & Bakker, F. C. (2002). The effects of baseball experience on movement initiation in catching fly balls. Journal of Sports Sciences, 15, pp. 587-595.

Panchuk, D., & Vickers, J. N., (2006). Gaze behaviours of goaltenders under spatial-temporal constraints. Human Movement Science, 25, pp. 733-752.

Pelz, J., Hayhoe, M., & Loeber, R. (2001) The coordination of eye, head, and hand movements in a natural task. Experimental Brain Research, 139, pp. 266-277.

Peters, R. J., Gabbiani, F., & Koch, C. (2003). Human visual object categorization can be described by models with low memory capacity. Vision Research, 43, pp. 2265-2280.

Pierno, A. C., Becchio, C., Wall, M. B., Smith, A. T., Turella, L., & Castiello, U. (2006). When gaze turns into grasp. Journal of Cognitive Neuroscience, 18 (12), pp. 2130-2137.

Podniece, A. (2006). Eye velocities in complex image recognition tasks (Acu kustību ātrumi sarežģītu attēlu atpazīšanas uzdevumos), University of Latvia: Bachelor Thesis (supervisor Paeglis, R.).

Proudlock, F. A., Shekhar, H., & Gottlob, I. (2003) Coordination of Eye and

Head Movements during Reading, Investigative Ophthalmology & Visual Science, 44 (7), pp. 2991-2998.

Radach, R., & Kennedy, A. (2004).Theoretical perspectives on eye movements in reading: Past contraversies, current issues, and an agenda for future research. European Journal of Cognitive Psychology, 16, pp. 3-26.

Rayner, K. (1997). Understanding Eye Movements in Reading. Scientific Studies of Reading, 1 (4), pp. 317-339.

Rayner, K. (1998). Eye Movements in Reading and Information Processing: 20 Years of Research. Psychological Bulletin, 124 (3), pp. 372-422.

Rayner, K., & Juhaz B. Eye movements in reading: Old questions and new directions. European Journal of Cognitive Psychology, 16, pp. 340-352.

Rayner, K., & Pollatsek, A. (1981) Eye movement control during reading: evidence for direct control. Quarterly Journal of Experimental Psychology A, 33 (Pt 4), pp. 351-373.

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, pp. 2714-2726.

Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. Vision Research, 46, pp. 310-323.

Reichle, E. D., Rayner K., & Pollatsek A. (1999). Eye movement control in reading: accounting for initial fixation locations and refixations within the E-Z Reader model. Vision Research, 39, pp. 4403-4411.

Riesenhuber M, Poggio T (2000) Models of object recognition, Nature Neurosci. Supplement, 3, November, pp. 1199-1204.

Rousselet, G.A., Thorpe, S.J., & Fabre-Thorpe, M. (2004). Processing of one, two our four natural scenes in humans: the limits of paralelism, Vis. Res., 44, pp. 877-894.

Sabatini, J. P., Venezky, R. L., Kharik, P., & Jain, R. (1995). Cognitive Reading Assessment for Low Literate Adults: An Analytic Review and New Framework. URL: www.literacyonline.org/products/ncal/pdf/TR0001.pdf, Accessed on 01.02.2007.

Schnitzer, B. S., & Kowler, E. (2006). Eye movements during multiple readings of the same text. Vision Research, 46, pp. 1611-1632.

Scott, P., Johnson, S. P., Amso, D., & Slemmer J. A. (2003) Development of object concepts in infancy: Evidence for early learning in an eye-tracking paradigm, Proceedings of the National Academy of Sciences, 100 (18), pp. 10568-10573.

Seo H., & Lee, C. (2002) Head-free reading of horizontally and vertically arranged texts. Vision Research, 42, pp. 1325-1337.

Shi J, Malik J (2000) Normalized Cuts and Image Segmentation. IEEE Transactions on Pattern Analysis aand Machine Intelligence 22 (8), pp. 888-905.

Smit, A. C., & Van Gisbergen, J. A. M. (1987). A parametric analysis of human saccades in different experimental paradigms. Vision Research, 27, pp.

1745-1762.

Snyder, L. H., Calton, J. L., Dickinson, A. R., & Lawrence, B. M. (2002). Eye-Hand Coordination: Saccades Are Faster When Accompanied by a Coordinated Arm Movement. Journal of Neurophysiology, 87, pp. 2279-2286.

Svik, N., Oddvar, A., & Samuelstuen, M. (2000) Eye-movement parameters and reading speed. Reading and Writing, 13, pp. 237-255.

Stahl, J. S. (1999) Amplitude of human head movements associated with horizontal saccades. Experimental Brain Research, 126, pp. 41-54.

Stahl, J. S. (2001) Eye-head coordination and the variation of eye-movement accuracy with orbital eccentrity. Experimental Brain Research, 136, pp. 200-210.

Starr, M. S., & Rayner, K. (2004). Eye movements during reading: some current controversies. Trends in Cognitive Sciences, 5 (4), pp. 156-163.

Thorpe, S., Fize, D., & Marlot, C. (1996). Speed of processing in the human visual system. Nature, 381, pp. 520-522.

Van der Geest, J. N., & Frens M. A (2002) Recording eye movements with videooculography and scleral search coils: a direct comparison of two methods. Journal of Neuroscience Methods, 114, pp. 185-195.

van der Linde, I., Rajashaker, U., Cormack, L.K., & Bovik, A.C. (2005). A study of human recognition rates for foveola-sized image patches selected from initial and final fixations on calibrated natural images, SPIE Human Vision & Electronic Imaging X, 5666, March, pp. 27-38.

Van Rullen, R., Gautrais, J., Delorme, A., & Thorpe, S. (1998). Face processing using one spike per neurone, BioSystems, 48, pp. 229-239.

VanRullen, R., Guyonneau, R., & Thorpe, S.J. (2005). Spike times make sense, TRENDS in Neuroscience, 28 (1), pp. 1-4.

VanRullen, R., Koch, Ch., Perona, P. (2002). Rapid natural scene categorization in the near absence of attention, PNAS, 99, pp. 9596-9601.

VanRullen, R., & Thorpe, S.J. (2001). Is it a bird? Is it a plane? Ultra - rapid visual categorization of natural and artifactual objects. Perception, 30, pp. 655-668.

Vickers, J. N. (1992). Gaze control in putting. Perception, 21, pp. 117-132.

Vickers, J. N. (1996). Visual control when aiming at a far target. Journal of Experimental Psychology: Human Perception and Performance, 22, pp. 342-354.

Vickers, J. N. (2006). Gaze of Olympic speedskaters skating aat full speed on a regulation oval: perception-action coupling in a dynamic performance environment. Cognitive Processing, pp. 102-105.

Vilkauša, L. (2007). Gaze shift and fixations in observing complex body movements(Skata pārnese un fiksācijas, novērojot sarežģītas ķermeņa kustības). University of Latvia: Bachelor Thesis (supervisor Paeglis, R.).

Vitu, F., Lancelin, D., Jean, A., & Farioli, F. (2006) Influence of foveal distractors on saccadic eye movements: A dead zone for global effect. Vision Research, 46, pp. 4684-4708.

Wang, X., Zhang, M., Cohen, I. S., & Goldberg, M. E. (2007) The proprioreceptive representation of eye position in monkey primary somatosensory cortex. Nature Neuroscience,10 (5), pp. 640-646.

Williams, A. M., & Grant, A. (1999). Training perceptual skill in sport. International Journal of Sport Psychology, 30, pp. 194-220.

Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1994). Visual search strategies in experienced and inexperienced soccer players. Research Quarterly for Exercise and Sport, 65, pp. 127-135. h