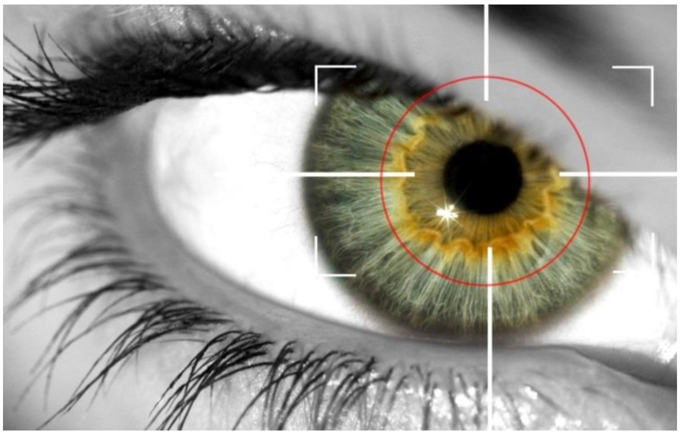
UNIVERSITY OF CRETE

MSc **“OPTICS AND VISION”**

MSc dissertation:

“Effect of optical factors in eye movements during reading”



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Heraklion, 2014

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This study was submitted as part of the obligations for the conferment of the Master in Science certification of the MSc Program “Optics and Vision” and was presented at the three-member committee constituted by:

1) Tsilimbaris M., Associate Professor
2) Pallikaris I. G., Professor
3) Kymionis G., Assistant Professor

Heraklion, 2014

ABSTRACT

Purpose

The purpose of this study was to investigate the effect of contrast, print size, and luminance as well as the learning effect, on eye movement behavior when reading. The impact on the distribution of fixation duration was investigated using eye-movement recording and ex-Gaussian analysis.

Methods

A group of 23 persons (age; 39 -45 years) participated in the study. Two experiments were conducted. The first experiment investigated the effect of contrast and print size on reading as well as the learning effect. The second experiment evaluated the effects of luminance on reading. Two types of reading cards were used in the study; the Greek versions of the Colenbrander Reading Cards (both normal and mixed contrast) and a paragraph of fixed print size, the “long text”. The eye movement recording was performed at a distance of 40 cm using the eye tracker EyeLink II by SR Research Ltd.

Results

No statistical significant difference was found in median fixation duration between the first and the second time of reading the text at all print sizes. Mean number of fixations per sentence was found to decrease by about one fixation in the second time of reading in all print sizes. Median fixation duration was significantly affected by print size when letters were smaller than 0.4 logMAR and the effect was more pronounced as letters reduced further in size. Contrast influenced fixation duration in a statistically significant matter when letters were smaller than 0.4 logMAR ($p=0.023$). In contrary, luminance had a significant effect on median fixation duration at all letter sizes (at 0.9 logMAR, $p=0.014$). The change on fixation duration in low luminance is getting more evident in 0.5 logMAR print size and for smaller letters. Using the ex-Gaussian analysis and a print size of 0.4 logMAR we found that the

fixation duration distribution was identical between the first and the second time of reading the same text ($p=0.181$; Kolmogorov-Smirnov test). On the contrary, the contrast had a significant effect on the distribution ($p=0.009$; Kolmogorov-Smirnov test), which means that low contrast distribution is different and with smaller values that the high contrast distribution ($p=0.006$; Kolmogorov-Smirnov test).

Conclusions

The ex-Gaussian analysis was proved to be a very precious tool for understanding eye movement behavior when reading. We found that optical factors, like luminance and contrast affect in the fixation duration distribution. Ex-Gaussian parameters give a quantitative view of great importance.

To our opinion, the combination of standardized long texts with a proper analyzing method, like the one that we followed, will lead to a much better understanding on the effect of several factors on reading. Moreover, further studies can work on distinguishing the optical effects (contrast, luminance, print size, aberrations etc.) from cognitive (dyslexia, understanding problems etc.), psychological and neurological factors (anxiety, autism, etc.)

ΠΕΡΙΛΗΨΗ

Σκοπός

Σκοπός αυτής της εργασίας ήταν να μελετήσει την επίδραση του contrast, του μεγέθους των γραμμάτων και της φωτεινότητας, καθώς και το αποτέλεσμα της εκμάθησης, στις οφθαλμικές κινήσεις κατά την ανάγνωση. Ερευνήθηκε η επίδραση στην κατανομή της διάρκειας των σημείων προσήλωσης καταγράφοντας τις οφθαλμικές κινήσεις και χρησιμοποιώντας την ανάλυση ex-Gaussian.

Μέθοδοι

Στην έρευνα συμμετείχε μια ομάδα 23 ατόμων ηλικίας 39-45 χρόνων. Πραγματοποιήθηκαν δύο πειράματα. Το πρώτο πείραμα μελέτησε την επίδραση του contrast και του μεγέθους των γραμμάτων καθώς και το αποτέλεσμα της εκμάθησης. Το δεύτερο πείραμα μελέτησε την επίδραση της φωτεινότητας στην ανάγνωση. Στη μελέτη χρησιμοποιήθηκαν δύο τύποι καρτών ανάγνωσης: η ελληνική έκδοση των καρτών ανάγνωσης Colenbrander (με κανονικό και με μικτό contrast) και μια μεγάλη παράγραφος με συγκεκριμένο μέγεθος γραμμάτων. Η καταγραφή των οφθαλμικών κινήσεων έγινε σε απόσταση 40 cm με τον ανιχνευτή οφθαλμικών κινήσεων EyeLink II από την SR Research Ltd.

Αποτελέσματα

Δε βρέθηκε στατιστικά σημαντική διαφορά στη διάμεσο της διάρκειας των σημείων προσήλωσης μεταξύ της δεύτερης και της πρώτης φοράς ανάγνωσης σε όλα τα μεγέθη των γραμμάτων. Ο μέσος αριθμός των σημείων προσήλωσης που γίνονται σε κάθε πρόταση βρέθηκε να μειώνεται κατά ένα περίπου σημείο προσήλωσης την δεύτερη φορά ανάγνωσης σε όλα τα μεγέθη γραμμάτων. Η διαφορά στη διάμεσο της διάρκεια των σημείων προσήλωσης είναι σημαντική μεταξύ μεγέθους 0,4 και 0,3 logMAR ($p=0.000$) και γίνεται πιο έντονη σε μικρότερα γράμματα. Η επίδραση του contrast στη διάρκεια των σημείων προσήλωσης είναι σημαντική στα 0,4 logMAR ($p=0.023$) και για μικρότερα γράμματα. Η επίδραση της φωτεινότητας είναι σημαντική από τα 0,9 logMAR ($p=0.014$). Η επίδραση του μεγέθους των γραμμάτων

είναι σημαντική από τα 0,5 logMAR. Χρησιμοποιώντας την ανάλυση ex-Gaussian, δείξαμε ότι η κατανομή της διάρκειας των σημείων προσήλωσης είναι παρόμοια στις δύο φορές ανάγνωσης. Το Kolmogorov-Smirnov test έδωσε p-value=0.181. Αντιθέτως, σημαντική ήταν η επίδραση του contrast στην κατανομή της διάρκειας των σημείων προσήλωσης (Kolmogorov-Smirnov test; p=0.009), το οποίο σημαίνει ότι η κατανομή για το χαμηλό contrast είναι σημαντικά διαφορετική απ' αυτήν του υψηλού contrast.

Συμπεράσματα

Η ανάλυση ex-Gaussian αποδείχτηκε πολύ χρήσιμο εργαλείο για την κατανόηση της οφθαλμοκίνησης κατά την ανάγνωση προσδίδοντας μια ποσοτική ανάλυση της κατανομής. Δείξαμε ότι οπτικοί παράγοντες, όπως η φωτεινότητα και το contrast επηρεάζουν την κατανομή της διάρκειας των σημείων προσήλωσης.

Πιστεύουμε ότι ο συνδυασμός κάποιων τυποποιημένων μεγάλων κειμένων και μιας κατάλληλης μεθόδου ανάλυσης των αποτελεσμάτων, όπως αυτή που ακολουθήσαμε, θα μας βοηθήσει σε μία βαθύτερη κατανόηση του πώς συγκεκριμένοι παράγοντες επηρεάζουν την ανάγνωση. Επόμενες έρευνες θα μπορούσαν να μελετήσουν το διαχωρισμό οπτικών παραγόντων (contrast, φωτεινότητα, μέγεθος γραμμάτων, οπτικές εκτροπές κλπ) από γνωσιακούς (δυσλεξία, προβλήματα κατανόησης κλπ) και ψυχολογικούς/νευρολογικούς (άγχος, αυτισμός κλπ).

Contents

PART 1. INTRODUCTION

1. Visual Processing And Visual Performance

Visual perception begins in retina. The rays of light are focused by the optic elements of the eye to the outer layers of the retina. There, light is converted to electrical signal which is then sent through the optic nerve to higher centers of the brain for further processing. Careful examination of the retina and the visual pathways is useful for understanding how the light is converted to electrical signal and how it transmits to the brain.

1.1 The Retina – Early Visual Processing

The retina lies at the posterior pole of the eye and is the photosensitive layer where the rays of light are focused on and so the conversion of light energy to electrical signal takes part. As we can see in Fig.1, light is focused by the cornea and the lens, it passes through the vitreous humor and then it reaches retina.

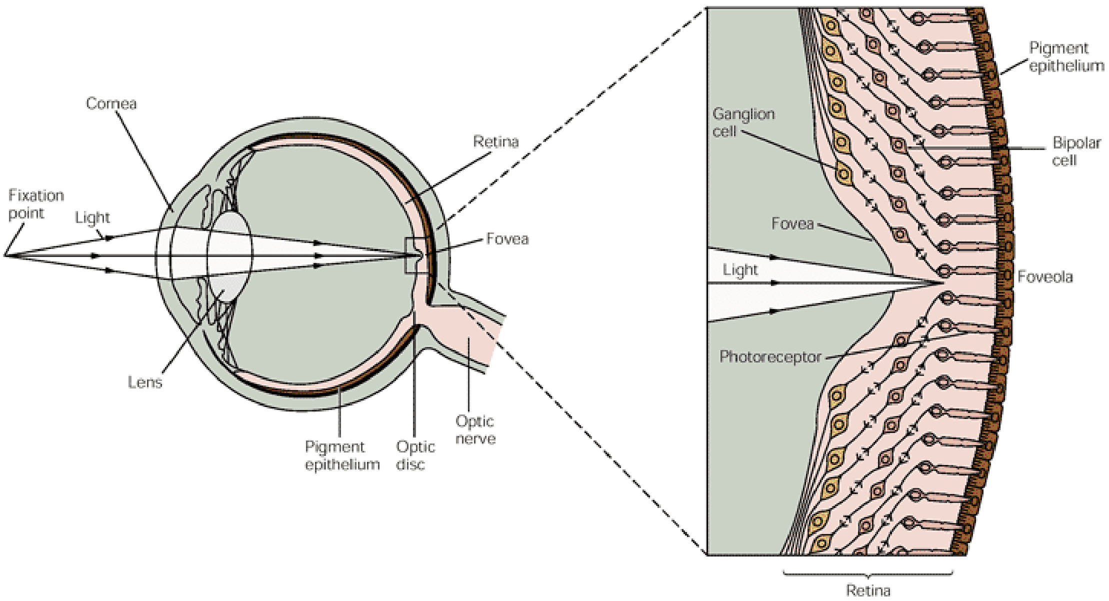

Fig.1: *The path of the light through the cornea and the vitreous humor until retina is shown at left. Detail of retina at the fovea is shown on the right.*

The retina has three distinctive areas (Fig. 2):

- The macular lutea which is an area of about 5mm (~20° of visual angle),

- The fovea, at the center of macular lutea with a diameter of about 1.5mm (~5°) and the foveola at the center of the fovea (~1°). The foveola is the thinnest part of the retina. It approximates to the visual axis and is responsible for high resolution vision because cones are highly densed at this point.

- The optic disk which is about 15° of visual angle nasally from foveola.

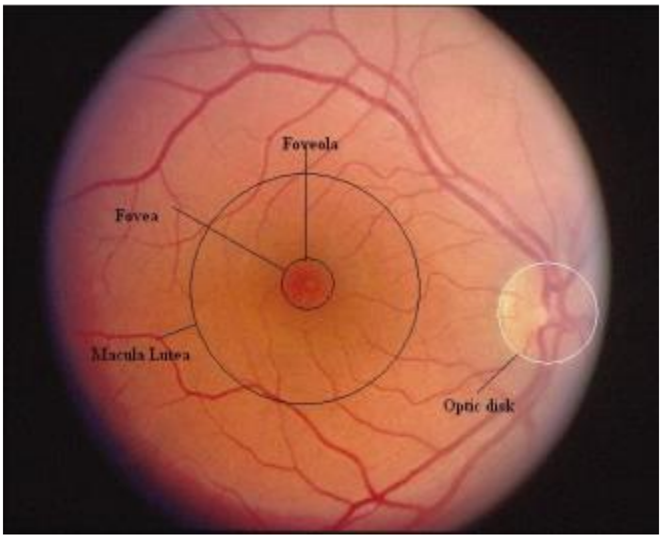

Fig. 2: *Retina's distinctive areas. The macular lutea, the fovea and foveola and the optic disc.*

The retina consists of five different neuron cells (Fig.3): The photoreceptors, the horizontal, the bipolar, the amacrine and the ganglion cells. Every kind of these cells is responsible for a different function.

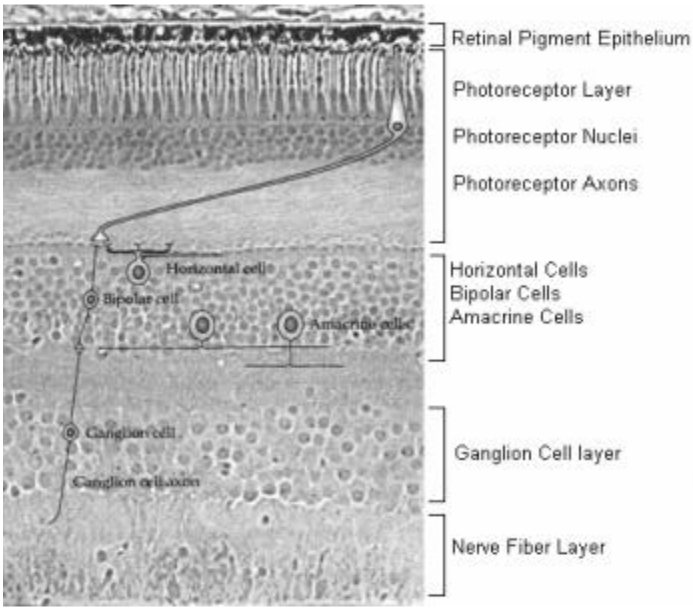

Fig. 3: *Retina's layers and the neuron cells.*

The photoreceptors are responsible for the conversion of light energy to potential difference. There are two kinds of photoreceptors, rods and cones. Cones are responsible for day vision and color processing, while rods for night vision. Cones provide higher acuity and better resolution than rods. Rods are very sensitive to light and therefore they function well in dim light, when cones cannot be excited. Although rods are more sensitive to light than cones, they are "achromatic".

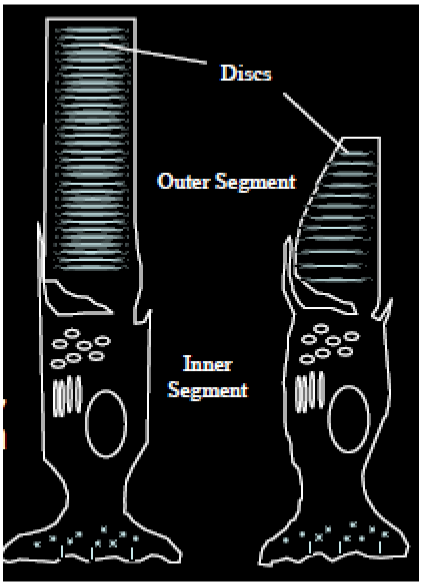

Fig. 4: *Rods' and cones' structures.*

There are three types of cones which show absorption of different wavelengths, i.e. the S-cones which are most sensitive at 420nm, the M-cones sensitive at 534nm and the L-cones which are most sensitive at 564nm (Fig. 5).

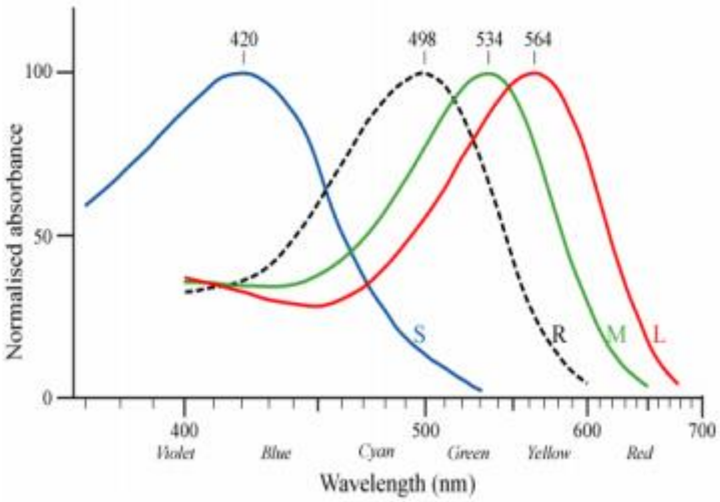

Fig. 5: *Absorption of the three kinds of cones in different wavelengths*

The cone density is higher at foveola and decreases to the periphery. On the contrary, the rod density is higher at about 20° from the center of macula lutea. Rods are absent from the foveola and only cones are present in this area. This is why the foveola has the highest resolution and sensitivity. In addition, at the center of the fovea, each cone is connected to a single horizontal cell but at the periphery more than one cones and rods converge to a single cell.

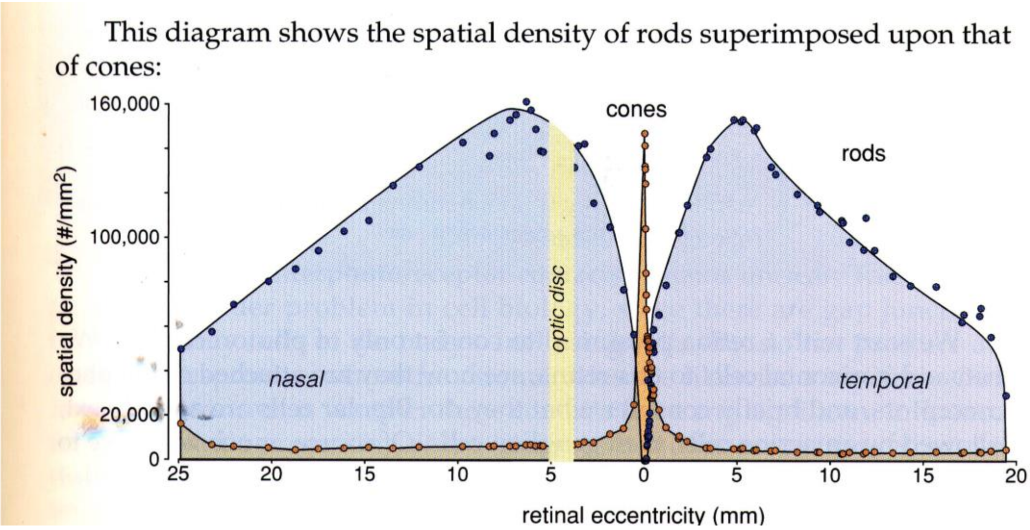

Fig. 6: *Cone and Rod density in retina.*

1.2 Later Visual Processing

The electrical signal that the photoreceptors produce is transmitted by the retinal ganglion cells. The axons of the retinal ganglion cells stream toward the optic disc and together they form the optic nerve. The optic nerve from each eye project to the optic chiasm and afterwards it forms the bilateral optic tracts that project to three major subcortical targets: 90% of the axons project to the lateral geniculate nucleus, while the rest of the axons project to the superior colliculus and the prerectum. The lateral geniculate nucleus (LGN) is the main terminus for input to the visual cortex, the superior colliculus controls saccadic eye movements and the prerectum of the midbrain controls pupillary reflexes. The projections mentioned, are displayed in fig. 7.

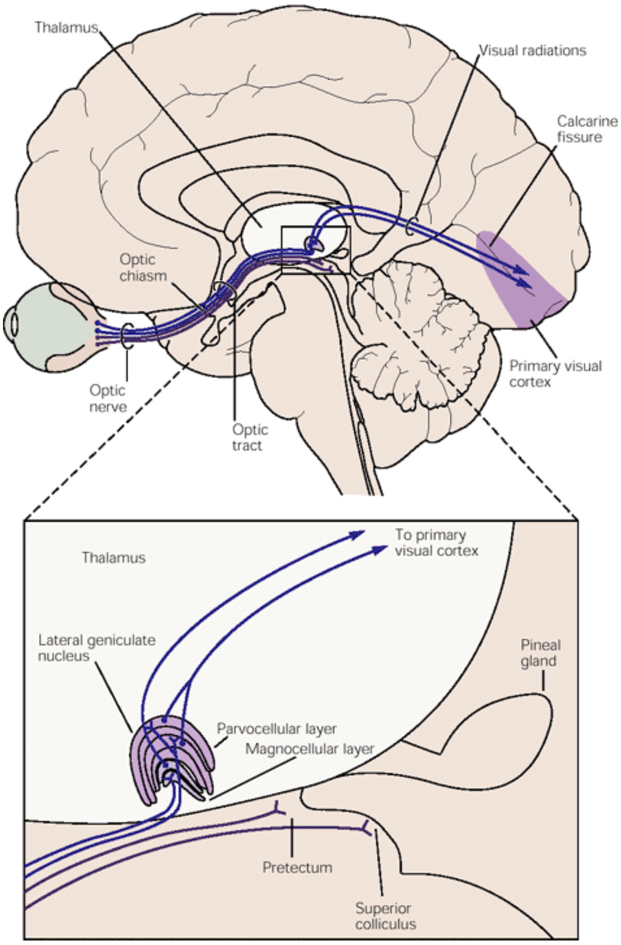

Fig. 7: *A simplified diagram of the projections from the retina to the lateral geniculate nucleus, prerectum and superior colliculus.*

The information for each ganglion cell comes from the same photoreceptors in a specific area of the retina. This area constitutes the receptive field of the ganglion cell. The receptive field of each cell differs in size in different retina areas. Close to the fovea the receptive fields are smaller than in the periphery.

There are three kinds of retinal ganglion cells. M cells are very few (about 10%), they are in the retinal periphery and they have big receptive field. As a result, they have low spatial frequency, but high contrast sensitivity. The P cells are about 10 times more than the M cells, they are mainly in central retinal area and are responsible for the process of color vision, as they receive information by L and M cones. Their receptive fields are small and as a result they have high spatial frequency. Finally, there are the konio cells, which are responsible for the color perception of blue-yellow, as they receive information by the S cones.

The three kinds of cells transfer different information and they transmit it to different layers of the LGN. The LGN contains six layers of cell bodies separated by intralaminar layers of axons and dendrites. The layers are numbered from 1 to 6, ventral to dorsal. The two most ventral layers of the nucleus contain relatively large cells and are known as the magnocellular layers; their main retinal input is from M ganglion cells. The four dorsal layers are known as parvocellular layers and receive input from P ganglion cells. Between the parvocellular layers there are some very thin layers, the konio layers (fig. 8).

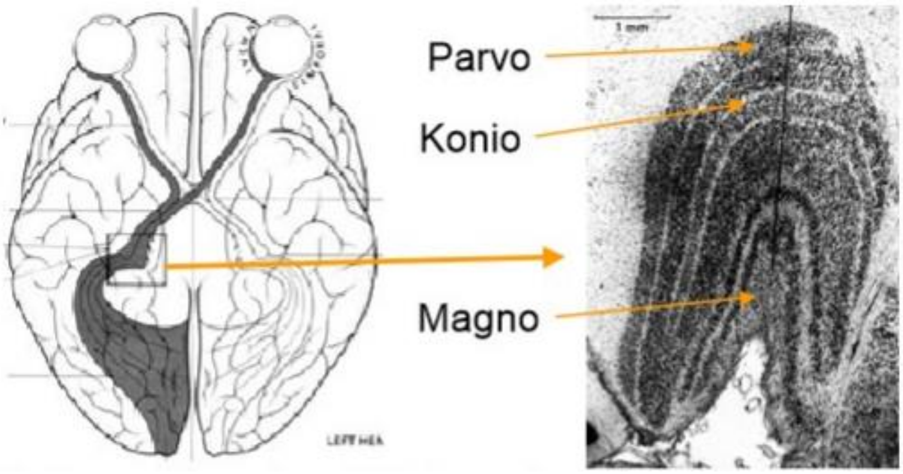

Fig. 9: *On the left, LGN and its layers. Fibers from left area of the retina go to the right LGN. The 2 lowest layers of the LGN are the magnocellular, the layers 3 to 6 are the parvocellular and between the parvo, there are the koniocellular layers.*

The three different layers project to three different layers of the primary visual cortex (V1). M pathway projects to 4Ca layer of the V1, the P pathway projects to 4Cb layer and koniocellular pathway projects to layer 3 of the V1 (fig. 10). After V1 the pathways continue to V2 and other parts of the extrastriate cortex for higher process.

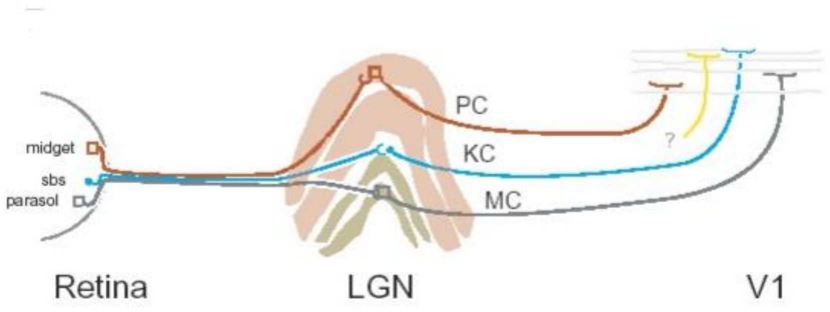

Fig. 10: *Connections between retina, LGN and V1. On the left, schematic display of the retina, in the center schematic display of the layers of the LGN and on the right, the layers of V1.*

1.3 Visual Performance

Over the years, various tests have been used to assess the quality of the optical image. We can divide them to three main categories related to:

- *The anatomy of the eye.*

  The study of the anatomic characteristics of the neurons and of other structures of the eye is essential for the understanding of the flow of the optical information.

- *The neurophysiology*

  Neurophysiology tests study the process of the optical information in the visual pathway.

- *The psychophysics*

Psychophysical experiments study the functional characteristics of the optical system through the correlation of the physical parameters of the stimuli with what the patient reports.

1.3.1 Visual Acuity

Visual acuity is a psychophysical method of assessing the quality of the optical image and certainly the preferred test for estimating the spatial resolution of the visual system, both in clinical and research studies. Spatial resolution is defined as the ability of the, best corrected, eye to distinguish two spots in space as different.

Spatial resolution depends on various factors. First of all, it depends highly on the quality of the image on the retina, i.e. the pupil size (diffraction), chromatic and monochromatic aberrations, accommodation errors etc. Anatomic and physiologic factors also affect spatial resolution, such as the photoreceptor density in fovea, the physiology of the ganglion cells and neural process in higher levels of the visual path. Finally, the eye movements affect the spatial resolution and this is topic that will be discussed further on. Visual acuity is usually evaluated using optotypes, i.e. letters, numbers or other symbols, thus it may involve compensatory cognitive mechanisms, such as letter interpretation, when compared to other spatial resolution measures.

1.3.2 Contrast Sensitivity

In addition to visual acuity, contrast sensitivity is an important parameter of visual perception. Any optical system that provides less-than-perfect focus will reduce edge contrast [1]. The contrast effect is more noticeable in small objects, such as letters, than in larger objects.

Contrast Sensitivity is a psychophysical method that is used to assess the observer's perceptual sensitivity to stimuli of different spatial frequency, luminance, orientation etc. through the calculation of the contrast threshold. The test usually uses gratings with different characteristics, e.g. contrast, luminance, direction, spatial and temporal frequency, phase etc.

There is a range of methods for the effect of contrast on vision, including the low contrast Bailey-Lovie optotypes, the Pelli-Robson optotypes, the Freiburg test and the Colenbrander mixed contrast reading card (Fig. 7). The more precise and thorough evaluation is achieved using a monitor and patterns, such as gratings. The result is described by the Contrast Sensitivity function.

Contrast loss may be the result of optical factors, such as refractive error, presbyopia, higher-order aberrations, or scatter, as from cataract and other opacities. Contrast perception also depends on the sensitivity of the retinal receptors and on their neural connections [1].

Because of the effect of many factors on contrast perception, establishing a differential diagnosis in a case of contrast loss is not easy. Finding a contrast deficit however is helpful in explaining the patient's complaints, especially when visual acuity is not affected [1].

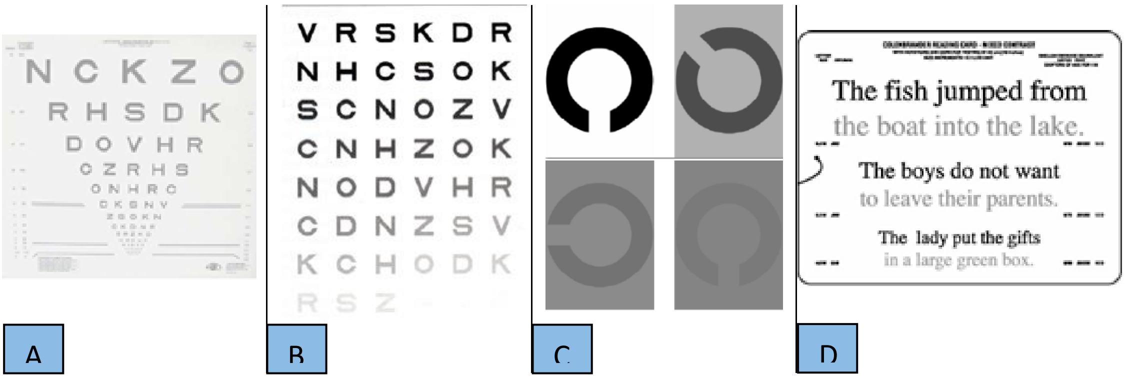

Fig. 7: *Various methods of assessment of the contrast effect.* ***A:*** *Bailey-Lovie optotypes,* ***B:*** *Pelli-Robson optotypes,* ***C:*** *Freiburg test and* ***D:*** *Mixed Contrast Colenbrander Reading Card.*

1.3.3 Visual Field

Visual field is the sum of the points in space that are perceivable at the same time, when the eye is focuses at a certain point. The normal visual field of an eye extends to approximately 60 degrees nasally from the vertical meridian of the eye, 100 degrees temporally, 60 degrees above and 75 below the horizontal meridian.

On the contrary to the visual acuity test, the visual field test gives us information not only for the central, but also for the peripheral vision. It is used as a basic ophthalmologic test for various diseases of the eye and the visual path, such as glaucoma, optic nerve and visual path damages.

Usually the visual field test is done separately for each eye.

1.3.4 Reading Performance

The most common complaint of patients referred for low vision services is reading difficulty. Thus, many clinical reading tests have been used to measure reading performance. More specifically, reading performance has been used to measure the effectiveness of low vision rehabilitation and the outcome of therapeutic interventions, such as laser photocoagulation, submacular surgery, anti-VEGF, treatments for AMD and cataract treatments.

The first known reading test dates back to 1854 and it was developed by Eduard von Jaeger. Since then, many tests have been developed. The most common tests used today are the MNREAD Test, the International Reading Speed Texts (IREST) and the Colenbrander Reading Card.

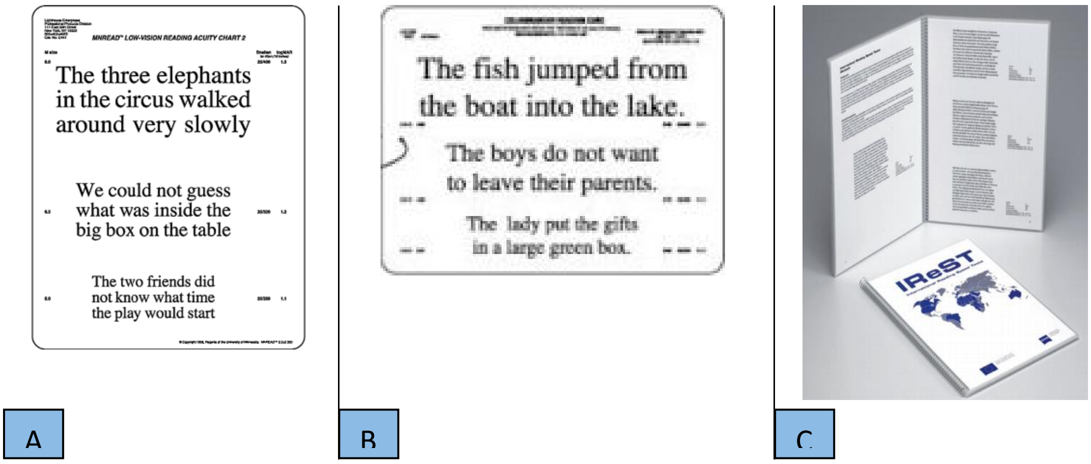

Fig. 8: *Reading tests:* ***A:*** *MNRead test,* ***B:*** *Colenbrander Reading Card and* ***C:*** *IREST.*

The MNREAD Acuity Chart consists of standardized sentences displayed in a wide range of letter sizes. It is designed to measure reading acuity, maximum reading speed and critical print size. In MNREAD reading acuity corresponds to the smallest letter size that can be read and maximum reading rate is the number of words read correctly per minute for the sentence with the shortest reading time. Critical print size is the smallest letter size that can be read at the maximum speed and is an indication of the minimum magnification required for best reading.

The International Reading Speed Texts (IREST) are paragraphs of about 170 words and since they are designed for cross-language comparisons, they are equated across languages for word frequency and syntactic complexity.

The Colenbrander Mixed Contrast Reading Card consists of alternating lines of high (100%) and low (10%) contrast words. The letter size decreases in a logarithmic way. The test is designed to study contrast and reading performance simultaneously. This reading test along with the Colenbrander normal contrast reading card, were used in our study and will be further discussed in Methods.

The question that rises is which reading test is the best. The answer would be "it depends". If we want to measure reading performance after a certain treatment, then a test with multiple print sizes, like MNREAD or the Colenbrander normal contrast reading card, would be better. If we want to evaluate how well a patient reads with a low vision aid, then a test with longer passages with fixed print size, like IREST, would be more suitable. If we want to evaluate the contrast effect we should use the Colenbrander mixed contrast reading card.

As a conclusion, still we haven't found an agreed way to evaluate reading performance as there is for other methods of measuring visual performance, like visual acuity and contrast sensitivity [2].

2. Gaze system

As we have already mentioned, the retina is anisotropic. At the center of it there is the fovea. The fovea is less than 1 mm in diameter and detects just a small part of the visual field. However, because of the high density of cones, the resolution of this area is very high. This is why when we want to examine an object, we have to place the image of the object on the fovea. The gaze system is responsible for this function.

The gaze system consists of two subsystems: the oculomotor and the head movement system. The first one moves the eyes in the orbits, while the latter moves the orbits in space. The gaze system also keeps the image of the object stable to the fovea. It keeps the eye still when the object is still and stabilizes the image when the object or the head moves.

2.1 Neuronal Control Systems That Keep The Fovea On Target

We can outline five different movement systems, three of which keep the fovea on a visual target and two that stabilize the eye when the head moves.

- *Saccadic eye movements* move the fovea rapidly to a visual target
- *Smooth pursuit movements* keep the image of a moving target on the fovea
- *Vergence movements* move the eyes in opposite directions so that the image is positioned on both foveae
- *Vestibulo-ocular movements* hold images still on the retina during brief head movements
- *Optokinetic movements* hold images during sustained head rotation

All of them, but the vergence movements are conjugate. That means that both eyes move in the same direction and by the same amount. Vergence movements are disconjugate: The eyes move in different directions and sometimes by different amounts.

Finally, there is a sixth system, the *fixation system* which suppresses the eye movements in order to hold the eye still during intent gaze.

2.1.1 The Fixation System

It would be expected that vision would be most accurate when the eyes stay still. However, steady fixation doesn't really exist. A fixation consists of very small movements: microsaccades, drifts and tremor. Although unstable fixation may result to visual degradation, there is now evidence that small fixational eye movements may improve perception.

2.1.1.1 Microsaccades

Microsaccades are very small saccades with mean amplitude of 6 arcmin. They occur at a mean frequency of approximately 120 Hz. They move the retinal image in a distance of some hundreds of cones and they have a relatively constant duration of 25 msec and this is why a linear correlation of their velocity with their amplitude is being observed (Fig. 9). Microsaccades are most possibly conjugate eye movements.

Their main role is to correct shifts of the eyes caused by the drifts. They also play a role on the avoidance of the neuronal adaptation.

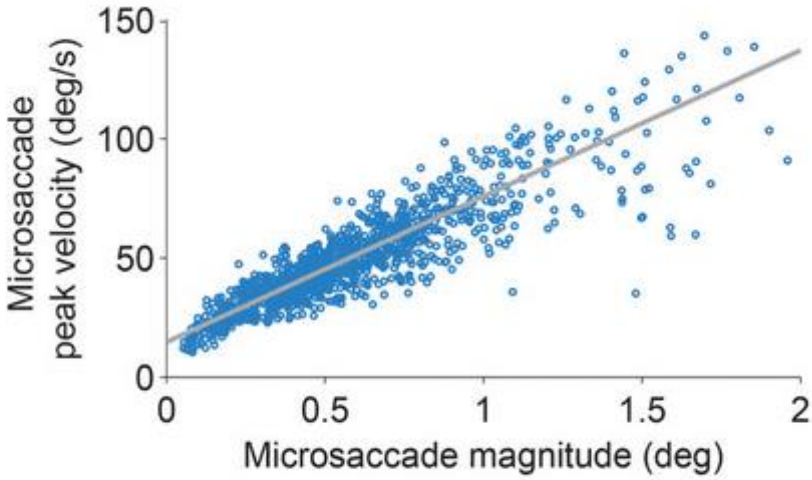

Fig. 9: *Correlation of microsaccade amplitude and its peak velocity.*

2.1.1.2 Drifts

Drifts' velocity is less than 20 arcmin per second. They move the retinal image about 5-15 photoreceptors. They have been recorded both as conjugate and as disconjugate eye movements.

Their function is still under discussion. First, drifts' existence was attributed to the instability of the extraocular muscles and to their antagonistic role with the microsaccades. However some recent studies have stated that they greatly contribute to the fixation's accuracy and that they prevent the image of a stable object from fading.

2.1.1.3 Tremor

Tremor is a continuous, high frequency ocular motor activity that underlies both microsaccades and drifts. Its frequency is about 50-100 Hz and its mean amplitude is less than 1 arcmin. Tremor is quite difficult to record because its amplitude and frequency usually is around the range of the recording system's noise.

Tremor's role on vision is not yet defined. Its frequency is so high that the image's tremor is not recognizable by the eye. Tremor is different in each eye with a possible effect on stereoscopic vision.

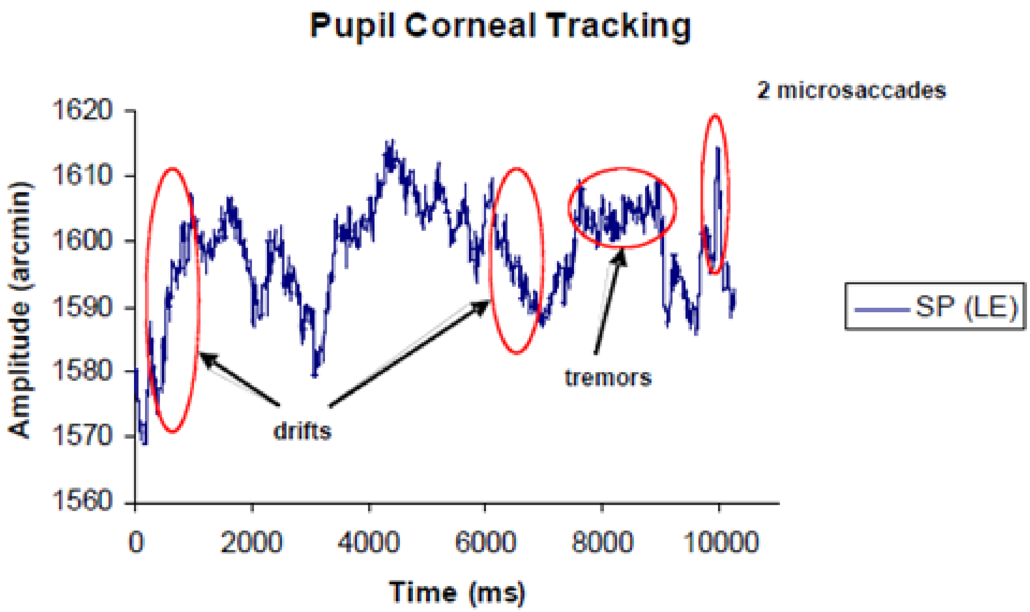

Fig. 10: *Recording of fixational eye movements while focusing in a point.*

2.1.2 The Saccadic System

We explore the world in a series of fixations connected by saccades. The purpose of the saccades is to move the eyes as quickly as possible so that the image of an object is brought to the fovea.

Saccades are fast, ballistic and conjugate eye movements. They can be made not only towards a visual target but also towards auditory or tactile stimuli, or even towards memorized targets and verbal commands.

The target determines the amplitude and the direction of a saccade. On the contrary, its velocity and duration are not voluntary controlled. Its velocity is highly connected with the amplitude of the saccade, i.e., the distance of the target. That means the greater the distance of the target, the higher the saccade's velocity.

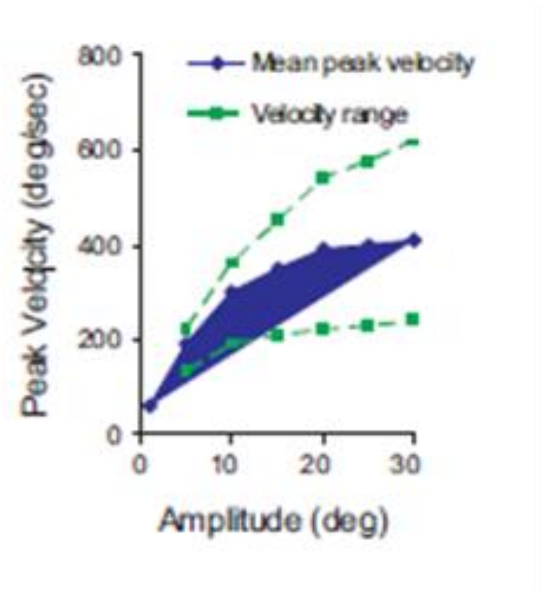

Fig.11: *Mean saccade velocity and velocity range vs saccade amplitude.*

Normally there is no time for visual feedback to modify the course of a saccade. Corrections to the direction or the amplitude of a saccade are made by successive saccades.

The velocity and the duration of saccades of similar amplitude can highly vary even for the same individual. There are many factors that have predictable effect on saccadic velocity. A saccade is slowed down by drugs, fatigue or pathological states. Saccades are also slower when made in complete darkness, when made in anticipation of targets moving in a predictable way or when made in the opposite direction of a visual stimulus.

The saccadic velocity is also affected by the direction of the movement and the initial and final orbital position. Saccades towards the center tend to be faster than the ones that are directed towards the periphery.

Generally, we can say that the normal range for the saccade velocity is 30-700°/sec and for the saccade duration is 30-100 msec for amplitude ranging from 0.5-40°. The normal interval between the appearance of a target and the onset of a saccade is

150-250 msec. This interval is the sum of perceptual and response (eye muscles) time.

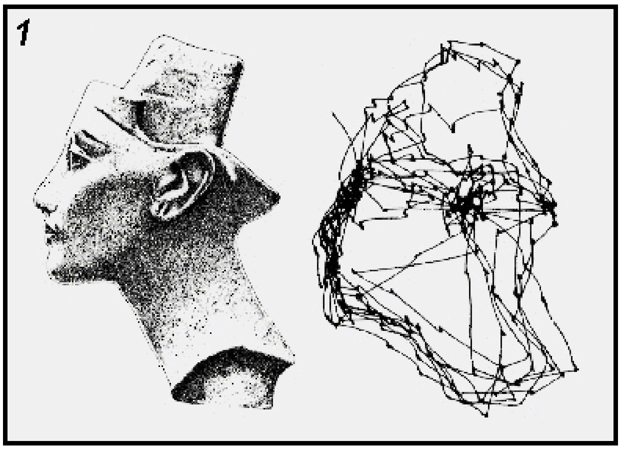

Fig.12: *On the right, saccadic eye movements' orbit during scanning of a picture.*

2.1.3 The Smooth Pursuit System

The smooth pursuit system consists of eye movements that track a slowly moving object so that its image is kept on the fovea. This is done by calculating how fast the target is moving and then moving the eyes accordingly. Only animals with foveae make smooth pursuit eye movements. Animals that do not have fovea use their optokinetic eye movements in order to track objects of their environment. Humans have both smooth pursuit and optokinetic movements, but smooth pursuit predominates.

The system requires a moving stimulus in order to calculate the proper eye velocity. This means that a verbal command or an imagined image cannot produce smooth pursuit. Smooth pursuit movements have a maximum velocity of about 100°/s and latency (initiation time) 100-130 msec. Drugs, fatigue, alcohol, and even distraction degrade the quality of these movements.

2.1.4 The Vergence System

The vergence eye movements shift the gaze point in depth so that the image of a target is kept simultaneously on both fovea. At any given time the entire visual field is not in focus on the retina. When we look at something nearby, distant objects are out of focus and when we look at something far away, near objects are blurred. So, the vergence movements bring the new object of interest in focus.

As we have already said, the vergence movements are the only disconjugate eye movements. That means that in order to move from a far to a near target, the eyes converge (i.e., rotate towards the nose) and in order to aim from a near to a far target, the eyes diverge (i.e., rotate towards the temples).

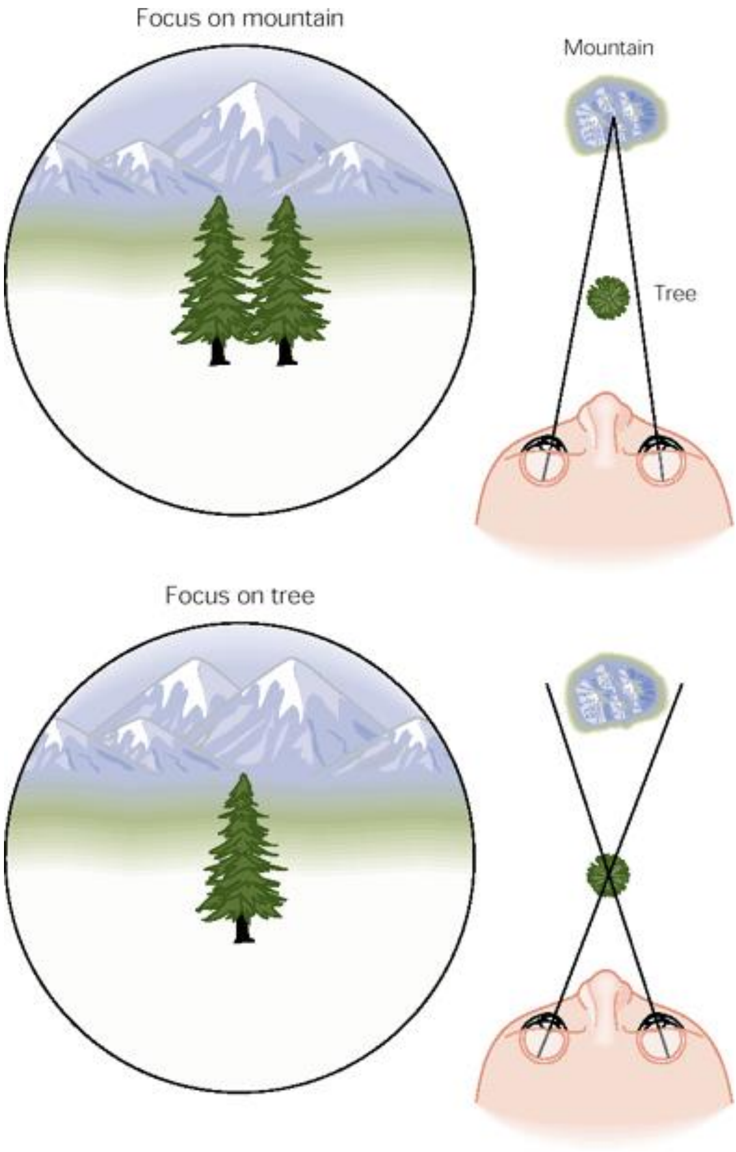

Fig.13: *When the eyes focus on a distant mountain, the nearer tree occupies relatively different retinal positions in the two eyes and is seen as a double image. When the viewer wishes to look at the tree, the vergence system must rotate each eye inward. Now the tree image occupies the same position on both retinas and is seen as one object, but the mountain occupies different locations on the retinas and appears double.*

Vergence is linked with the accommodation of the lens and the pupillary constriction. These three linked systems comprise the near response (or near triad), because they occur when we move our gaze from a far to a near target.

The main stimuli for vergence are the retinal image blur and the retinal disparity. The retinal disparity is the slight difference of retinal position between the two eyes, that the visual system uses, to create the sense of depth.

Vergence eye movements are very slow and last 1 second or longer. One reason for this may be that vergence, unlike saccades, is driven by visual feedback, which normally takes at least 80 msec. Another reason may be that the speed of vergence movements is limited by how fast the lenses change shape (accommodation) and how fast the pupils constrict, since they all occur simultaneously.

The latency of the vergence movements is about 200 msec for retinal blur stimuli and 80-160 msec for retinal disparity stimuli.

2.1.5 The Vestibulo-Ocular System

The Vestibulo-Ocular Reflex (VOR) stabilizes retinal images during head movements by counter-rotating the eyes at the same speed as the head but in the opposite direction. Image stabilization by vestibule processing is much faster and more efficient than visual processing, performed by other kinds of eye movements. This is because visual information takes about 100 msec to travel from the visual cortices through a series of brain structures, to the ocular motoneurons that move the eyes. On the contrary, vestibular information takes only about 7-15 msec to travel from the vestibular sensors, through the brainstem, to the ocular motoneurons. This short latency allows the eyes to compensate for the rapid oscillation of the head.

2.1.6 The Optokinetic System

The Optokinetic system supplements the Vestibulo-Ocular reflexes. The vestibular apparatus does not perfectly transduce the head movements and this is where the optokinetic system provides the central vestibular system with visual information that is used to stabilize the eyes. The optokinetic reflex responds to very slow visual image motion and it builds up slowly so as to provide a motion signal that can take over as the vestibular signal decays.

3. Extraocular Muscles

The eye movements are controlled by a system of six extraocular muscles that form three complementary pairs. To understand how these muscles move the eyeball, it is essential to understand the geometry of the eye and the functions of the muscles.

There are four rectus (superior, inferior, medial, and lateral) and two oblique (superior and inferior) muscles attached to each eye. The recti originate at the apex of the orbit and insert on the sclera, anterior to the equator of the eye. The oblique muscles approach the eye from the antero-medial aspect and insert behind the equator.

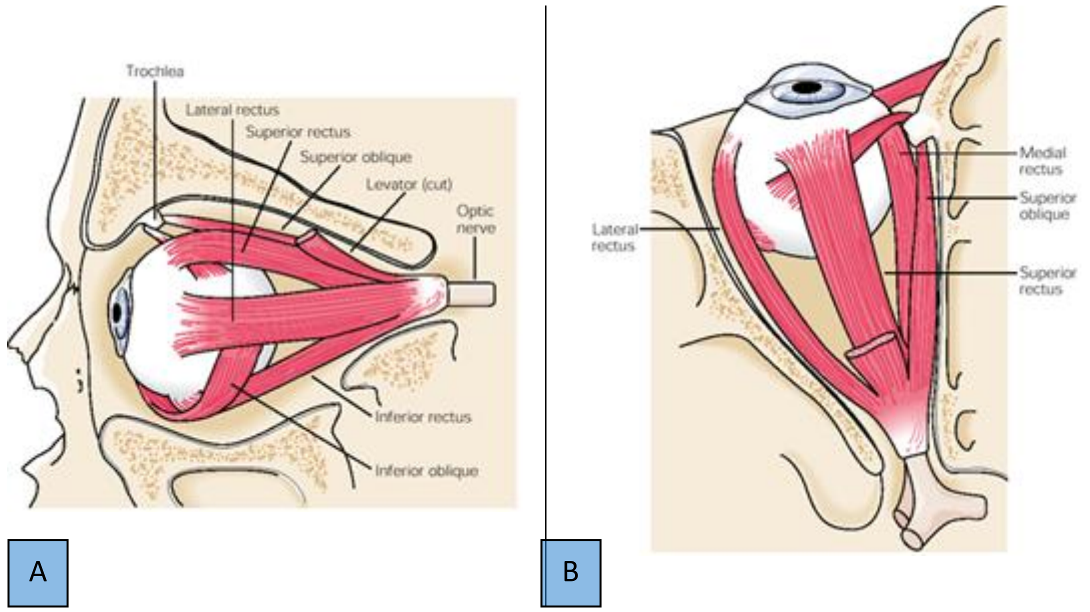

Fig. 14: *On the left, lateral view of a left eye and the extraocular muscles. On the right, a superior view of a left eye.*

The eyeball rotates about three axes: horizontal, vertical, and torsional. Eye rotations are achieved by coordinated contraction and relaxation of the muscles.

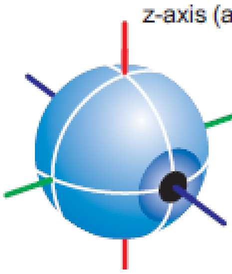

Fig. 15: *The axes of the eye.*

The medial rectus adducts the eye while the lateral rectus abducts it. The rest of the muscles do not perform purely vertical or torsional rotations but a combination of the two. The proportion of torsional and vertical rotation performed by each muscle depends on the horizontal position of the eye in the orbit.

Extraocular Muscles	Primary Action	Secondary Action	Tertiary Action
Lateral rectus	Abduction	None	None
Medial rectus	Adduction	None	None
Superior rectus	Elevation	Incyclotorsion	Adduction
Inferior rectus	Depression	Excyclotorsion	Adduction
Superior Oblique	Incyclotorsion	Depression	Abduction
Inferior oblique	Excyclotorsion	Elevation	Abduction

Table 1: *The extraocular muscles and their primary, secondary and tertiary actions.*

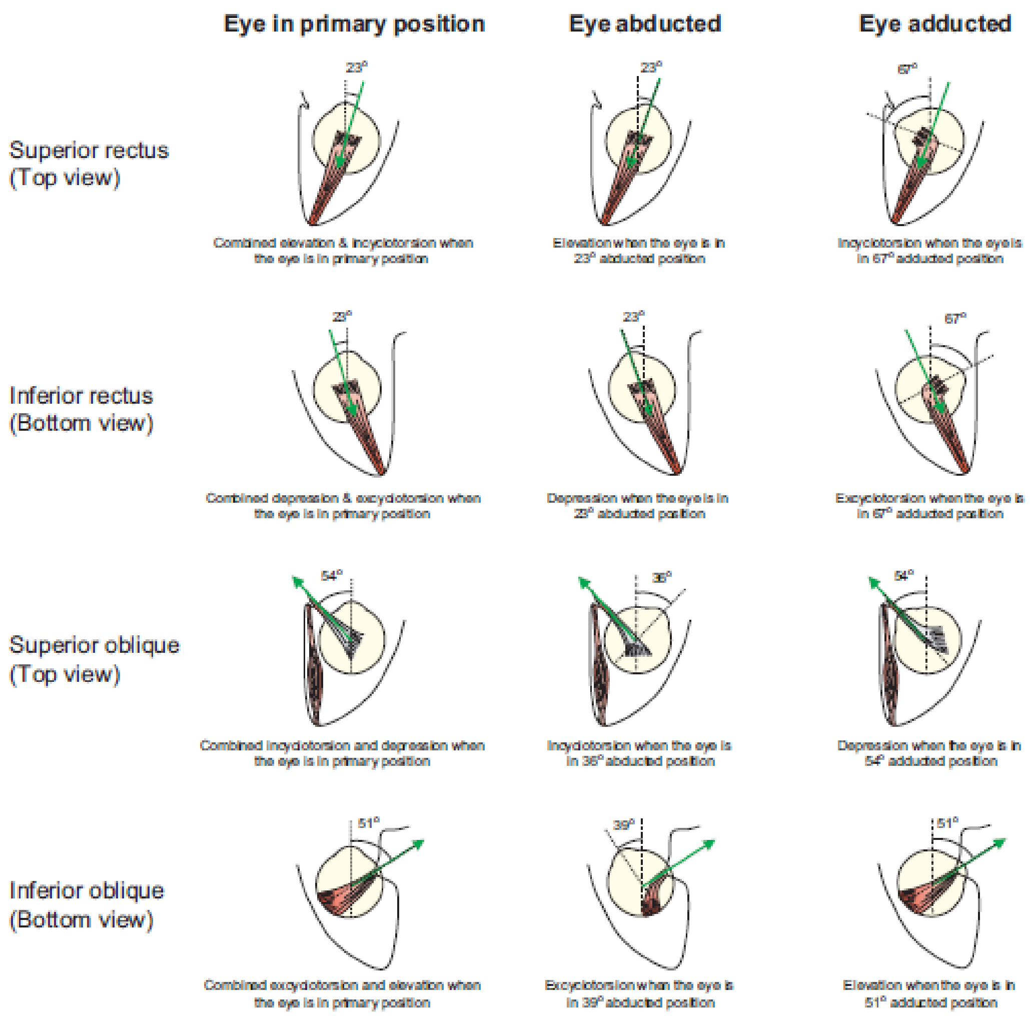

Fig. 16: *The extraocular muscles and their actions according to the eye position.*

4. Eye Movements During Reading

During reading, our eyes move along the lines of the text with saccades of variable amplitudes and with a direction to the front or to the back. Between the saccades, there are fixations of variable durations. Typically, the eyes move forward from a word to the next one, but they sometimes make an additional fixation on the currently fixated word (a case known as *within-word refixation*) or they move back, a case which is called *regression*.

Regressions are a natural part of the reading process. In cases when they are eliminated, by forcing presentation of just one word after the other, comprehension of the text falls dramatically [3].

There is a great controversy among researchers whether eye movements during reading are controlled by low-level oculomotor strategies or whether they are influenced by cognitive processes. Based on these two thoughts, there are two kinds of eye-movement control models: oculomotor and processing models. Oculomotor models claim that the decisions of where and when to move the eyes are mainly determined by low-level visuomotor factors, such as word length, spaces between words and by limitations of visual acuity [4]. In addition to it, fixation duration is claimed to be determined by the position of the fixation in the word. For these models, higher-level processing (e.g. lexical, syntactic, contextual) affect eye-movement behavior just obliquely [5].

On the contrary, processing models claim that the decisions of when to move the eyes is mainly determined by cognitive processing while the decisions of where to move them is determined by visuomotor factors with a small effect of linguistic factors [5].

We will first report some universal eye-movement characteristics and then we will demonstrate the effects of both visuomotor and cognitive factors on variables, like word skipping, probability of refixation, saccade length, percentage of regressions and fixation duration.

4.1 Eye-Movement Characteristics

For skilled readers, the mean saccade amplitude is 7-9 letter spaces and the mean fixation duration is 200-250 msec. About 10-15% of the time, a skilled reader makes regressions [6].

However, both saccade length and fixation duration vary considerably with the word fixated, the text read, the reader and the optical parameters of the text and the environment. This variability is the main goal of eye-movement research.

We can see in Table 2 that as the reader is getting more experienced the eye movement behavior changes. Less skilled readers (beginners, poor and dyslexic readers) have longer fixations, shorter saccades, they make more fixations and more regressions than skilled readers.

4.1.1 Word Skipping and Initial Landing Site

In Table 2 we can also see that nearly every word is fixated by a skilled reader. There are however, some words that are skipped and others that are fixated more than once [6]. The probability of word skipping decreases with word length, dropping from about 76% for 1-and-2 letter words to about 42% for 4-letter word an 5% for words of 9-10 letters. Word skipping also depends on the location of the prior fixation [7].

	Grade level[a]						
	1	2	3	4	5	6	Adult
Fixation duration (ms)	355	306	286	266	255	240	233
Fixations per 100 words	191	151	131	121	117	106	94
Frequency of regressions (%)	28	26	25	26	26	22	14

[a] Grade 1 children in the US are typically 6 years old, when reading instruction begins.

Table 2: *Developmental characteristics of eye movements during reading.*

The landing site in words is also linked with the word length and the launch site. In languages read from left to right, the eyes' landing site in words tends to be in the center of short words and a bit to the left for longer words. This effect is called

Preferred Viewing Position (PVP effect). There is evidence that launch site determines the landing position more than the word length does [7].

4.1.2 Probability of Refixation

As shown if Fig. 17, the probability of refixation is lower when the initial landing site is close to the center of the word than when the first fixation is at the beginning or end of the word [7-10].

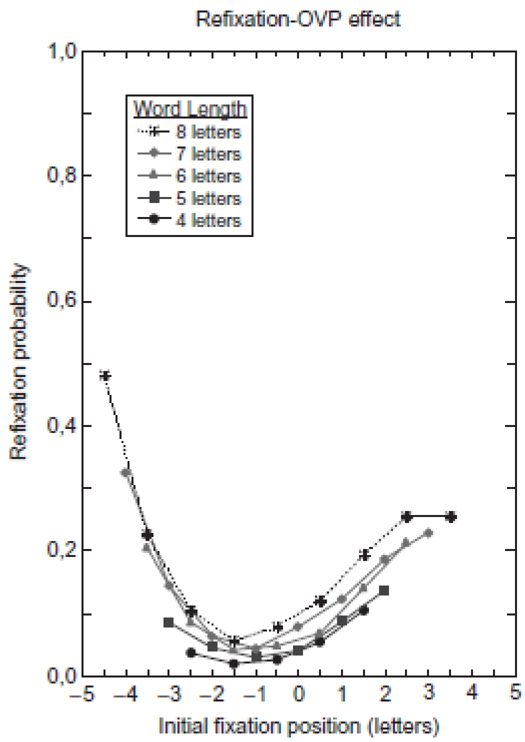

Fig. 17: *Refixation probability as a function of Initial Fixation Position.*

The probability of refixation is also higher in low-frequency words, i..e words that are not encountered frequent in written language, than on high-frequency words[5] and on bigger words[11].

4.1.3 Saccade Length and Regressions

The saccade length can be measured in two ways: in degrees of visual angle and in number of letter spaces. It has been shown that the saccade length, measured in letter spaces, remains constant if the text is read at different distances, even though the letter spaces subtend different visual angle [12, 13].

The probability of making a regression is highly depended on the length of the prior, progressive saccade. More specifically, the longer the prior saccade, the higher it is the probability of a regression. Regressions are also more likely to happen after a word that was skipped, especially if it's a long word [7].

About 70% of the regressions are towards one of the previous words (*inter-word regressions*). They are mainly small-amplitude saccades which bring the eyes right to the previous word. Sometimes however, longer regressions are made to some words before [7].

Saccade length is affected by monocular reading. Regressive saccades showed an increase in their length in monocular reading compared to binocular reading [14].

4.1.4 Fixation Duration

The fact that some words are skipped and some others are fixated more than once, makes it difficult to measure processing time for a word [15]. *Mean Fixation Duration* is inadequate because it underestimates the times the eyes are on a word. Using *Single Fixation Duration,* we take into account just the words that are fixated only once. This is also problematic because there are words that are skipped and some that are refixated. Therefore, there are two measures that are mainly used. *First Fixation Duration* is the duration of the first fixation regardless of whether it is the only fixation of the word or the first of multiple fixations. *Gaze Duration* is the sum of all fixations on a word before moving to the next word. A final measure is also used. *Total Time on a Word* is the sum of all fixations including regressions. It cannot however, measure the initial processing time. In cases where the unit of analysis is not a word but a sentence or a text, it is appropriate to distinguish first pass reading time from the second-pass time [6].

Regarding fixation duration, it has been shown that word frequency has a great effect on it. Readers spend more time on lower frequency words than on higher frequency words. Words that are highly predictable from previous context are also fixated for less time. For this reason, function words are fixated only about 35% of the reading time, while content words are fixated about 85% of the time [6, 16].

Juhasz et al. showed that words with alternating case (e.g. AlTeRnAtInG cAsE) were fixated longer than those which were presented in normal case [17], giving more evidence on the processing models.

Fixation duration is also affected by the initial fixation location. As we can see in Fig. 18, fixation duration is longer when the fixation is near the center of short words and to the left of the center of long words. This phenomenon applies both to first fixations and second fixations [7].

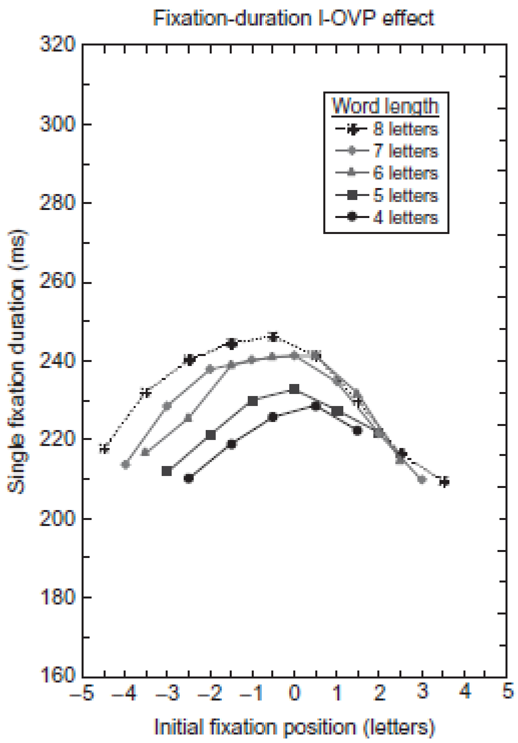

Fig 18: *Single fixation duration as a function of Initial Fixation Position.*

Monocular vision also affects fixation duration. Johansson et al. showed that monocular reading results in significant increase in fixation duration at 8.9% [14]. It has also been shown that the binocular advantage becomes more prominent in low contrast condition. Binocularity contributes increasingly to reading performance, by lowering the fixation duration, as stimulus contrast decreases [18].

Leyland et al. have also showed that partial word shading, produce longer gaze durations and that readers spend more time re-reading target words when they are partially shaded [19].

White et al. examined the influence of the stimulus quality and more specifically, the contrast of the text, on the distribution of fixation durations. To do it, they used ex-Gaussian fitting and it revealed that stimulus quality affected the mean of the normal component and not the exponential component. Ex-Gaussian fitting will be further discussed later on (see paragraph 6.5.1). The study showed also that the fixations were longer when the sentence was faint (i.e. of low contrast) than when the sentence was presented normally. In addition to that, fixations were much longer on a single faint word embedded in normal text than when the entire sentence was faint [20].

4.1.5 Reading Performance

There are also some measures to evaluate reading performance as a whole. Such measures are reading speed, threshold print size, reading acuity etc.

Chung et al. showed that print size of the text affects reading performance. Reading speeds rise with increasing print size until a plateau is reached, at all retinal eccentricities [21]. Chung et al. also showed that dioptric blur affects binocular reading performance. The negative effect of blur both on maximum reading speed and threshold print size is visible from about 2D and mainly at 3D of blur [22].

4.2 Perceptual Span

Although visual acuity is very high in foveola (central 1 degree of vision), it is not as high in the parafovea (up to 5 degrees) and it's even poorer in periphery (region beyond the parafoveal) [6]. Because of this anisotropy, the question of the extraction of information from parafoveal vision rises. The perceptual span is the number of letters that can be extracted in a single fixation [7]. Studies have indicated that the perceptual span is relatively small. It ranges from about 3-4 letters to the left of the fixation up to 14-15 letters to the right of the fixation. However, in order to identify words we need information that can be taken only up to about 7-8 letters to the right of the fixation [6]. In order to divert the number of letters to units of angle, we can have an example. A letter of 0.4 logMAR in a distance of 40 cm, correspond to an angle of 2.5 degrees. That is, the perceptual span of 7-8 letters corresponds to 17.5-20 degrees. Readers also focus their attention in order not to acquire information from below the currently fixated line [23]. The characteristics of the writing system and reading system have major impacts on perceptual span [24].

The fact that there is a higher probability of skipping a word if it is a short function word or if it's highly predictable, is a simple indication that there is some kind of parafoveal process. There are many low-level factors that affect reading behavior through the parafoveal process. Some of these effects are the following. Saccade length is influenced by both the length of the fixated word and the next word. The further the launch site of a saccade, the closer to the beginning of the word the landing site is. Also, if the beginning of a word contains an orthographically irregular letter, the initial landing position of the eyes shifts to the beginning of the word [6].

There is little evidence on the effect of higher-level factors on the landing position of the eyes. There is however, high interest in the effect of parafoveal words on fixation durations. It has been indicated that if parafoveal information is denied, reading rates decrease rapidly [6].

This advantage gained by the availability of useful information in the parafovea is called 'parafoveal-preview benefit'. There is however a great debate on the extent of this information gained. It is not clear yet whether we obtain from the parafovea just sub-lexical and phonological information or we also obtain higher-level lexical and semantic information [6].

4.3 Word Processing

Until recently, most of the researchers took for granted that word processing during reading is serial. That means that attention during reading acts like a spotlight shifting from word to word in a serial way. Models of reading like E-Z Reader use this kind of processing.

This belief was not out of nowhere. There were studies that showed that the word to the right of fixation and its frequency had only small effect on the processing of the currently fixated word [16, 25, 26].

However, some recent studies have indicated that words may be, to some extent and under some circumstances, processed in parallel [6]. These studies have shown that fixation times on target words were shorter when the word to the right constituted a plausible continuation of the sentence or when it was consistent with prior sentence context as compared with an implausible continuation or with a word of a random letter string [6].

5. Eye Movement Recording Methods

Over the years, numerous techniques have been developed to record the eye movements. We can divide them to three categories according to the physical characteristics of the eye which are used.

1. Techniques based on reflected rays
2. Techniques based on recording of the electrical impedance
3. Techniques based on contact lenses

5.1 Techniques Based On Reflected Rays

5.1.1 Limbus Tracking

The iris of the eye is clearly distinguishable from the sclera and is the basis for the normal visual assessment of the angle of gaze. The position of the limbus may be measured with respect to the head, so either the head must be held quite still or the apparatus must be fixed to the user's head. The ratio between dark iris and bright sclera observed can be measured directly by photosensors or indirectly on an image of the eye. This ratio is directly related to the horizontal position of the eye. Usually, white light is used [27].

5.1.2 Pupil Tracking

Tracking the direction of gaze by the pupil tracking technique is similar to limbus tracking, only here the smaller boundary between the pupil and the iris is used instead. The pupil can be separated from the surrounding iris optically. This can be especially sharpened with the use of infrared light which will be nearly entirely absorbed once entering the eye, consequently making the pupil much darker than the surrounding iris [27].

The apparatus must be held completely still in relation to the head. The advantages of this technique over limbus tracking is that the pupil is far less covered by the eyelids than the limbus, and thus enables vertical tracking, too and that the border of the pupil is often sharper than that of the limbus and thus yields a higher resolution. The disadvantage is that the difference in contrast is lower between the pupil and iris than between the iris and sclera-thus making the border detection more difficult.

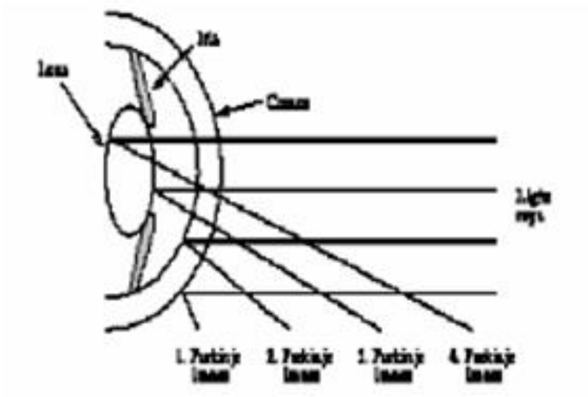

Fig. 19: *The four Purkinje images are reflections of incoming light on the boundaries of the lens and cornea (from John Glenstrup et al., 1995).*

5.1.3 VideoOculoGraphy (VOG)

Video-oculography is a video-based technique of measuring horizontal, vertical and torsional position of the eyes. Pupil tracking and corneal reflection are used for recording. A head-mounted mask with small cameras is used.

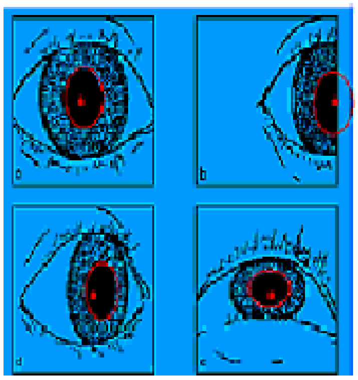

Fig. 20: *Images of the eye in four positions used in VideoOculoGraphy (from http://www.metrovision.fr).*

5.1.4 Infrared Oculography (IROG)

Infrared oculography is based on the principle that if a fixed light source is directed at the eye, the amount of light reflected back to a fixed detector will vary with the eye's position. Infrared light is used as this is invisible to the eye, and doesn't serve as a distraction to the subject. As infrared detectors are not influenced to any great extent by other light sources, the ambient lighting level does not affect measurements. Spatial and temporal resolution is good for this technique. It is better for measuring horizontal than vertical eye movements. Blinks can be a problem, as not only do the lids cover the surface of the eye, but the eye retracts slightly, altering the amount of light reflected for a short time after the blink.

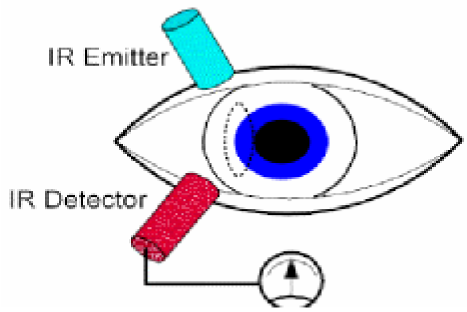

Fig. 21: *Infrared Oculography*

5.2 Techniques Based On Recording Of Electrical Impedance

5.2.1 ElectroOculoGraphy (EOG)

A potential difference of up to 1 mV between the cornea and the retina normally exists in the eye and is used as the basis of electrooculography (EOG). Small voltages can be recorded from the region around the eyes which vary as the eye position changes. By carefully placing electrodes it is possible to separately record horizontal and vertical movements. However, since the electric field is not aligned with the optic axis, any torsional rotation of the eye introduces a potential change which can be mistaken for horizontal or vertical eye movement [27].

The electrodes are placed on the skin around the eye, so this technique does not require a clear view of the eye. The contact of electrodes to the user makes this technique difficult though. Another disadvantage is that the signal can change even with no eye movement. It depends on the state of dark adaption and metabolic changes in the eye. There have also been reports that the velocity of the eye as it moves may itself contribute an extra component to the EOG. It is not a reliable method for quantitative measurement, particularly of medium and large saccades.

5.3 Techniques Based On Contact Lenses

These techniques are not proposed for everyday use. There are some health issues concerning high-frequency electromagnetic fields. In addition, the user has to wear special contact lenses, possibly connected to wires, a fact that makes this technique hard for clinical use.

5.3.1 System Of Plane Mirror Surfaces On The Lens

In this technique, one or more plane mirror surfaces are grounded on the lens and reflect light from a light source. These reflections are used to calculate the position of the eye.

5.3.2 Scleral Search Coils

When a coil of wire moves in a magnetic field, the field induces a voltage in the coil. If the coil is attached to the eye, then a signal of eye position will be produced. In order to measure human eye movements, small coils of wire are embedded in a modified contact lens. This is inserted into the eye after local anesthetic has been introduced. A wire from the coil leaves the eye at the temporal canthus. The field is generated by two field coils placed either side of the head. This allows horizontal eye movement to be recorded. If it is necessary to also monitor vertical eye movements, then a second set of field coils, usually set orthogonally to the first set, it used. If the eye coil is of an appropriate design, then torsional movements can also be recorded. The advantage of this method is that it has a very high temporal and spatial resolution allowing even the smallest types of eye movements (e.g. microsaccades) to be studied. Its disadvantage is that it is an invasive method, requiring something to be placed into the eye.

PART 2. EXPERIMENTS

6. Participants And Methods

6.1 Participants

A group of 23 persons participated in the study. Ten of them were male and thirteen female. Their mean age was 30.7 years, ranging from 19 to 45 years. All of them were native Greek speakers. We chose our participants in a way so that we will assure similar education level for all of them. 21 of them had a university degree and 2 were still under their graduate studies. The participants did not have any ocular or systemic pathology. The experiments were performed with the participants' habitual refractive correction (if needed) as long as visual acuity was better than 0.0 logMAR in each eye. None of them had previously seen the two versions of the Reading Cards used in this study, or any of the sentences, prior to participating in the study. Distance VA was measured (at 4 m) using the European-wide ETDRS visual acuity charts, that were developed in the University of Crete. Near visual acuity was measured (at 40 cm) again using the European-wide ETDRS visual acuity charts. Eye dominance was evaluated using the hole in card method.

Their characteristics are displayed in Table 3.

Subject	Sex	Year of Birth	Dom. Eye	VA far (logMAR)			VA near (logMAR)			Glasses
				OD	OS	Bin	OD	OS	Bin	
1	M	1977	OD	-0.28	-0.24	-0.30	-0.22	-0.22	-0.22	Yes
2	F	1981	OS	-0.16	-0.24	-0.28	-0.08	-0.16	-0.12	No
3	M	1988	OD	0.00	-0.04	-0.04	-0.02	0.00	-0.04	Yes
4	F	1985	OD	-0.26	-0.16	-0.28	-0.10	-0.08	-0.14	No
5	F	1982	OS	-0.22	0.00	-0.26	-0.04	-0.06	-0.02	Yes

6	F	1984	OD	-0.20	-0.16	-0.18	-0.16	-0.10	-0.16	No
7	F	1984	OS	-0.06	-0.14	-0.14	-0.10	-0.10	-0.10	Yes
8	F	1981	OS	-0.04	0.00	-0.06	-0.06	0.00	-0.04	Yes
9	M	1988	OD	-0.16	-0.16	-0.26	-0.16	-0.16	-0.20	No
10	M	1989	OD	-0.24	-0.20	-0.24	-0.18	-0.08	-0.14	No
11	M	1969	OS	-0.12	-0.12	-0.20	-0.14	-0.14	-0.18	No
12	M	1986	OD	-0.18	-0.20	-0.22	-0.12	-0.12	-0.18	Yes
13	M	1982	OS	-0.10	-0.22	-0.18	-0.20	-0.22	-0.26	No
14	M	1982	OD	-0.22	-0.14	-0.28	-0.24	-0.20	-0.20	Yes
15	F	1992	OD	-0.04	0.00	-0.08	-0.04	0.00	-0.06	Yes
16	M	1978	OD	-0.30	-0.30	-0.30	-0.16	-0.16	-0.18	No
17	M	1995	OD	-0.08	0.00	-0.10	0.00	0.00	-0.08	No
18	F	1980	OS	-0.20	-0.30	-0.30	-0.16	-0.16	-0.14	No
19	F	1978	OD	-0.12	-0.12	-0.16	-0.06	-0.02	-0.12	No
20	F	1982	OS	-0.16	-0.08	-0.22	-0.08	-0.06	-0.10	Yes
21	F	1984	OD	-0.28	-0.28	-0.28	-0.06	-0.12	-0.20	No
22	F	1986	OS	-0.20	-0.06	-0.24	-0.20	-0.08	-0.16	No
23	F	1982	OD	-0.10	-0.04	-0.20	-0.12	-0.06	-0.10	Yes

Table 3: *Characteristics of the subjects*

6.2 Reading Cards

Two types of reading cards were used in the study; the Greek versions of the Colenbrander Reading Cards (both normal and mixed contrast) and a paragraph of fixed print size, the "long text". All reading cards were printed and were placed at eye level (in the center of a display screen) for facilitating eye recordings.

The contrast of the text in the normal Reading Card was 100% while the contrast of the text in the mixed contrast reading card was 100% (upper lines) and 10% (lower lines). The print size ranges from 1.2 to -0.1 logMAR. For the experiments, the back side of the card was used, which means that the print size ranged from 0.9 to -0.1 logMAR. The sentences on the two versions (normal and mixed contrast) were exactly the same. The only difference was that in the mixed contrast reading card the contrast of the half of the lines (lower lines for each print size) was 10% (see Fig. 22).

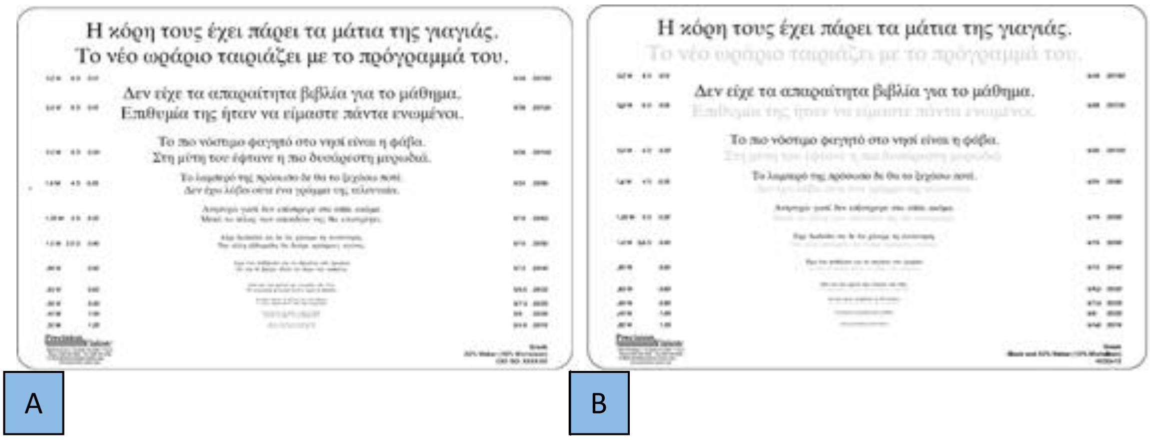

***Fig. 22: A:** the normal Colenbrander Reading Card and **B:** the mixed contrast Colenbrander Reading Card.*

The paragraph used in the "long text" was advanced by the study group and contained simple sentences about the island of Crete. It consists of 141 words (911 characters) with a print size of 0.4 logMAR placed at a distance of 40 cm.

To ensure comprehensive reading, observers had to answer five multiple choice questions after reading each of the two texts.

6.3 Recording Eye Movements

Eye movements were monitored using an Eye-Link II eye tracker (SR Research Ltd.). The Eye-Link II has a high resolution (noise-limited at $<0.01°$) and maximum data rate of 500 samples per second (hz). The EyeLink II system consists of three miniature cameras mounted on a padded headband. One head-tracking camera was used to detect infrared markers in the world, while two eye cameras focus on the left and right eyes respectively.

As we can see in Fig. 23, the system consists of a Host PC, a display PC, the headband and a PCI card. The Host PC connects to the headband and powers four infrared markers (for head tracking) that are mounted on the corners of Display PC's monitor. It also hosts the EyeLink II Host application where you can control the tracker and change the options of the recording. The Display PC runs experiment software for control of the Host PC and presents the stimuli to the monitor. The headband has the cameras which record the eye movements. Finally, the PCI card is connected with the headband and is hosted in the Host PC. It performs the powerful image processing required to achieve the high temporal and spatial resolution of the system.

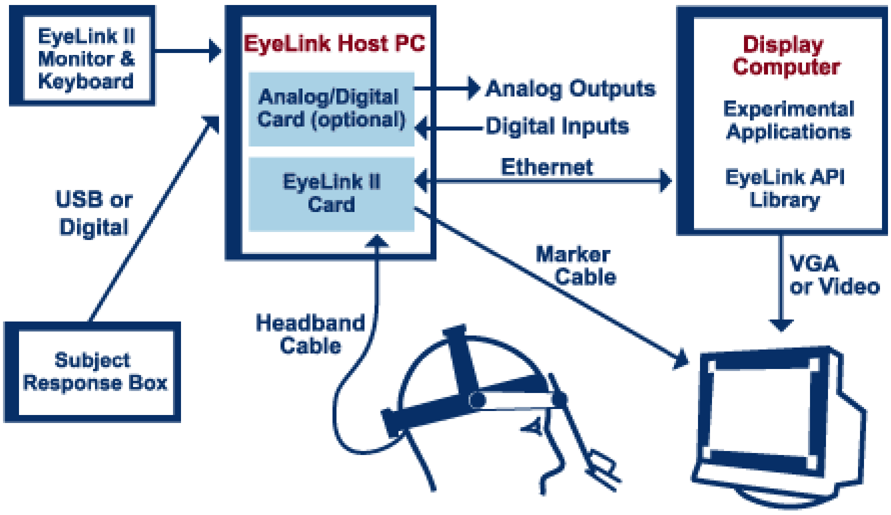

Fig. 23: *The EyeLink II system.*

In our study we chose the pupil tracking mode at a rate of 500Hz. Viewing and recording were binocular. Studies have shown that there are no significant differences between the dominant and non-dominant eye in monocular reading [14, 18], thus only recordings from the right eye were taken for further analysis. The calibration and validation points were presented in a high resolution monitor (SONY, GDM 520), which was supported by a high resolution graphic card (VSG 2/5, Cambridge Research System).

6.4 Experimental Procedure

The observer was seated in front of the display screen at a distance of 40 cm with the head stabilized using a chin rest to limit any head movements. The illuminance of the observer's eye was measured with a luxmeter and the luminance of the reading card was measured with a photometer.

Prior to each experiment, a calibration / validation session was conducted. The calibration was a five-point cross figure. After the validation, the display screen was switched off and the session commenced. The observer was instructed to read the text silently. The observer was asked to close his eyes until he was asked to open them. He was also asked to first look in a black spot at the bottom of the reading card and then start reading. He was informed that we needed him to comprehend the sentences and for this reason, he would have to answer five questions afterwards.

Two experiments were conducted. The first experiment investigated the effect of contrast, print size and any learning effect between the two sessions. About two months later, all participants of the first experiment were asked to take part to the second experiment which investigated the effect of luminance. From the 23 participants only 15 of them did finally attend to the second experiment.

6.4.1 Experiment 1: Effect Of Contrast

The first experiment of this study was conducted to investigate the effect of contrast and print size on reading as well as the learning effect.

The first experiment was conducted in photopic conditions and the cornea illuminance was measured with a luxmeter at about 60 lux. The photometer measured the chart background luminance at 55 cd/m^2. After the calibration and validation was conducted, the observers were asked to read comprehensively the “long text”, while their eye movements were recorded. Following the recording, comprehension was evaluated using five questions on the text. Subsequently, the 100% contrast Colenbrander Reading Card was used and the observers were asked to read the isolated lines, which were reduced in size, until the last sentence (of the smallest size) they could discriminate. Following the recording comprehension was evaluated using five questions on the text. Finally, the mixed contrast Colenbrander Reading Card was used and another set of five questions was put to the observer. Calibration and validation were performed after each session. The observer was not informed on the results of his answers until the end of the experiment.

6.4.2 Experiment 2: Effect of Luminance

The second experiment was conducted to evaluate the effects of luminance on reading. To achieve this, during the first part of the experiment, the lights of the room were turned off and the cornea illuminance was set to mesopic levels, of about 1.0 lux. The chart background luminance was measured with a photometer at right below 1 cd/m^2.

The first two sessions were performed at low illuminance levels (1.0 lux). The "long text" session was conducted first an after that, the 100% contrast Colenbrander Reading Card session. The second part of the second experiment was conducted in photopic conditions and the cornea illuminance was measured with a luxmeter at about 60 lux. The photometer measured the chart background luminance at 55 cd/m^2. First, the 100% contrast Colenbrander Reading Card session was performed and after that, the "long text" session.

Calibration and validation was conducted after each session. After each recording, comprehension was evaluated using five questions on the sentences and the text.

6.5 Mathematical And Statistical Analysis

6.5.1 Ex-Gaussian Analysis

In 1979, Ratcliff proposed the ex-Gaussian distribution as very good fitting of the empirical distributions of response times. Since then, many studies in single-word recognition literature have used it [20]. In 2010 and 2011, Staub et al. and Staub respectively, established that fixation durations in reading are also well fit by the ex-Gaussian distribution [28, 29].

The ex-Gaussian function is the convolution (a mathematical combination) of a Gaussian and an exponential distribution. The mode and standard deviation of the Gaussian component are approximated by μ and σ respectively, while the exponential function is approximated by τ, which reflects the mean and standard deviation of the exponential component [30]. A property of the ex-Gaussian distribution is that the sum of μ and τ equals with the mean of the distribution. Because of this property, the ex-Gaussian approach takes an important step toward making contact with the mean-dominated literature [30].

Fig. 24 displays the effect of the ex-Gaussian parameters on a distribution. Panel A shows a Gaussian distribution. Panel B shows a shift of the Gaussian distribution to the right, because of an increase on μ. Panel C shows a stretching of the tail of the distribution, as reflected by an increase of τ. Finally, Panel D shows a change of both parameters μ and τ, with the mean of the distribution being stable.

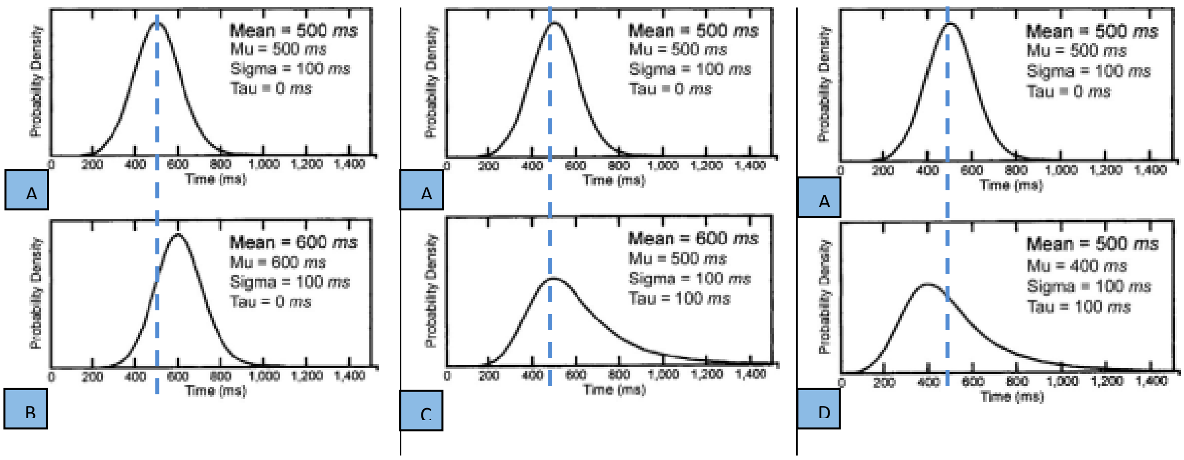

Fig. 24: *Changes in a distribution as a change of ex-Gaussian parameters.*

It has been shown that for low frequency words, the fixation duration distribution is shifted to the right and there is also an increase of the number of long fixations, as compared to the high-frequency words' fixation duration. That means that there is a change both in μ and τ [28]. It has also been shown that word predictability [29] as well as the word's contrast [20], affect just the μ parameter of the distribution.

Although it's quite tempting, we shouldn't link the ex-Gaussian parameters to the stage of cognitive processing [31]. It would be much wiser to assess whether a subset of fixations is particularly influenced by a certain factor.

6.5.2 Statistical Analysis

For the statistical analysis we used several statistical packages. For simple descriptive statistics we used Excel 2010 (Microsoft Corporation, USA). For further analysis, such as correlations, t-test, ANOVA and ANCOVA, we used the statistical package IBM SPSS Statistics 20 (IBM Corporation, USA). Stata (StataCorp, USA) was also used for the Colmogorov-Smirnov test.

Graphs were conducted by OriginPro 8 (OriginLab Corporation, USA), GraphPad Prism (GraphPad Software, Inc, USA). Pro Fit (QuantumSoft, USA) was also used for the distributions.

PART 3. RESULTS

7. Experiment 1

7.1 Test-Retest Repeatability

First of all, we tested the possible effect of the second time of reading on the characteristics of fixations and saccadic movements. In order to do it, we analyzed the reading behavior of each participant in the "first lines" of the two reading cards, i.e. the sentences 1, 3, 5, etc., which are exactly the same.

7.1.1 Fixations

Fig. 25 shows the median fixation duration (msec) as a function of the print size (in logMAR). We used the median and not the mean fixation duration, since we know that the fixation duration distribution is not a normal distribution. Each point of the graph represents the mean of participants' median fixation duration. Black line represents the first time of reading (Chart A), while the red one represents the second time of reading (Chart B). Both lines are fitted by Exponential Decay function:

$$y = y_0 + A_1 e^{-(x-x_0)/t_1}$$

For the chart-A-line, fitting parameters were found to be: $y_0 = 203.33$, $x_0 = -0.14$, $A_1 = 330.92$ and $t_1 = 0.19$.

For the chart-B-line, fitting parameters were found to be: $y_0 = 201.07$, $x_0 = -0.12$, $A_1 = 225.34$ and $t_1 = 0.26$.

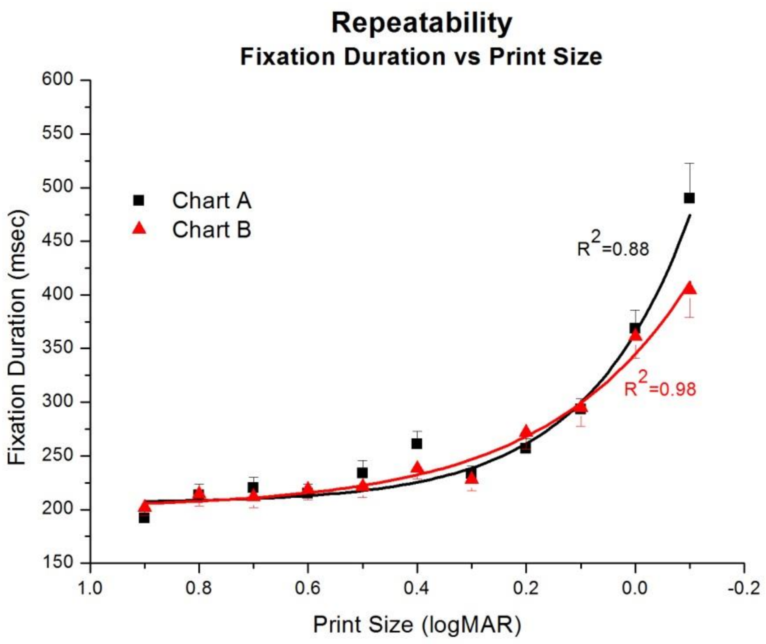

Fig. 25: *Learning effect: Median fixation duration as a function of the print size*

As far as the print size effect is concerned, we checked in which two successive print sizes, the difference of the median fixation duration is statistically significant. We found that in the first time of reading, the difference in the median fixation duration is significant from print size 0.2 logMAR to 0.1 logMAR ($p=0.049$) and it's getting greater in the next successive pairs. In the second time of reading, the difference gets significant in the pair 0.3 to 0.2 logMAR ($p=0.026$).

It is obvious that no difference exists in the median fixation duration between the two times of reading. There is a change just in the smallest letter (-0.1 logMAR), where fixation duration decreases from 490 msec to 404 msec, but the difference is not statistically significant ($p=0.131$).

Fig. 26 shows the mean number of fixation per sentence as a function of the print size (logMAR). Each point of the graph represents the mean of all participants' mean number of fixations. Black line represents the first time of reading (Chart A), while the red one represents the second time of reading (Chart B). Both lines are linear fittings.

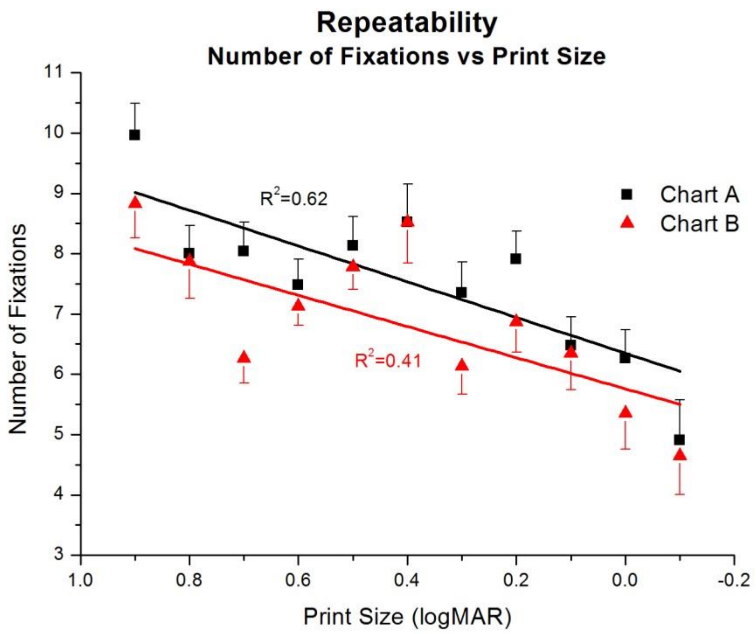

Fig. 26: *Learning effect: Mean number of fixation per sentence as a function of the print size for the two consecutive measures of the same text*

As we can see, there is a decrease in the number of fixations as the print size is getting smaller in both times of reading.

Figure 27 shows the difference in the number of fixations between the two times of reading as a function of the print size. This change seems to be stable as the print size changes and the ANOVA analysis shows that there is not statistically significant difference of the difference in the number of fixations as a function of the print size (p-value=0.721).

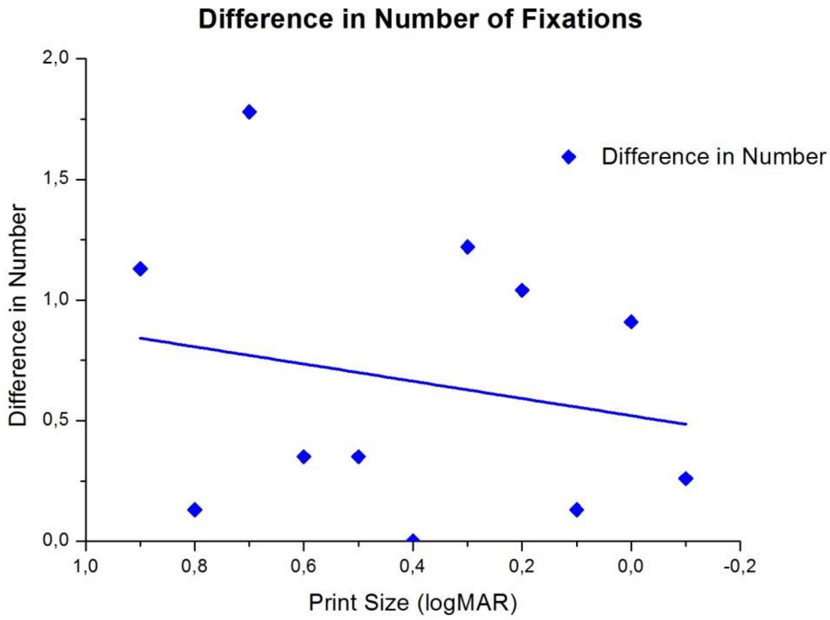

Fig. 27: *Difference in the number of fixations between two times of reading, as a function of the print size.*

7.1.2 Saccades

As far as the saccades are concerned, what interested us was i) the percentage of regressions among all saccades and ii) the mean saccade length.

Fig. 28 shows the percentage of regressions (%) among all saccades as a function of print size (logMAR). Again, black line represents the first time of reading (Chart A), while the red one represents the second time of reading (Chart B). Both lines are linear fittings.

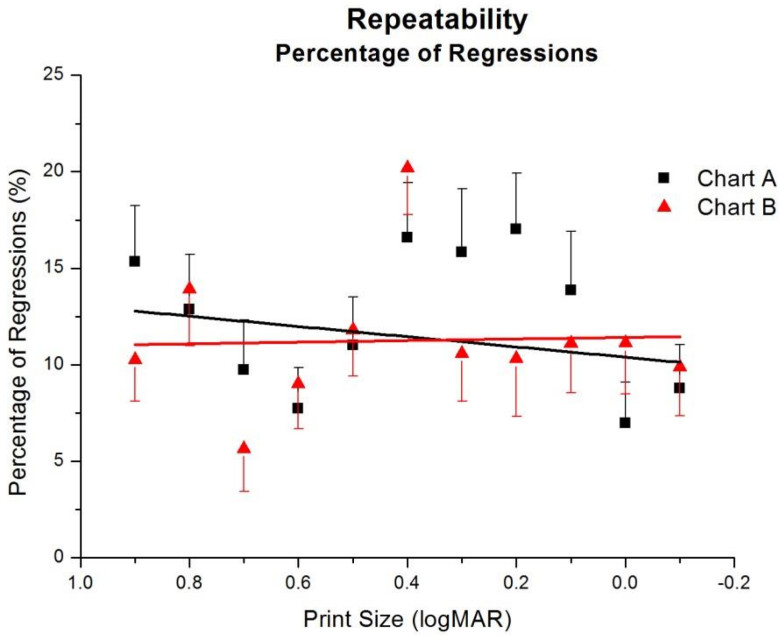

Fig. 28: *Learning effect: Percentage of regressions as a function of the print size for the two consecutive measures of the same text*

The percentage of regressions stays intact with the change of print size at about 10-12 % of all saccades. We can also see that the percentage is not different between the two times of reading.

Fig. 29 shows the forward saccade length measured in degrees of arc as a function of the print size (logMAR). As we can see, there is a linear relation of these two parameters. As the print size is getting smaller, the forward saccade length is getting smaller too. This is not surprising, since the decrease of the print size corresponds to a relative decrease of the sentence length and as a consequence, the saccade length is getting smaller in a relative way. We also see that there is no effect caused by the repeatability.

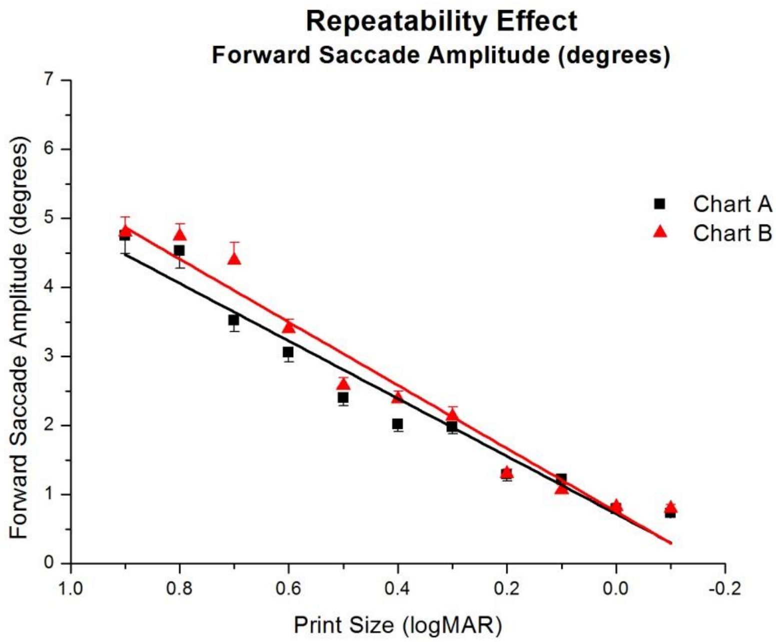

Fig. 29: *Learning effect: Mean forward saccade amplitude measured in degrees as a function of print size for the two consecutive times of reading*

Forward saccade length could also be expressed in characters. Fig. 30 shows the forward saccade length (characters) as a function of the print size (logMAR). Black line represents the first time of reading (Chart A), while the red one represents the second time of reading (Chart B). Both lines are linear fittings.

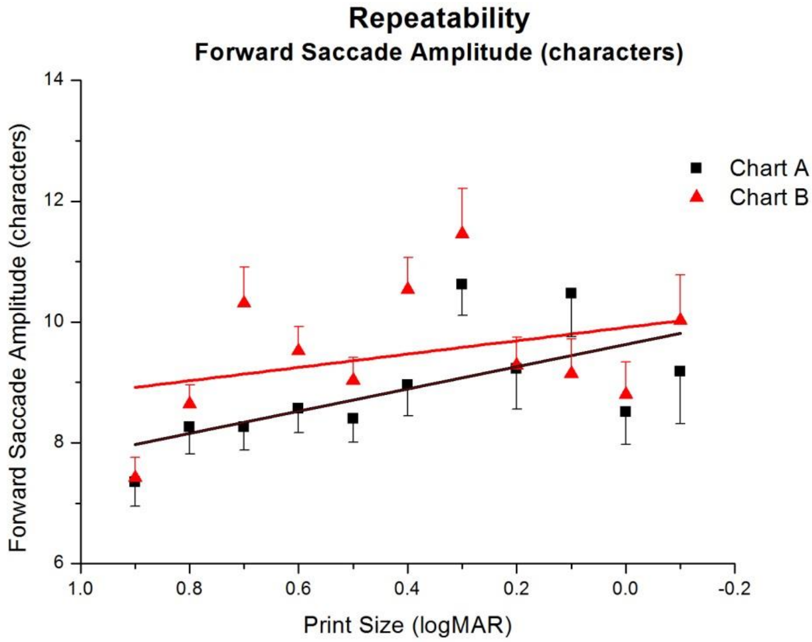

Fig. 30: *Learning effect: Mean forward saccade amplitude measured in number of characters*

It is clear that in the second time of reading the forward saccade length is greater, especially in big letters. This is in accordance with Fig. 26, which shows that in the second time of reading the mean number of fixations is smaller. In the first time of reading the amplitude is relatively stable with the print size, while in the second time of reading there is a small increase from about 8 to about 9 characters.

7.1.3 Reading Speed

In order to have a more general view of the time spent during reading, we used the parameter of reading speed, measured in characters per second (c.p.s). This parameter takes its value by the number of characters in each sentence (which, in Colenbrander Reading Cards is fixed to a number of 43) divided by the "total time" spent in each sentence. *Total time* equals to the mean fixation duration multiplied to the mean number of fixations. Reading speed takes into account both the fixation duration and the number of fixations.

$$\boldsymbol{Reading\ Speed} = \frac{Number\ of\ characters\ per\ sentence}{Total\ time}$$

$$= \frac{43}{mean\ fixation\ duration * mean\ number\ of\ fixations}$$

Fig. 31 shows the reading speed (c.p.s) as a function of the print size (logMAR). Each point of the graph represents the mean of all participants' mean reading speed. Black line represents the first time of reading (Chart A), while the red one represents the second time of reading (Chart B). Both lines are fitted by second order polynomial.

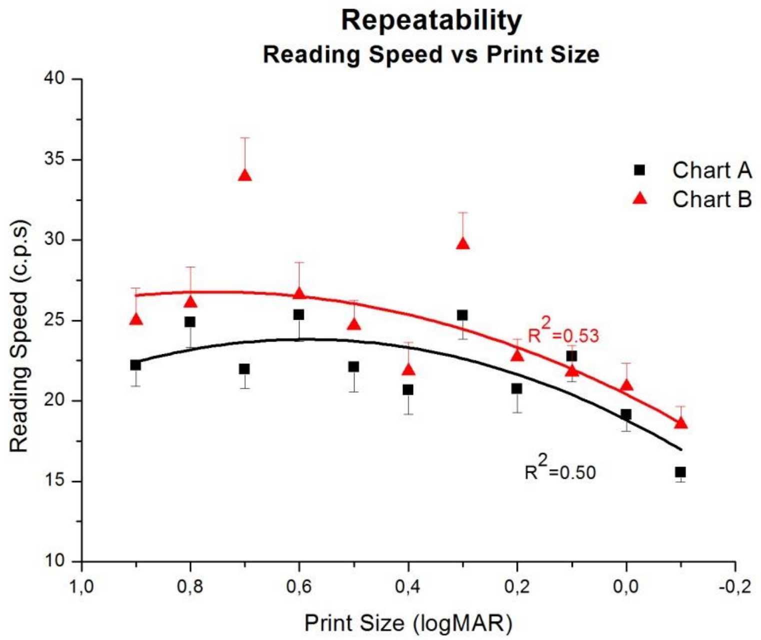

Fig. 31: *Learning effect: Reading speed measured in characters per second that were read as a function of the print size*

We can see that reading speed is higher in the second time of reading, especially in big letters. This change seems to be less evident in smaller letters.

7.2 Contrast Effect

In this section we test the effect of contrast on the characteristics of fixations and saccadic movements. In order to do it, we analyzed the reading behavior of each participant in the “second lines” of the two reading cards, i.e. the sentences 2, 4, 6 etc. The “second lines” of the first chart are on contrast 100%, while the sentences of the “second lines” of chart B are the same, but on contrast 10%.

7.2.1 Fixations

Fig. 32 shows the median fixation duration (msec) as a function of the print size (logMAR). We used the median and not the mean fixation duration, since we know that the fixation duration distribution is not a normal distribution. Each point of the graph represents the mean of all participants of the median fixation duration of each participant. Black line represents the first time of reading (Chart A) with 100% contrast, while the red one represents the second time of reading (Chart B). Both lines are fitted by Exponential Decay function:

$$y = y_0 + A_1 e^{-(x-x_0)/t_1}$$

For the line for 100% contrast, fitting parameters were found to be: $y_0 = 225.70$, $x_0 = -0.11$, $A_1 = 286.60$ and $t_1 = 0.16$.

For the line for 10% contrast, fitting parameters were found to be: $y_0 = 225.05$, $x_0 = -0.20$, $A_1 = 252.65$ and $t_1 = 0.12$.

Data for 10% contrast are presented only up to 0.2 logMAR. This is because the smallest letter that could be read by all participants was 0.2 logMAR.

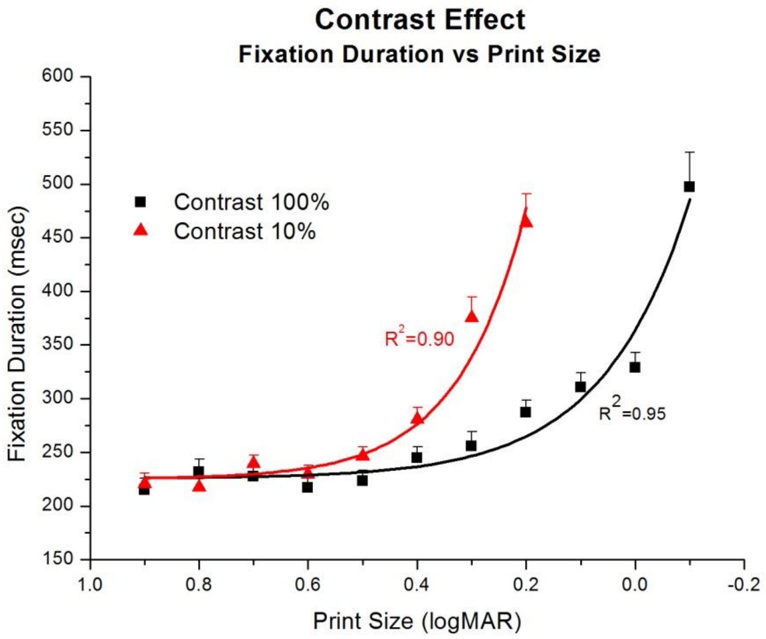

Fig. 32: *Contrast effect: Median fixation duration as a function of the print size*

As far as the print size effect is concerned, we checked for the 10% contrast, in which two successive print sizes, the difference of the median fixation duration is statistically significant. We found that the difference in the median fixation duration is statistically significant from print size 0.4 logMAR to 0.3 logMAR (p=0.000) and it's even greater in the successive pairs of smaller print sizes.

We can see that fixation duration in large letters is not affected by the change in contrast. The change on fixation duration is more evident in 0.4 logMAR print size (p=0.023) and for smaller letters.

Figure 33 shows the mean number of fixation per sentence as a function of the print size (logMAR). Each point of the graph represents the mean of all participants'mean number of fixations. Black line represents the first time of reading (Chart A), while the red one represents the second time of reading (Chart B).

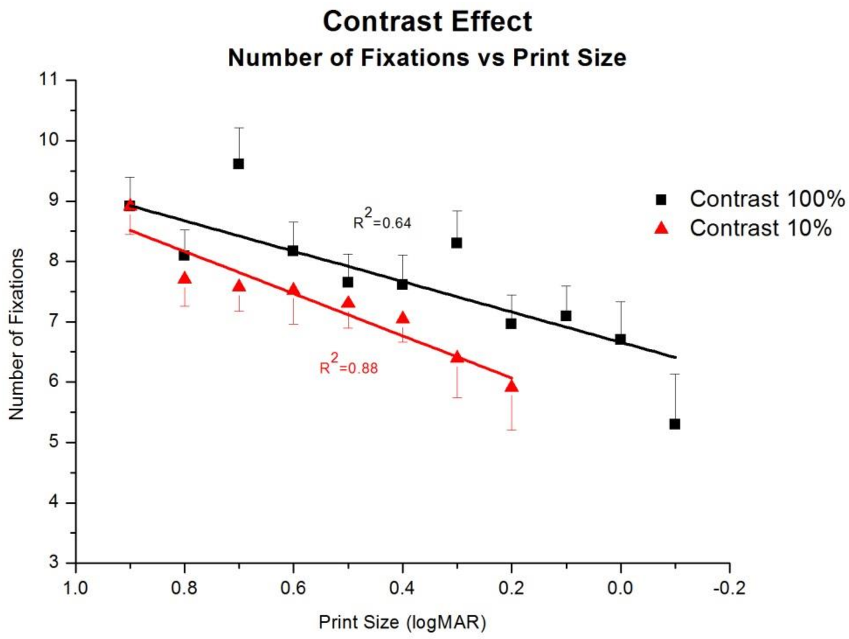

Fig. 33: *Contrast effect: Mean number of fixations as a function of the print size*

As we can see, the number of fixations decreases in both conditions as the print size is getting smaller.

Figure 34 shows the difference in the number of fixations between the two conditions of contrast as a function of the print size.

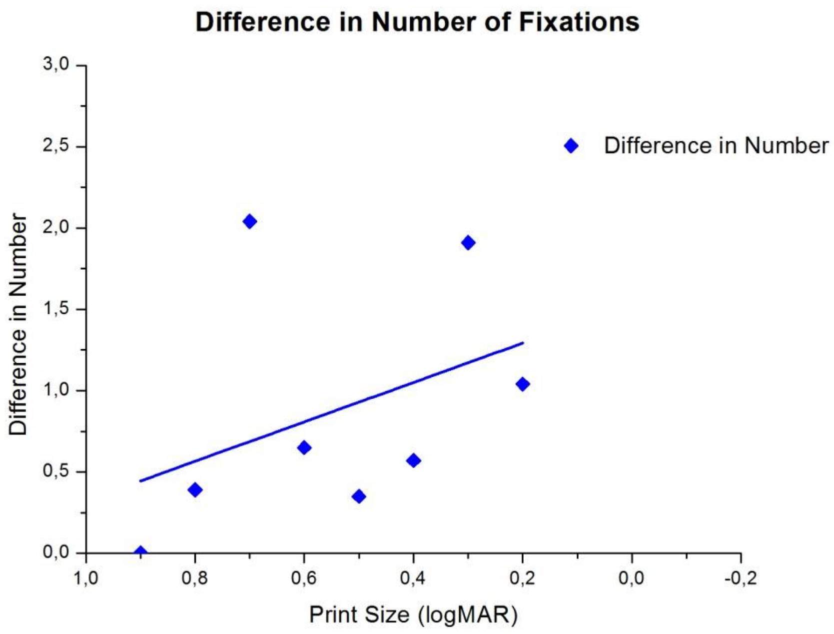

Fig. 34: *Difference in mean number of fixations between high and low contrast as a function of the print size*

As we can see, there is a small decrease of the number of fixations in 10% contrast compared to 100% contrast (by 0.5 to 2 fixations per line). This change seems to be more pronounced for smaller print size, but this is not statistically significant (p-value=0.313). We have to take into account though that the only difference between the sentences of 100% and 10% contrast is the contrast. Apart from that, the sentences are exactly the same. This means that the contrast effect contains the repeatability effect. The sentences of 10% contrast are read after the 100% contrast sentences, so the change observed is not entirely because of the contrast change.

7.2.2 Saccades

Fig. 35 shows the percentage of regressions (%) among all saccades as a function of print size (logMAR). Again, black line represents the first time of reading (Chart A) with 100% contrast, while the red one represents the second time of reading (Chart B) with 10% contrast. Both lines are linear fittings.

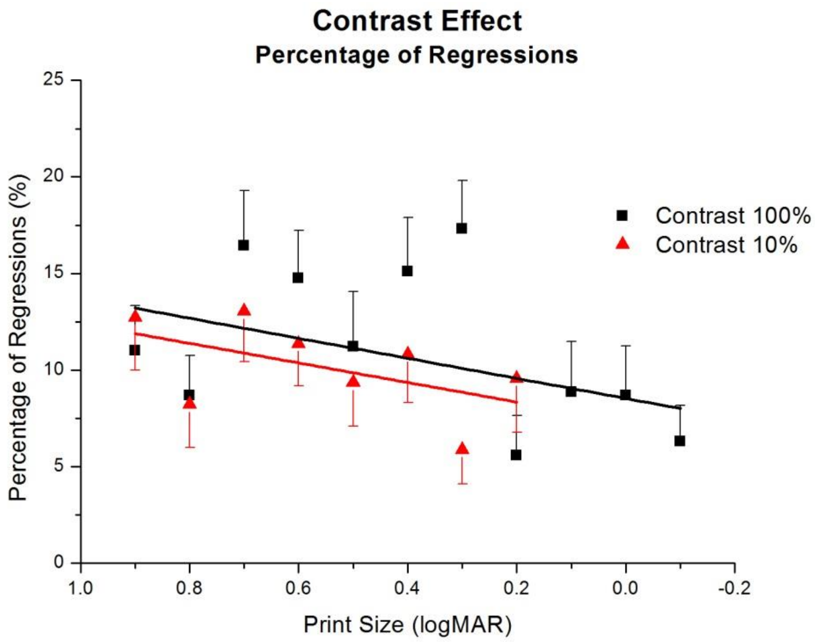

Fig. 35: *Contrast effect: Percentage of regressions as a function of the print size*

The percentage of regressions shows a small decrease with the change of print size in both conditions, 100% and 10% contrast. We can also see that the percentage is slightly affected by the change in contrast.

Fig. 36 shows the forward saccade length measured in degrees of arc as a function of the print size (logMAR). As we can clearly see, there is a linear relation of these two parameters. As the print size is getting smaller, the forward saccade length is getting smaller too. The contrast effect is not very evident. We can say that the decrease the forward saccade length in 10% contrast is steeper than in 10% contrast.

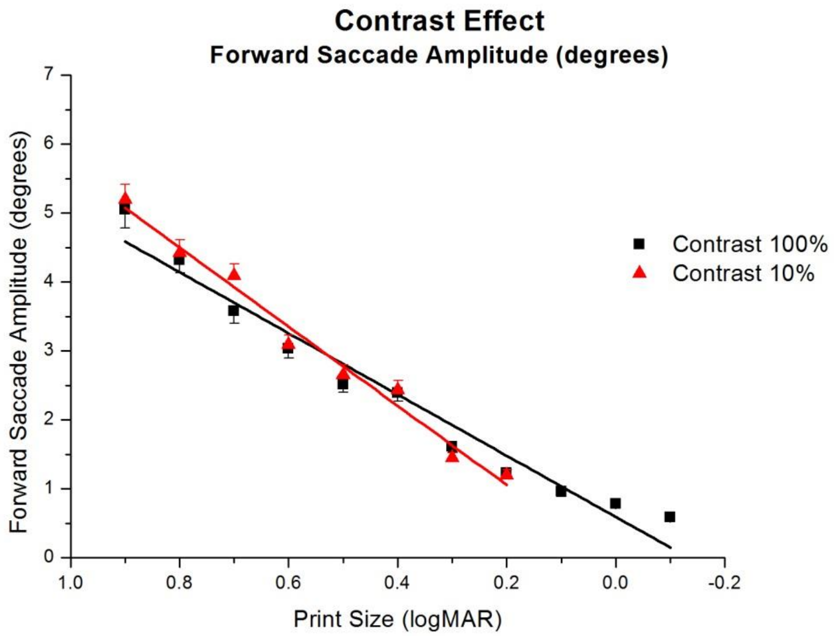

Fig. 36: *Contrast effect: Mean forward saccade amplitude measured in degrees as a function of the print size*

Fig. 37 shows the forward saccade length measured in characters as a function of the print size (logMAR). Black line represents the first time of reading (Chart A) with 100% contrast, while the red one represents the second time of reading (Chart B) with 10% contrast. Both lines are linear fittings.

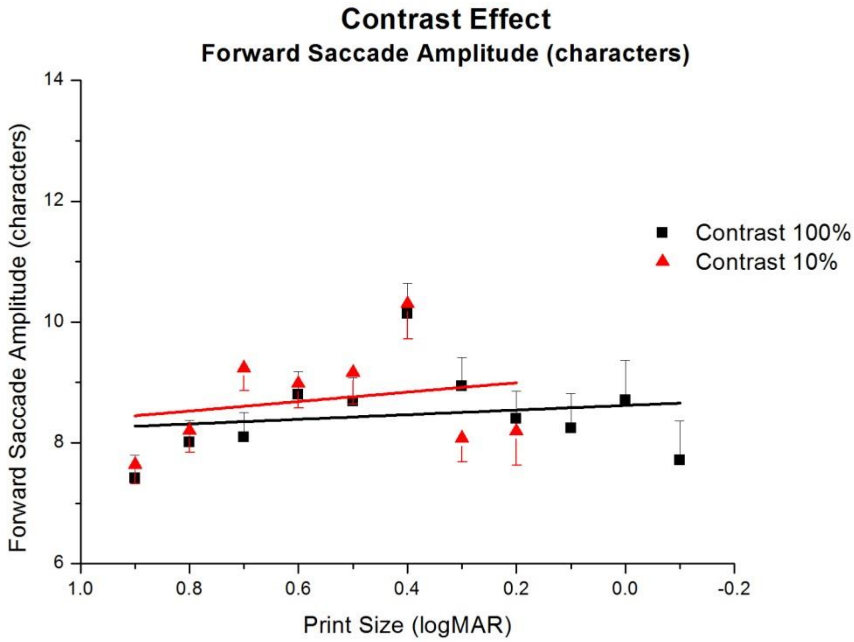

Fig. 37: *Contrast effect: Mean forward saccade amplitude measured in characters as a function of the print size*

As we can see, the forward saccade amplitude stays relatively intact with the change in contrast. In both conditions, print size does not affect the saccade amplitude.

7.2.3 Reading Speed

Fig. 38 shows the reading speed (c.p.s) as a function of the print size (logMAR). Each point of the graph represents the mean of all participants of the mean reading speed of each participant. Black line represents the first time of reading (Chart A) with 100% contrast, while the red one represents the second time of reading (Chart B) with 10% contrast. Both lines are fitted by second order polynomial.

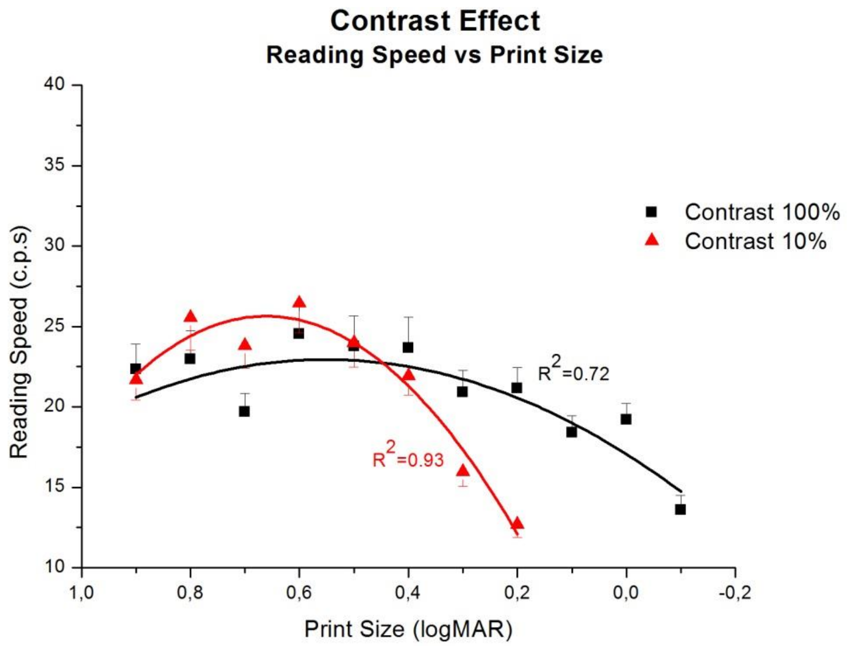

Fig. 38: *Contrast effect: Reading speed measured in characters read per second as a function of the print size*

In fig. 38 reading speed behavior is shown. In large letters, it seems to be higher in the second time of reading with 10% contrast. However, in 0.4 logMAR this situation changes and reading speed is higher in 100% contrast. The reason for this phenomenon may be the fact that in big letters the learning effect is more evident than contrast effect, while as the print size is getting smaller the effect of contrast is getting more important.

8. Experiment 2

8.1 Luminance Effect

In this section we test the effect of luminance on the characteristics of fixations and saccadic movements. In order to do it, we analyzed the reading behavior of each participant using the "second lines" of the 100% contrast reading card, i.e. the sentences 2, 4, 6 etc. The first time of reading is in 1 lux luminance, while the second time of reading is in luminance of about 64 lux.

8.1.1 Fixations

Fig. 39 shows the median fixation duration (msec) as a function of the print size (logMAR). Each point of the graph represents the mean of all participants of the median fixation duration of each participant. Black line represents the first time of reading (Chart A) with low luminance, while the red one represents the second time of reading (Chart A) with high luminance. Both lines are fitted by Exponential Decay function:

$$y = y_0 + A_1 e^{-(x-x_0)/t_1}$$

For the line of high luminance, fitting parameters were found to be: $y_0 = 210.26$, $x_0 = -0.15$, $A_1 = 263.27$ and $t_1 = 0.22$.

For the line of low luminance, fitting parameters were found to be: $y_0 = 247.39$, $x_0 = -0.28$, $A_1 = 206.45$ and $t_1 = 0.16$.

Data for low luminance are presented only up to 0.3 logMAR. This is because most of the participants read until this print size. More specifically, out of 15 participants, only 9 read down to 0.2 logMAR and 14 read down to 0.3 logMAR.

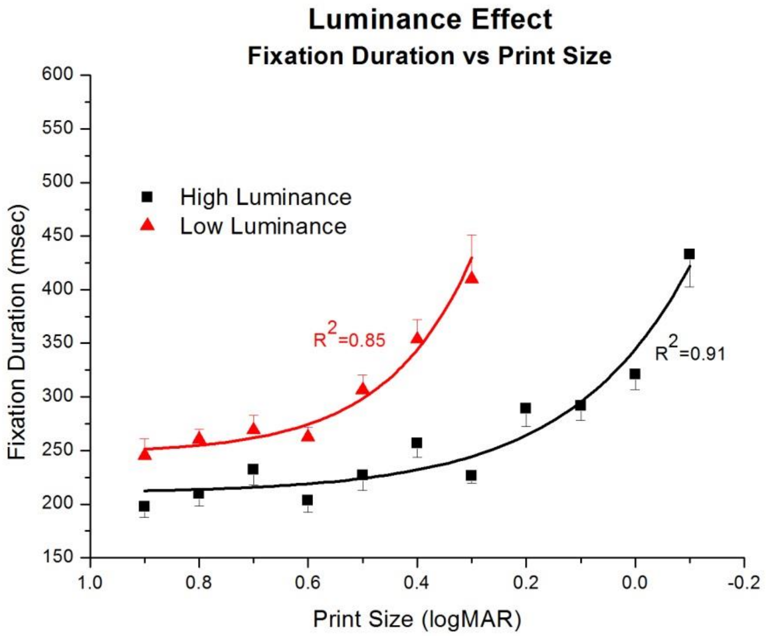

Fig. 39: *Luminance effect: Median fixation duration as a function of the print size*

As far as the print size effect is concerned, we checked for the low luminance condition, in which two successive print sizes, the difference of the median fixation duration is statistically significant. We found that the difference in the median fixation duration is significant from print size 0.4 logMAR to 0.3 logMAR (p=0.029) and it's getting greater in the next successive pair.

We can see that low luminance affects fixation duration right from the biggest letters. The difference is statistically significant in 0.9 logMAR (p=0.014). The change on fixation duration in low luminance is getting even more evident in letters of 0.5 logMAR and more pronounced for smaller letters.

Figure 40 shows the mean number of fixation per sentence as a function of the print size (logMAR). Each point of the graph represents the mean of all participants' mean number of fixations. Red line represents the first time of reading (Chart A) with low luminance, while the black one represents the second time of reading (Chart A) with high luminance.

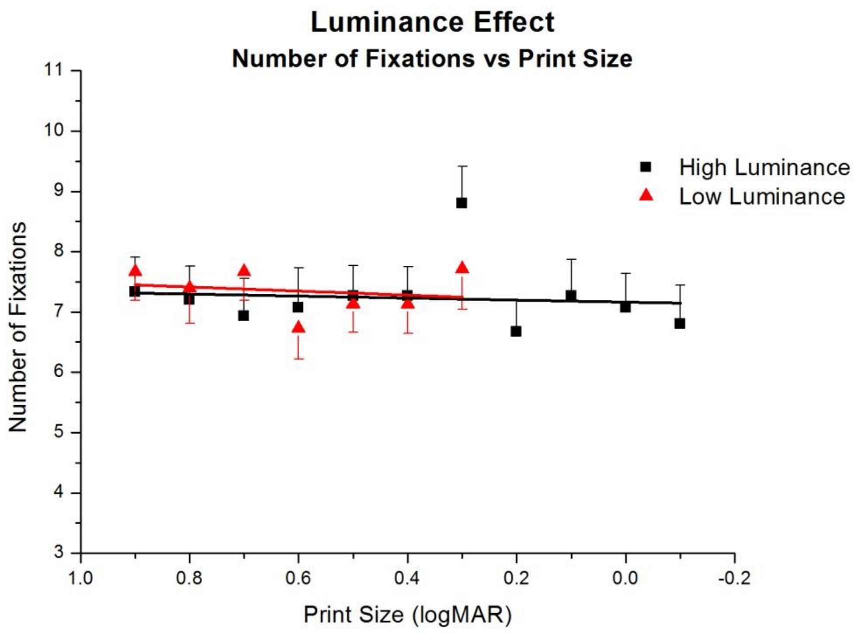

Fig. 40: *Luminance effect: Mean number of fixation per sentence as a function of the print size*

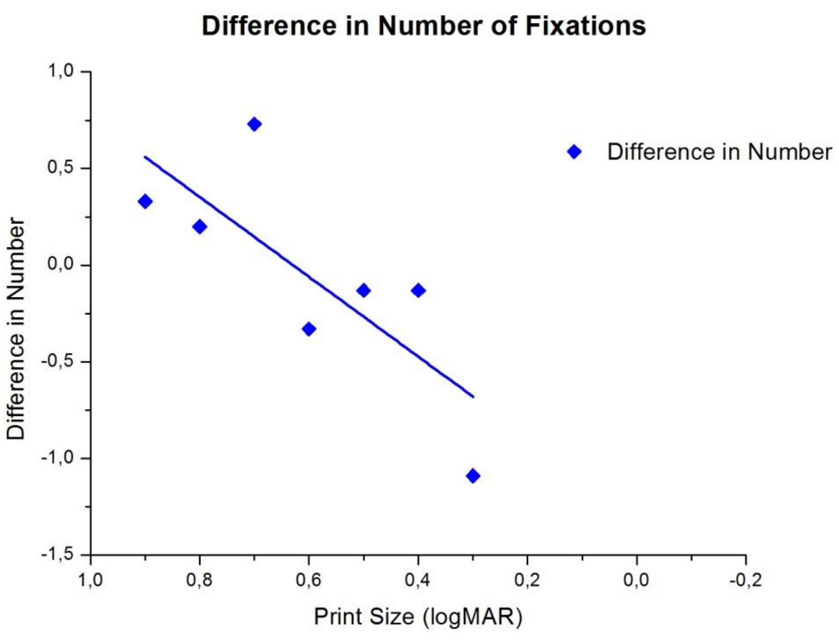

Fig. 41: *Difference in mean number of fixations between high and low luminance conditions as a function of the print size*

As we can see, the mean number of fixations in low and high luminance is the same. We have to take into account though that the luminance effect contains the repeatability effect. The sentences of low luminance are read before the high luminance sentences, so the change that we notice is not entirely because of the contrast change.

8.1.2 Saccades

Fig. 42 shows the percentage of regressions (%) among all saccades as a function of print size (logMAR). Again, red line represents the first time of reading (Chart A) with low luminance, while the black one represents the second time of reading (Chart B) with high luminance. Both lines are linear fittings.

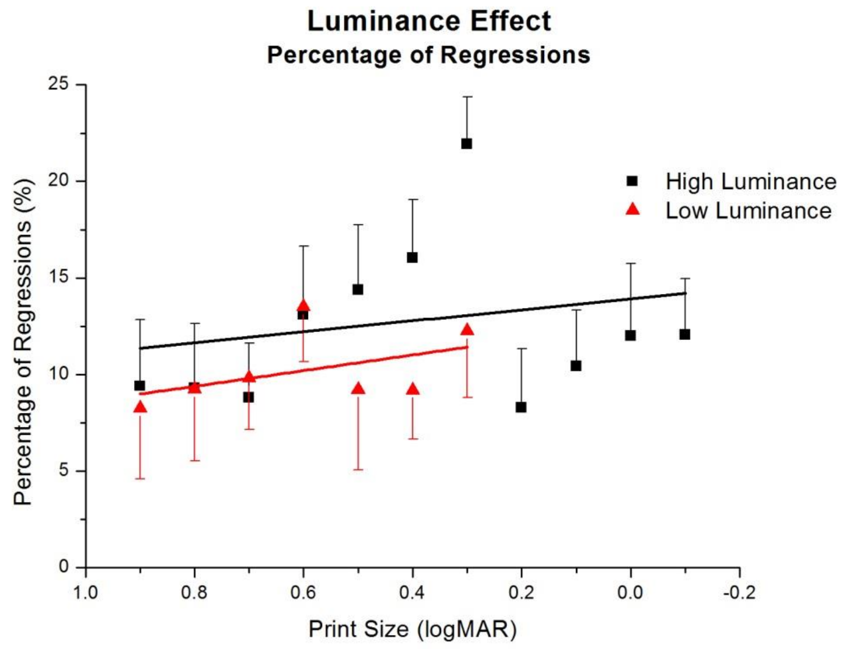

Fig. 42: *Luminance effect: Percentage of regressions as a function of the print size*

The percentage of regressions shows a small increase with the change of print size in both conditions, high and low luminance. We can also see that the percentage is affected by the change in luminance, with the low luminance condition showing smaller percentage of regressions.

Fig. 43 shows the forward saccade length measured in degrees as a function of the print size (logMAR). We can clearly see in this condition too, the linear relation of these two parameters. As the print size decreases, the forward saccade length is decreasing too. The luminance effect is not very evident.

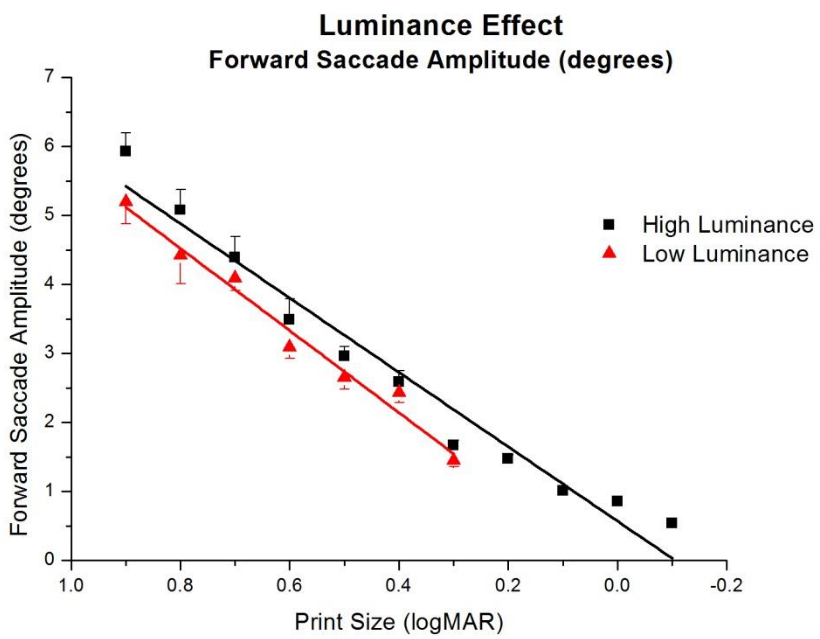

Fig. 43: *Luminance effect: Mean forward saccade amplitude measured in degrees as a function of the print size*

Fig. 44 shows the forward saccade length measured in characters as a function of the print size (logMAR). Again, red line represents the first time of reading (Chart A) with low luminance, while the black one represents the second time of reading (Chart B) with high luminance. Both lines are linear fittings.

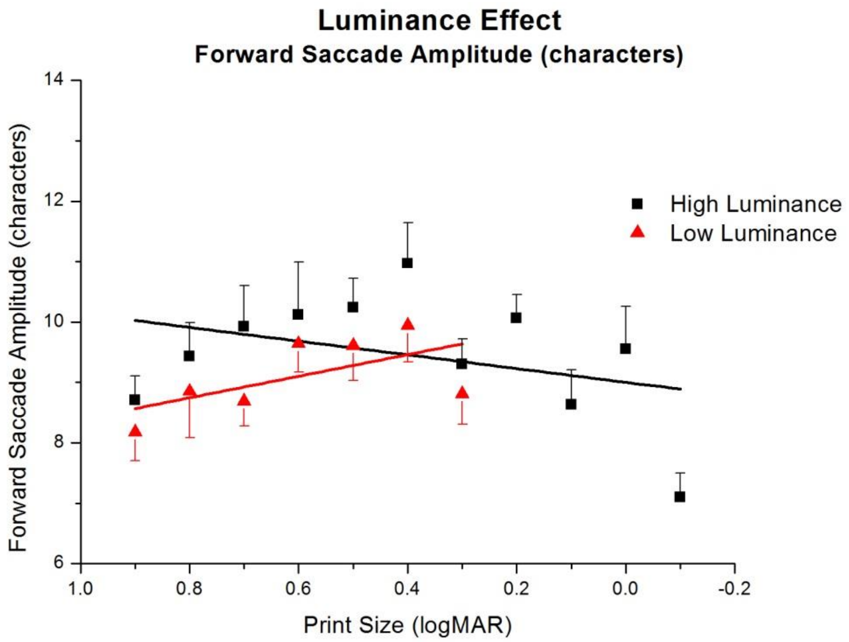

Fig. 44: *Luminance effect: Mean forward saccade amplitude measured in characters as a function of the print size*

As we can see, the forward saccade amplitude stays relatively intact with the change in luminance. In both conditions, print size does not affect the saccade amplitude.

8.1.3 Reading Speed

Fig. 45 shows the reading speed (c.p.s) as a function of the print size (logMAR). Each point of the graph represents the mean of all participants of the mean reading speed of each participant. Red line represents the first time of reading (Chart A) with low luminance, while the black one represents the second time of reading (Chart A) with high luminance. Both lines are fitted by second order polynomial.

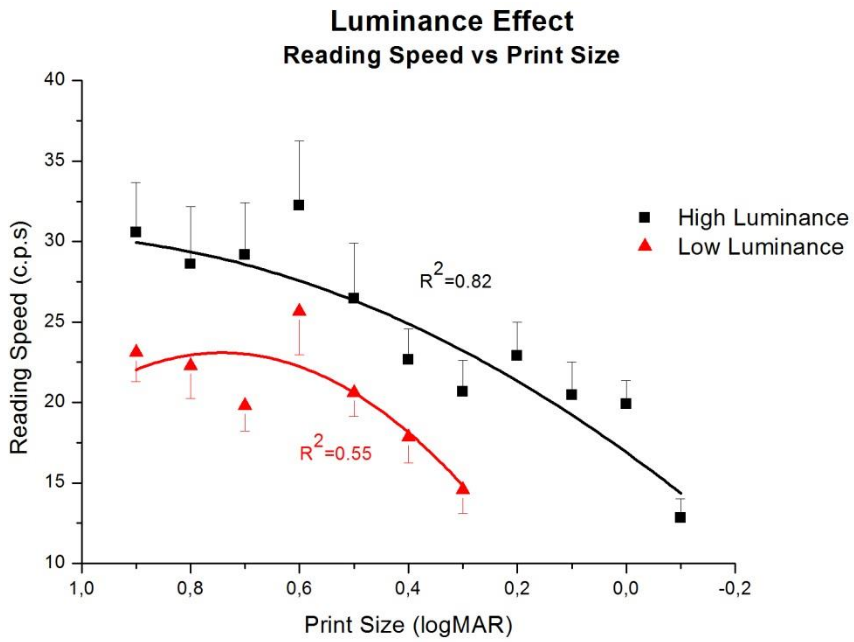

Fig. 45: *Luminance effect: Reading speed measured in characters read per second as a function of the print size*

In fig. 45 reading speed seems to be much higher in high luminance condition. This change appears both because of the luminance effect but also because the high luminance session was conducted after the low luminance session, so any learning effect is included.

8.2 Luminance vs Contrast Effect

Fig. 46 is a cumulative graph of the contrast and luminance effect. It is the median fixation duration (msec) as a function of the print size (logMAR). Each point in the graph represents the mean of all participants' median fixation duration. Black line represents the first time of reading (Chart A) with 100% contrast, the red one represents the second time of reading (Chart B) with 10% contrast and blue line represents low luminance condition. All lines are fitted by Exponential Decay function:

$$y = y_0 + A_1 e^{-(x-x_0)/t_1}$$

For the line for 100% contrast, fitting parameters were found to be: $y_0 = 225.70$, $x_0 = -0.11$, $A_1 = 286.60$ and $t_1 = 0.16$.

For the line for 10% contrast, fitting parameters were found to be: $y_0 = 225.05$, $x_0 = -0.20$, $A_1 = 252.65$ and $t_1 = 0.12$.

For the line of low luminance, fitting parameters were found to be: $y_0 = 247.39$, $x_0 = -0.28$, $A_1 = 206.45$ and $t_1 = 0.16$.

Data for 10% contrast are presented only down to 0.2 logMAR and for low luminance, down to 0.3 logMAR.

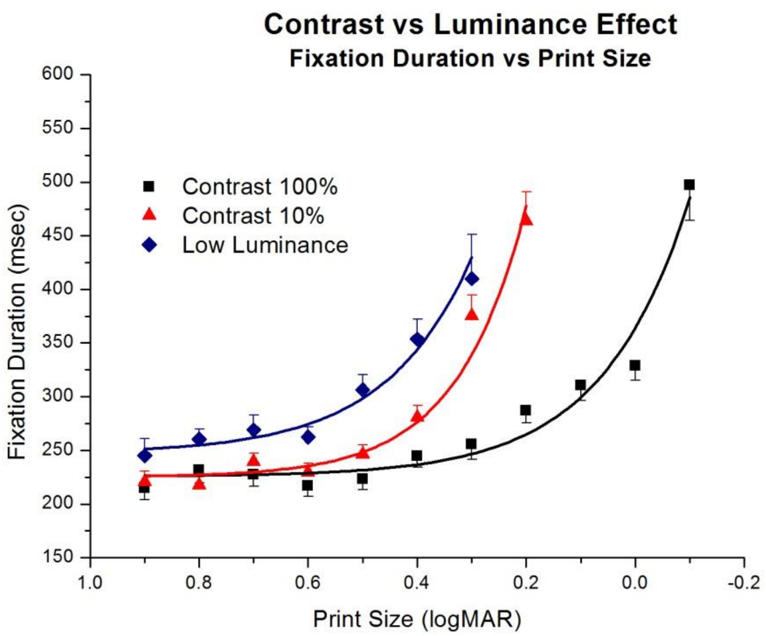

Fig. 46: *Contrast vs Luminance effect: Median fixation duration as a function of the print size*

In our study, we found that low luminance affects fixation duration right from the largest letters. This effect is more pronounced as the print size is reduced. On the contrary, we found that 10% contrast has a lesser effect on fixation duration. The effect is evident only from 0.4 logMAR.

Figure 47 shows the mean number of fixation per sentence as a function of the print size (logMAR). Each point of the graph represents the mean of all participants of the mean number of fixations of each participant. Again, black line represents the first time of reading (Chart A) with 100% contrast, the red one represents the second time of reading (Chart A) with 10% contrast and finally, blue line represents low luminance condition.

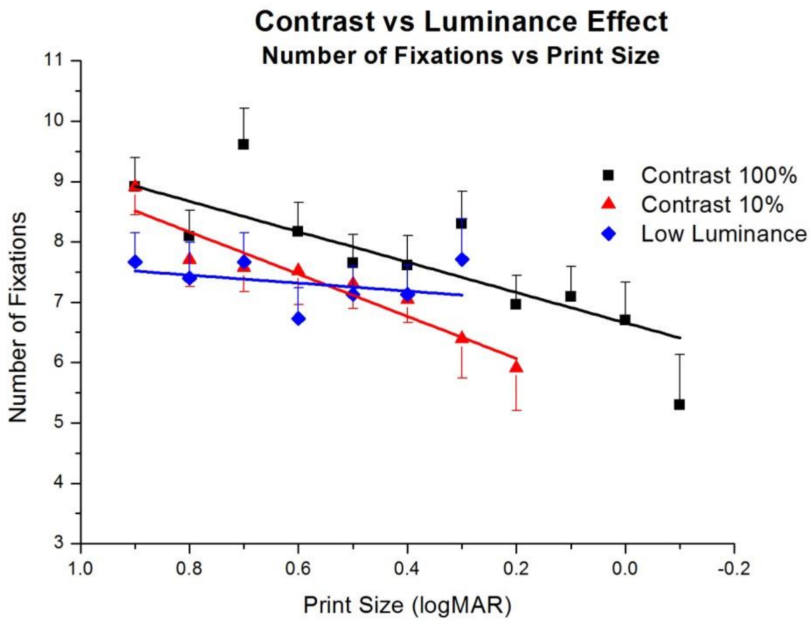

Fig 47: *Contrast vs Luminance effect: Mean number of fixations per sentence as a function of the print size*

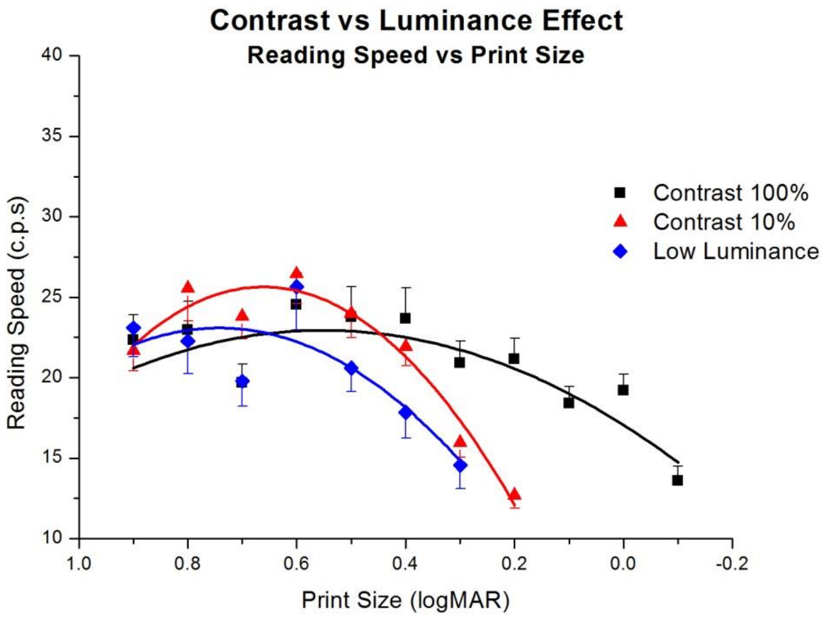

Fig. 47: *Contrast vs Luminance effect: Reading speed measured in characters read per second as a function of the print size*

9. Long Text vs Reading Card

9.1 Fixations

Figure 48 shows the median fixation duration for the "long text" in three conditions; first time of reading, second time of reading (both in high luminance) and low luminance.

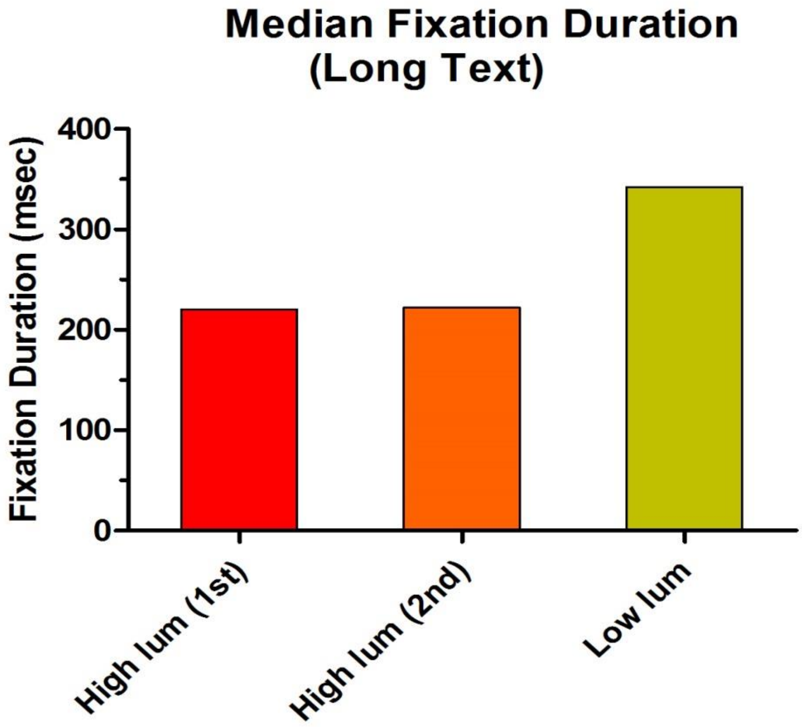

Fig. 48: *Median fixation duration in long text. High lum (1^{st}) column stands for the first time of reading in high luminance condition, High lum (2^{nd}) column stands for the second time of reading in high luminance condition and Low lum stands for the low luminance condition*

It is clear that there is no change in median fixation duration in the second time of reading, while there is a great increase in low luminance condition.

We notice similar pattern when using Colenbrander Reading Cards. Figure 49 shows the median fixation duration in four conditions; high contrast, high luminance, low contrast and low luminance for letters of 0.4 logMAR. We have to keep in mind that high contrast and high luminance conditions are exactly the same, but at different time period; high luminance session was conducted about two months after the high contrast session. These two conditions present about the same median fixation duration. The low contrast condition presents a small increase and the low luminance condition presents a significant change in median fixation duration.

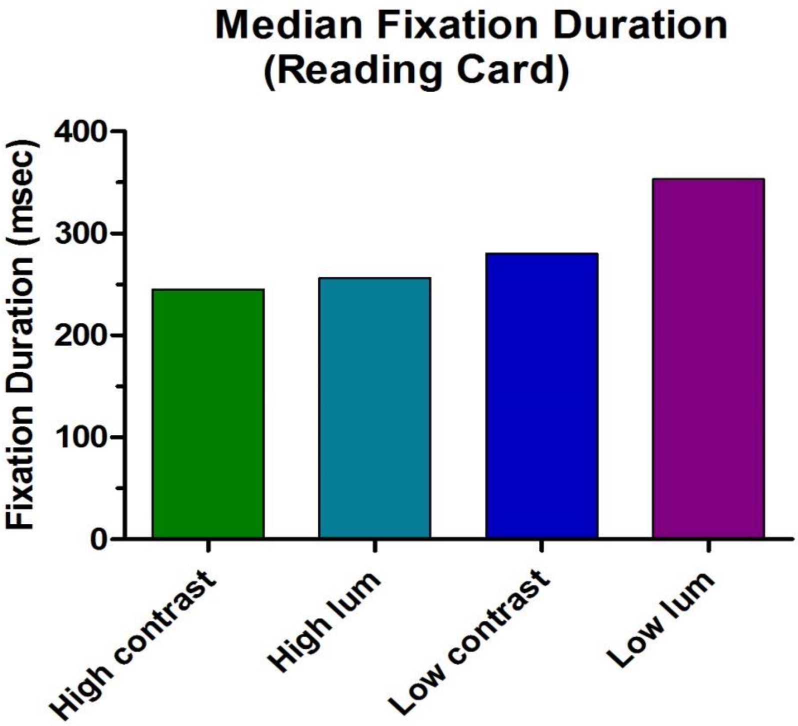

Fig. 49: *Median fixation duration for 0.4 logMAR letters in four recordings. High contrast, high luminance, low contrast and low luminance,*

9.2 Reading Speed

Comparison of the reading speed behavior in the different texts is indicative of the actual difference between them. Fig. 50 shows how reading speed differs in three conditions of the long text and four conditions of the reading cards.

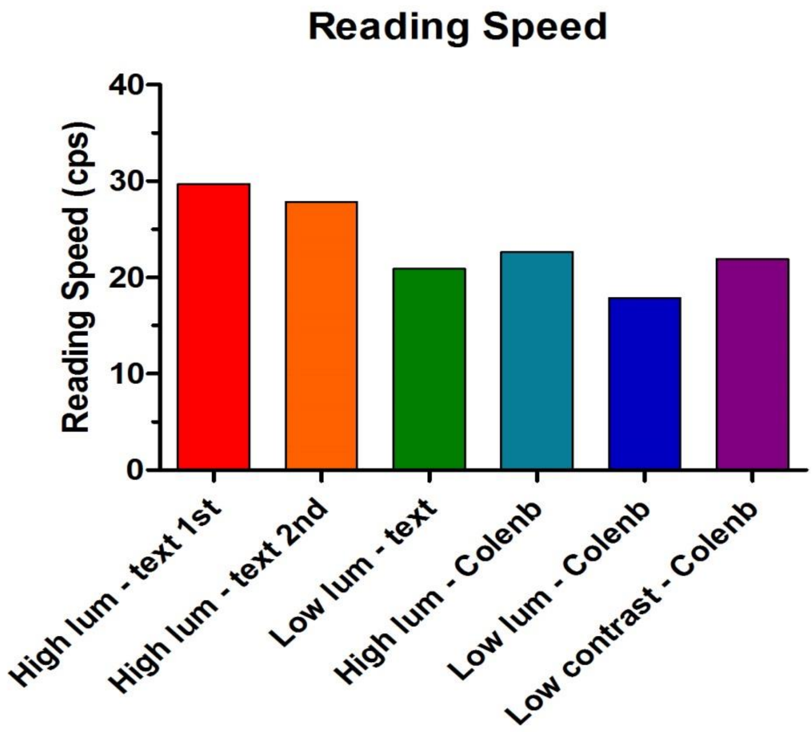

Fig. 50: *Reading speed in long text and in Colenbrander Reading Card in different conditions*

As far as the long text is concerned, we can see a slight difference in reading speed in the second time of reading compared to the first time. There is however a significant decrease in low luminance condition. In reading cards, the contrast effect is not evident, the luminance effect though, is. The most important finding though, is that in all conditions the participants were slower in the reading cards compared to the long text.

10. Fixation Duration Distribution

10.1 Distributions

We have already noted that examining the fixation duration distribution using the ex-Gaussian analysis, will give more detail regarding the eye fixation pattern during reading. To achieve this we analyzed the fixation duration distribution for each participant for each line of the reading card. Afterwards, we split fixation durations of each line into bins of 50 msec each. Starting from bin number 1; 51-100 msec, up until the last one; 951-1000 msec. Finally, we summed the bins for all lines of all participants, so as to have a distribution of fixation durations of all participants for each line.

Figure 51 shows an example of ex-Gaussian fitting in fixation duration distribution. We see the frequency of appearance of fixations with certain duration. This distribution is for the 10% contrast condition for the largest letters, 0.9 logMAR. It is clear that the distribution is not normal. There is positive skewness.

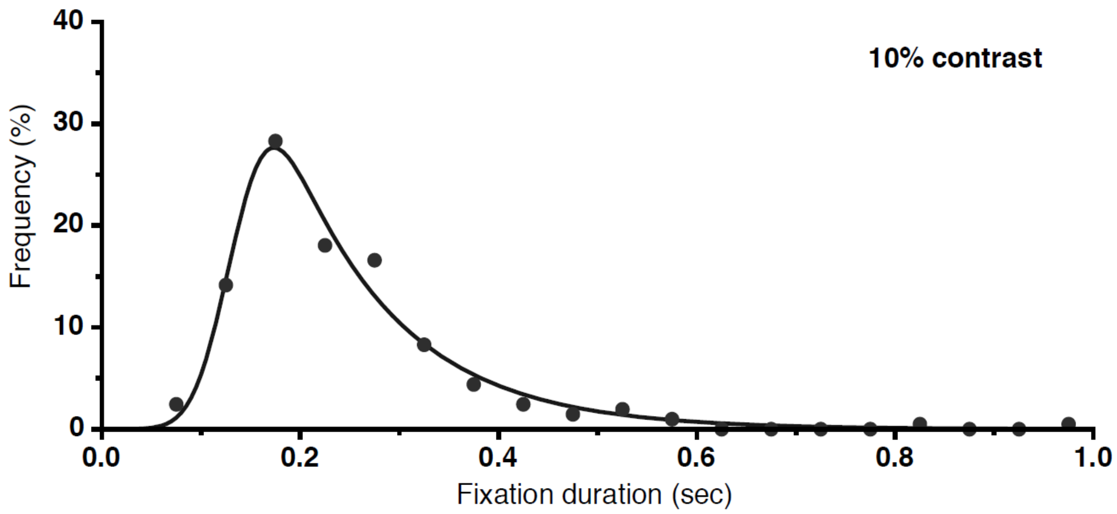

Fig. 51: *Ex-Gaussian fitting in fixation duration distribution in 10% contrast and for 0.9 logMAR letters.*

10.1.1 Overall View

We followed this exact procedure for all conditions and all print sizes. Fig. 52 shows how the fixation duration distribution changes as the print size is changing in first lines of the100% contrast condition. Fig. 53 shows distributions for the same condition but for the second lines. The only difference between these two graphs is that they show fixation duration distribution of different sentences. The darkest line represents the biggest letters i.e. 0.9 logMAR and as the ink is getting lighter, the print size is getting smaller.

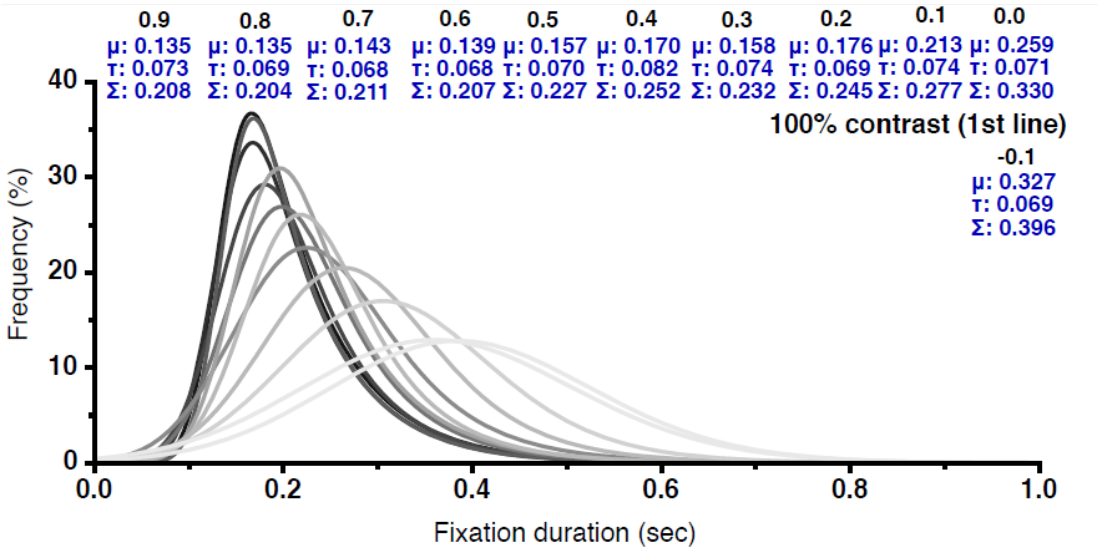

Fig. 52: *Ex-Gaussian fitting in fixation duration distribution in the 1st lines of Chart A in 100% contrast*

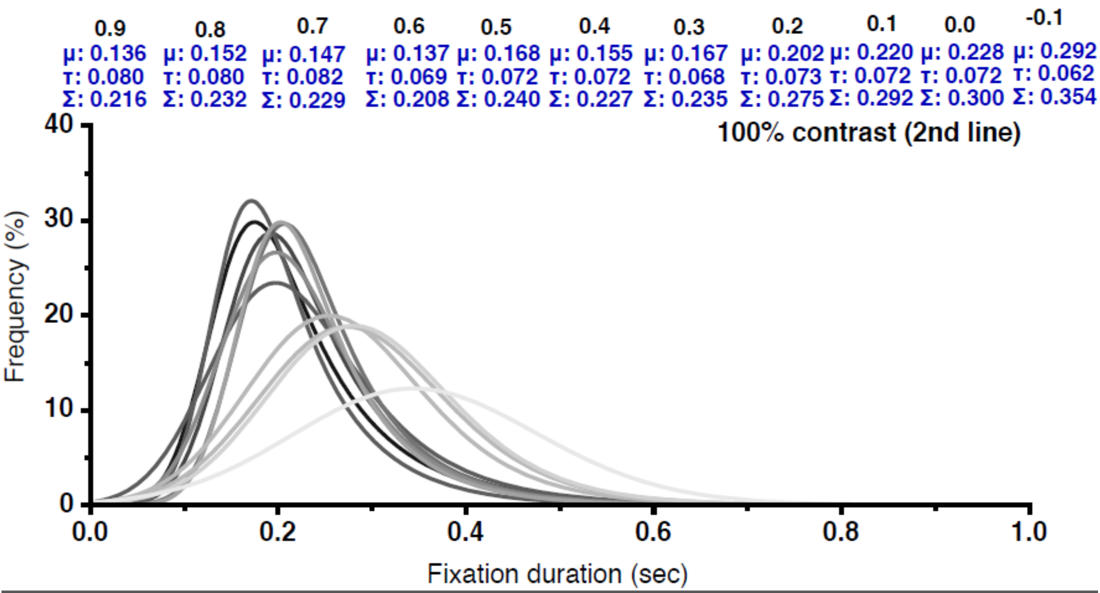

Fig. 53: *Ex-Gaussian fitting in fixation duration distribution in the 2nd lines of Chart A in 100% contrast*

We can see a gradual change in the distribution as the print size changes. We notice a shift of the distribution to the right for smaller letters. The data on top of the graphs are the ex-Gaussian parameters that will be discussed in paragraph 10.2. Taking a look at this data we can say that parameter μ shows a gradual increase as the print size is getting smaller, parameter Σ shows an analogous increase and parameter τ stays relatively stable. Further analysis of the parameters will be conducted in paragraph 10.2.

Figures 54 and 55 show the fixation duration distributions for Chart B. Fig. 54 is for the first lines, which are in 100% contrast and fig. 55 is for the second lines, which are in 10% contrast. Finally, fig. 56 shows the fixation duration distributions in low luminance condition.

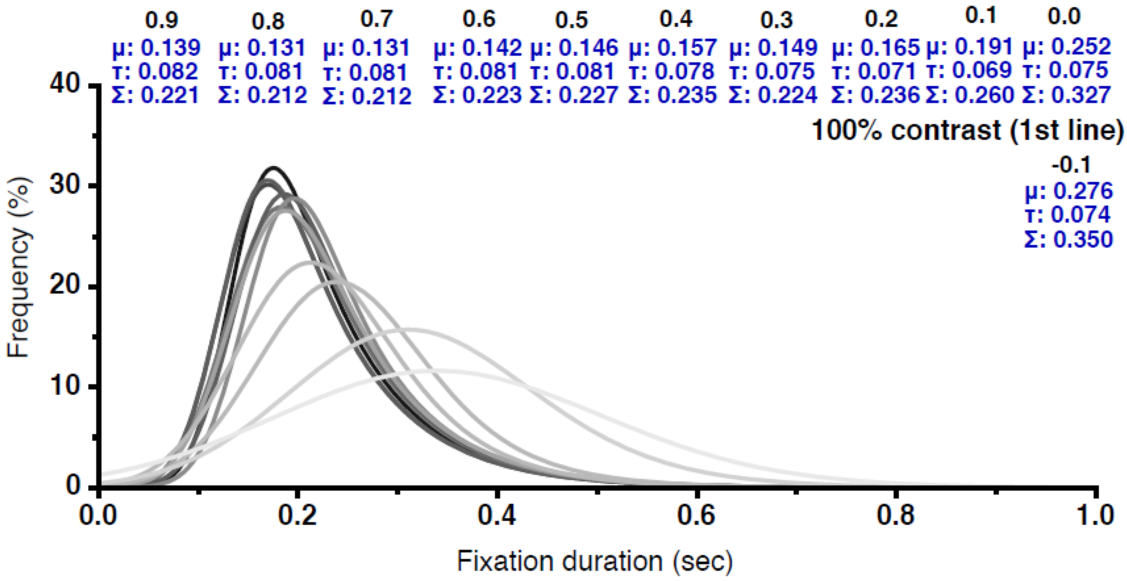

Fig. 54: *Ex-Gaussian fitting in fixation duration distribution in the 1st lines of Chart B in 100% contrast*

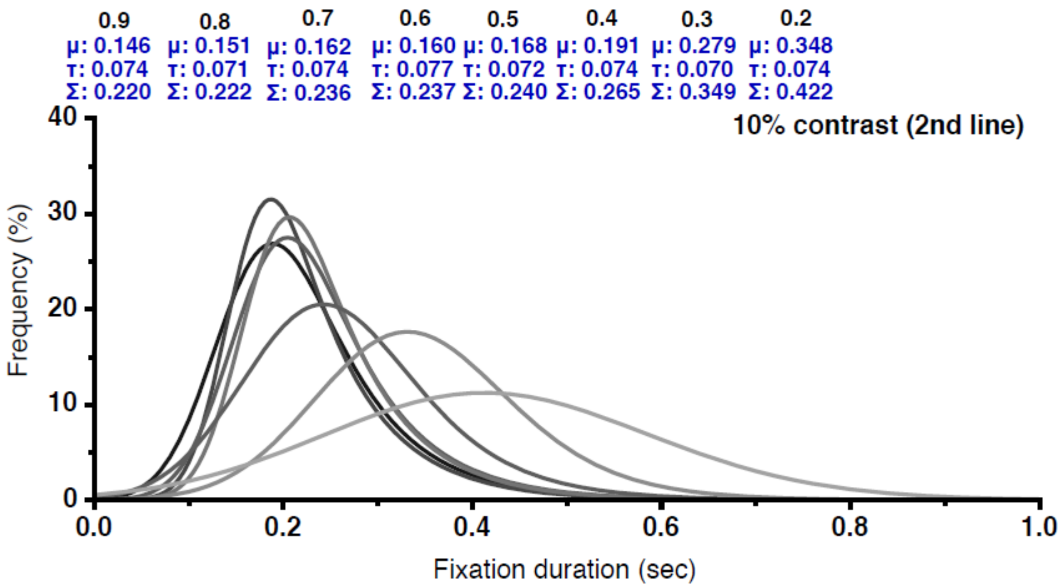

Fig. 55: *Ex-Gaussian fitting in fixation duration distribution in the 2nd lines of Chart B in 10% contrast*

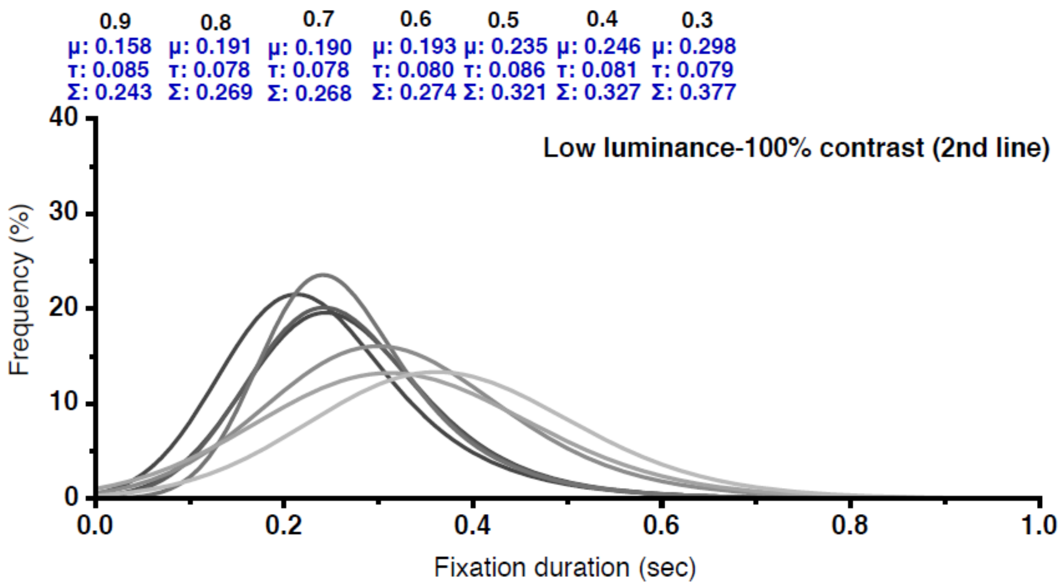

Fig. 56: *Ex-Gaussian fitting in fixation duration distribution in the 2nd lines of Chart A in low luminance*

10.1.2 Test-Retest Repeatability

Figure 57 shows the fixation distribution for the first lines of the reading cards for print size 0.4 logMAR. Blue line represents the first time of reading and red line represents the second time of reading. On the right we also present the ex-Gaussian parameters.

We notice a remarkable resemblance between these two distributions and the parameters show it too. Parameters μ, τ and σ are not affected by the second time of reading. This resemblance is proved by the two-sample Kolmogorov-Smirnov test for equality of distribution functions. The p-value was found 0.181 meaning that the two distributions are identical.

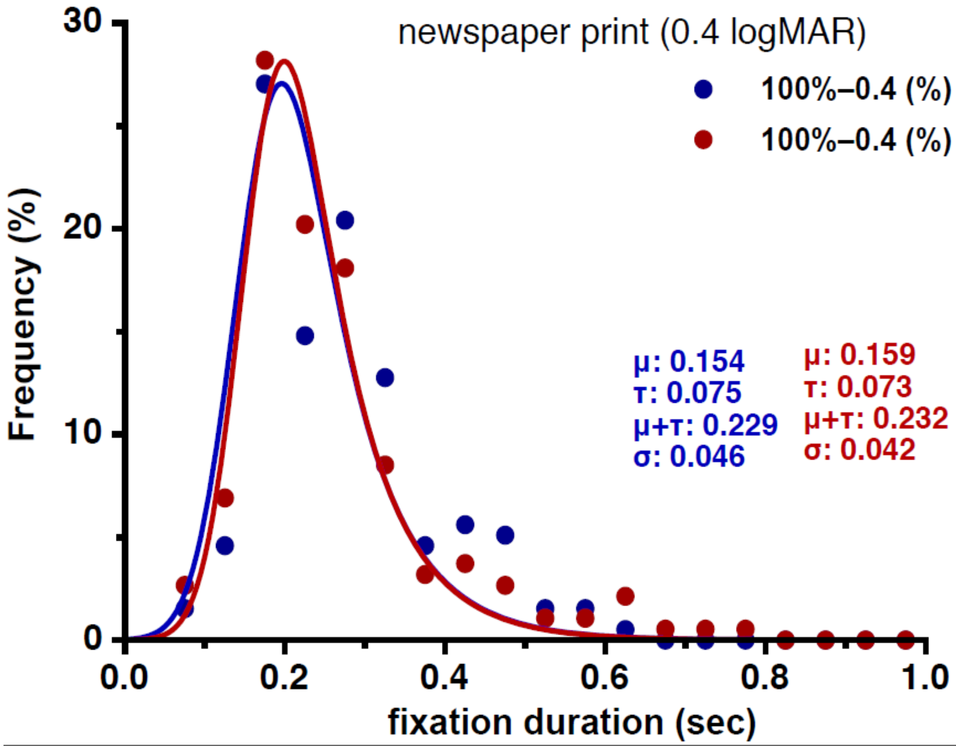

Fig. 57: *Learning effect: Ex-Gaussian fitting in fixation duration distribution for 0.4 logMAR letters in 100% contrast*

10.1.3 Contrast Effect

Figure 58 shows the fixation duration distribution for the second lines of the reading cards for print size 0.4 logMAR. Blue line represents the 100% and red line represents the 10% contrast. On the right we also present the ex-Gaussian parameters.

Apart from the obvious difference between the two distributions , we also have a qualitative analysis of them. Parameter μ increased 34.5% in 10% contrast, while parameter τ stays the same. Parameter σ also shows a great increase of 141%. The two-sample Kolmogorov-Smirnov test for equality of distribution functions gave p-value=0.009 meaning that the two distributions are different with the 100% contrast having smaller values (p=0.006).

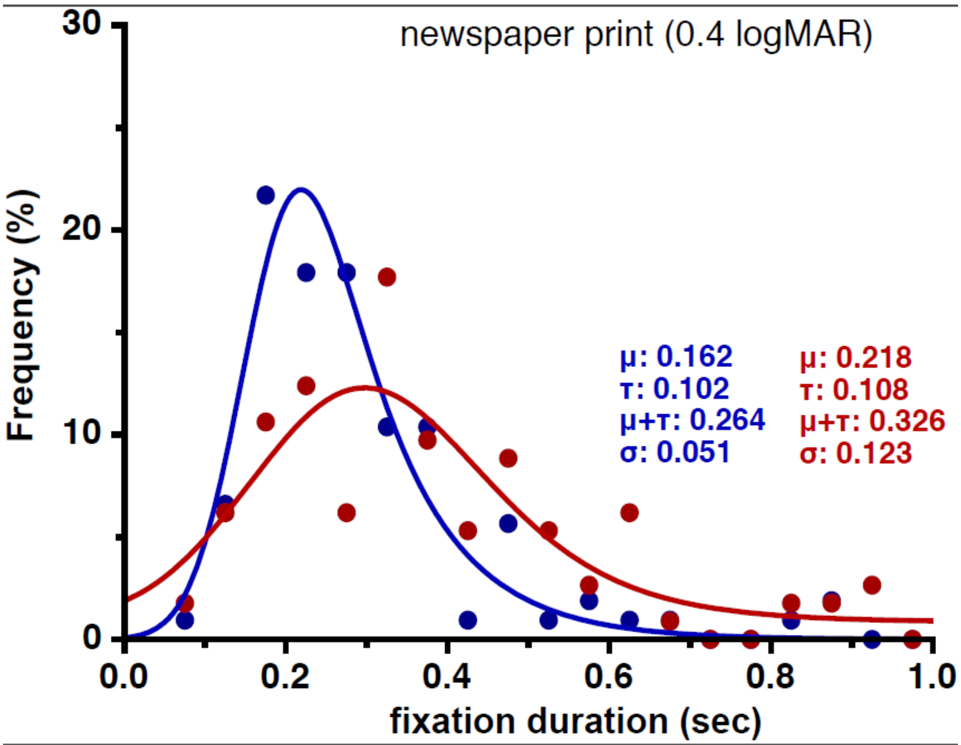

Fig. 58: *Contrast effect: Ex-Gaussian fitting in fixation duration distribution for 0.4 logMAR. Blue line represents 100% contrast and red line represents 10% contrast.*

10.1.4 Luminance Effect

Figure 59 shows the fixation duration distribution for the long text. Red solid line represents the first time for reading in high luminance, red dotted line represents the second time of reading in high luminance and blue line represents the low luminance condition. On the right we also present the ex-Gaussian parameters.

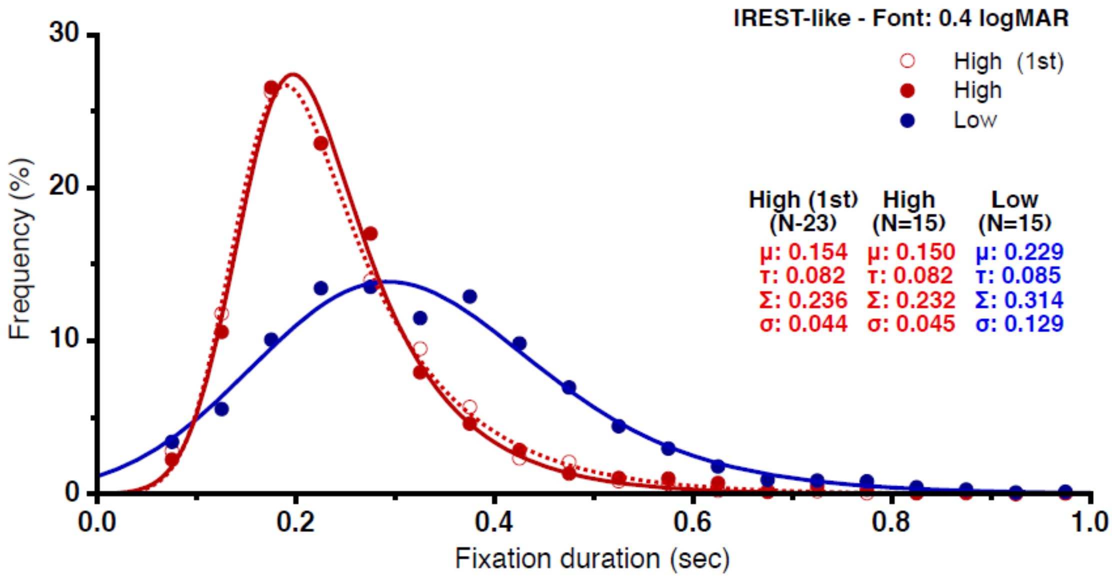

Fig. 59: *Luminance effect: Ex-Gaussian fitting in fixation duration distribution in the long text. Red solid line represents the first time of reading in high luminance, red dotted line represents the second time of reading 2 months after the first, in high luminance and blue line represents the low luminance condition*

Both times of reading in high luminance condition are very similar. Even with less participants in the second time of reading, both the shape of the distribution and the ex-Gaussian parameters are the same. Parameter μ increased from 154 msec to 229 msec (52.7% increase) in low luminance, parameter τ stayed the same and σ increased from 44 msec to 129 msec (186.7% increase).

10.2 Ex-Gaussian Parameters

The advantage of the ex-Gaussian analysis is that we can get into details of the distribution. The shape of the distribution gives a quantitative view of it. Analyzing however, the ex-Gaussian parameters we can say which part of the distribution changes and how much.

10.2.1 Parameter μ

As we have already mentioned, parameter μ represents the mode of the Gaussian (normal) part of the ex-Gaussian analysis. An increase of μ, with no change of any other parameter of the ex-Gaussian, would mean a shift of the whole distribution to the right without changing its shape. On the contrary, a decrease of μ means a left shift of the distribution.

Figure 60 plots parameter μ (msec) as a function of the print size (logMAR) in three conditions; 100% contrast, 10% contrast and at the low luminance condition. This graph resembles to figure 19.

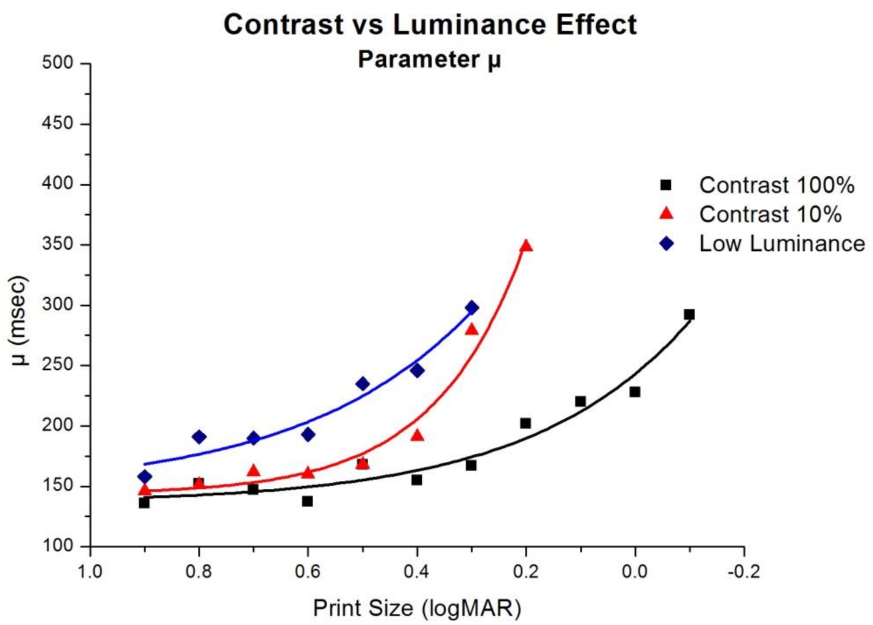

Fig. 60: *Contrast vs Luminance effect: Parameter μ as a function of the print size in 100% contrast, 10% contrast and low luminance*

In big letters there is no change in μ in all conditions. Of course, print size effect is evident in different sizes in each condition. In 100% contrast it's evident from 0.2 logMAR, in 10% contrast from 0.4 logMAR and in low luminance from 0.5 logMAR. We also notice a shift to the right in the distribution from 0.8 logMAR in low luminance and from 0.4 logMAR in 10% contrast.

Figure 61 shows how parameter μ changes in different conditions and in different stimuli. The first three bars show μ for the long text in high luminance first and second time of reading and in low luminance. The last four bars show μ for the reading cards in high contrast, high luminance, low contrast and low luminance condition for 0.4 logMAR print size.

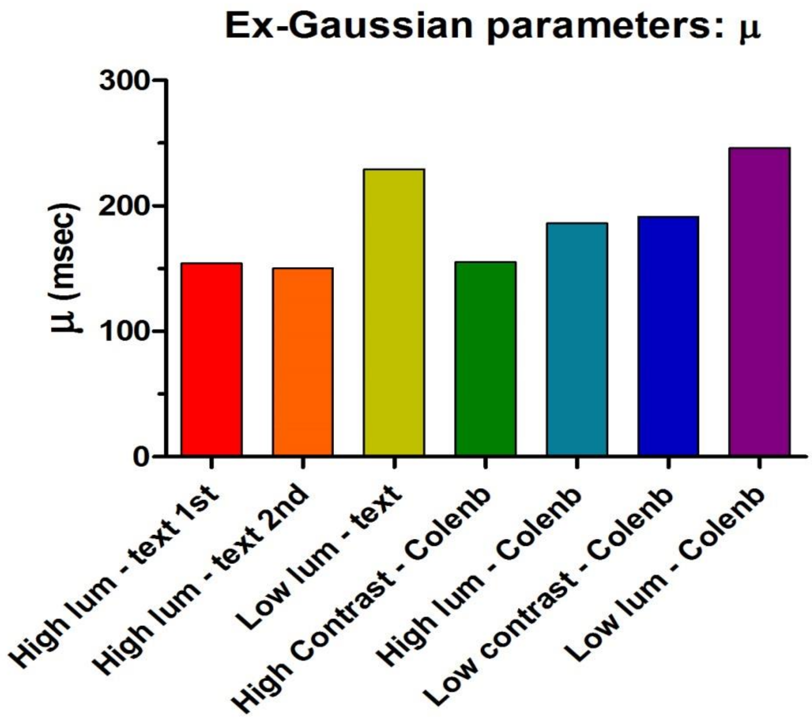

Fig. 61: *Parameter μ for long text and reading card in different conditions*

Low luminance affects greatly parameter μ in both texts. Reading cards show higher levels of μ compared to the long text.

10.2.2 Parameter σ

The standard deviation of the Gaussian component is approximated by parameter σ. An increase of σ would mean an increase of the width of the distribution. Figure 62 shows how parameter σ changes in different conditions and in different stimuli. The first three bars show σ for the long text in high luminance first and second time of reading and in low luminance. The last two bars show σ for the reading cards in high luminance and in low luminance condition for 0.4 logMAR print size.

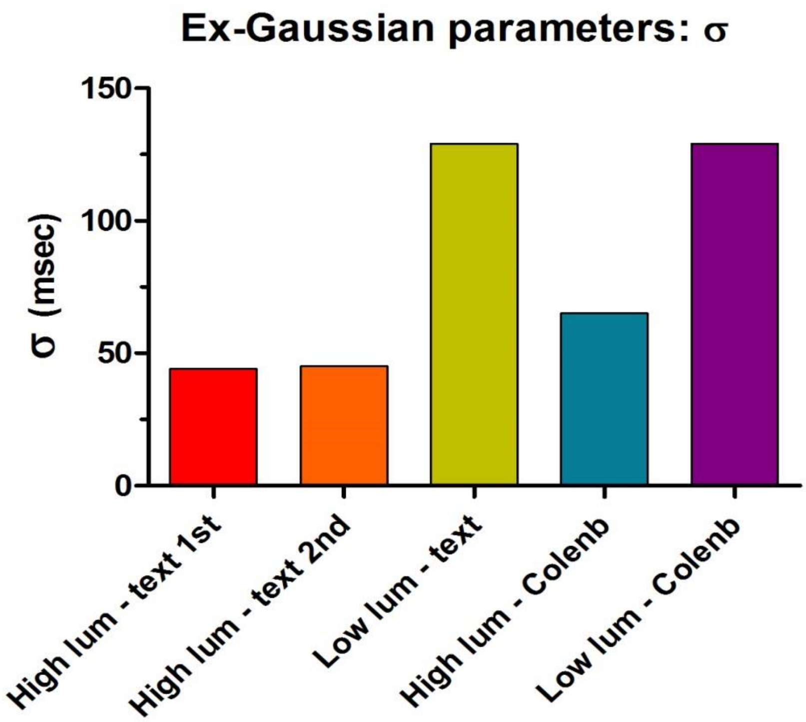

Fig. 62: *Parameter σ for long text and reading card in different conditions*

The low luminance effect is very evident in both texts. Parameter σ is not greatly affected by the kind of he stimuli.

10.2.3 Parameter τ

In paragraph 6.5.1 we said that parameter τ of the ex-Gaussian analysis approximates the exponential function and reflects the mean and standard deviation of the exponential component. Figure 63 shows parameter τ (msec) as a function of the print size (logMAR) in three conditions. An increase in τ with no other change in the rest of the ex-Gaussian parameters would mean an increase in the number of fixations with high duration with no shift of the distribution. It is clear that it stays intact both with the print size and the contrast and luminance effect.

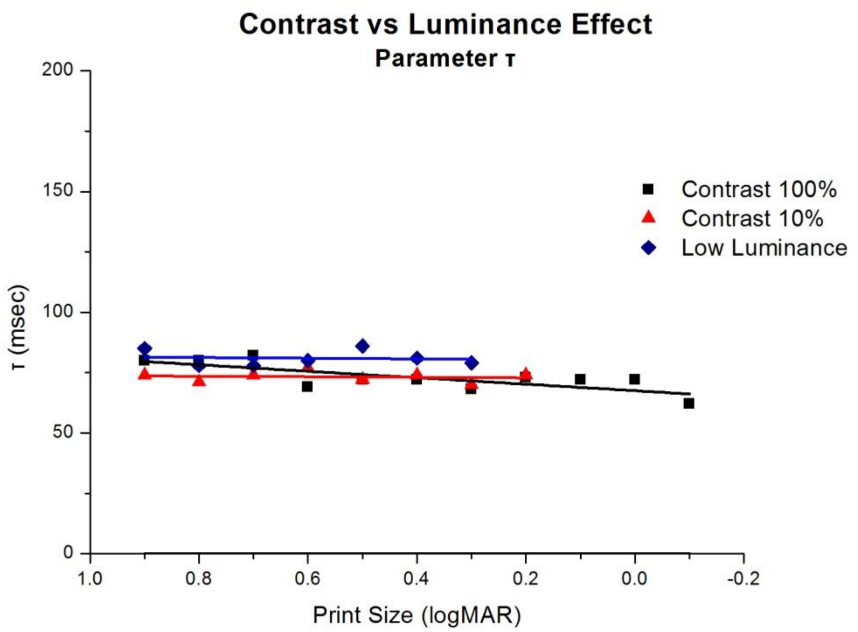

Fig. 63: *Parameter τ as a function of the print size in 100% contrast, 10% contrast and low luminance*

Figure 64 shows also this lack of any effect in parameter τ. In all conditions and in both texts it stays relatively stable.

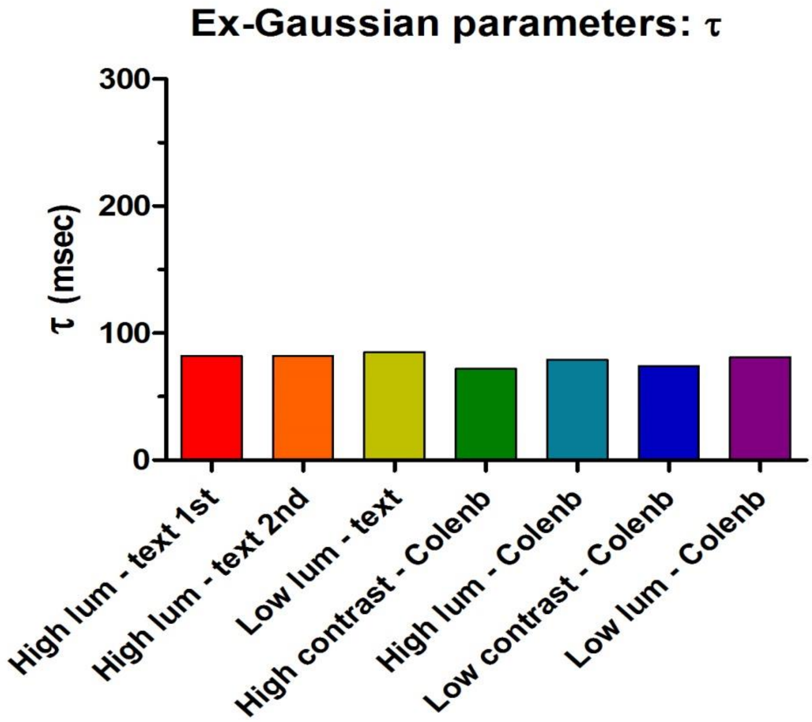

Fig. 64: *Parameter τ in relation for long text and reading card in different conditions*

10.2.4 Parameter Σ

The sum of parameters μ and τ equals with the mean of the distribution and it's signed with Σ. As we can see in figures 64 and 65 the graph of Σ resembles to the one of μ, shifted upwards, because of the addition of an almost constant number; parameter τ.

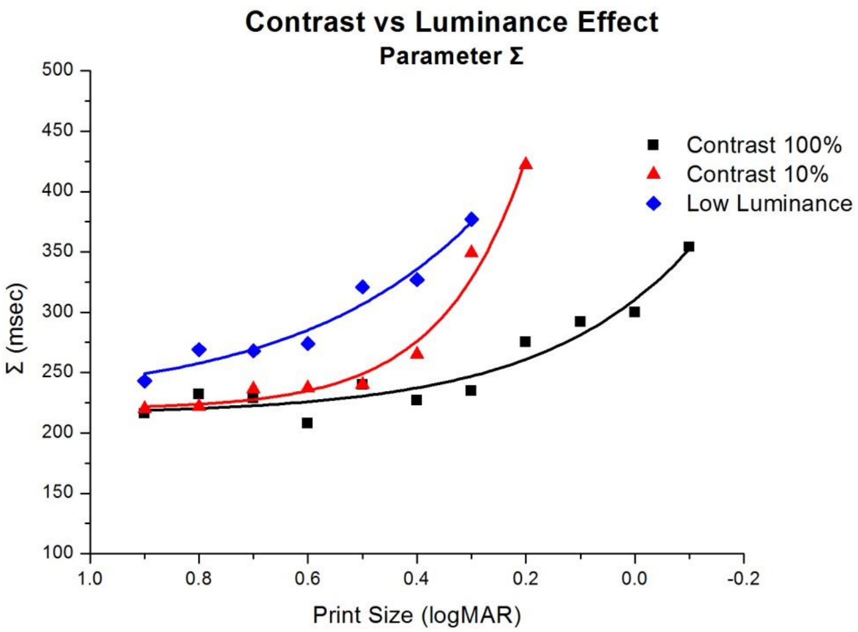

Fig. 64: *Parameter Σ as a function of the print size in 100% contrast, 10% contrast and low luminance*

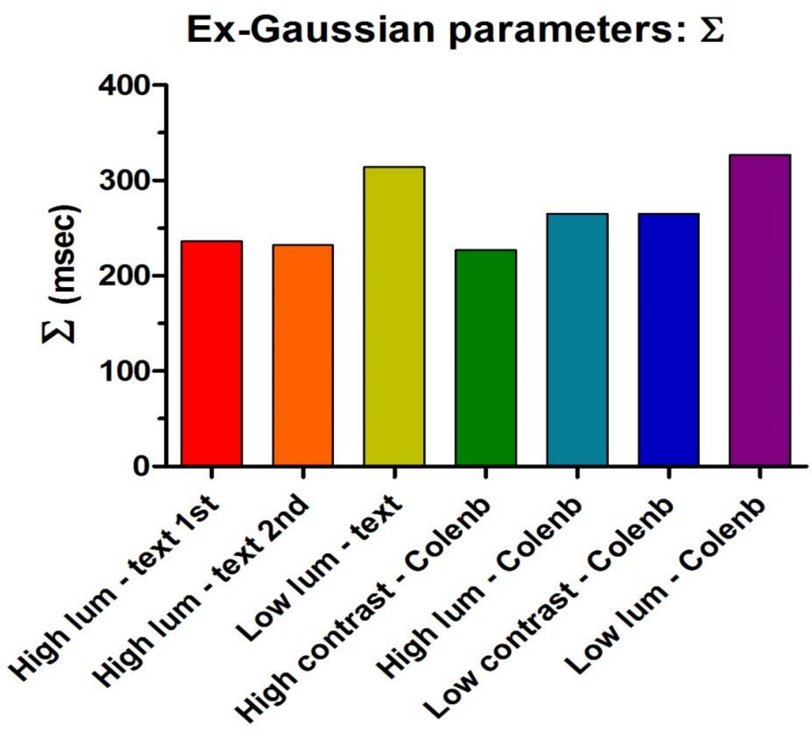

Fig. 65: *Parameter Σ for long text and reading card in different conditions*

PART 4. DISCUSSION

11. Conclusions And Perspectives

11.1 Conclusions

The current study dealt with three major optical factors that affect eye movements during reading; print size, contrast and luminance. The repeatability of the method was also assessed. The aim of the study was to examine the effect of these factors on various characteristics of the reading performance, such as fixation duration, the number of fixations, the reading speed, the percentage of regressions and the amplitude of the saccades. Apart from these characteristics, we also used the ex-Gaussian analysis in order to examine the fixation duration distribution. We used two types of texts; first, the Greek version of the Colenbrander reading cards and second, a paragraph of 141 words that was advanced for the need of the study. There were two reasons for it. First, the Colenbrander reading cards are standardized cards with gradual decrease of the print size of limited characters. The second reason is that we wanted to examine whether the reading performance will be different in these two kinds of texts and in what extent.

As far as the learning effect is concerned, we found that reading speed is higher the second time of reading the same text. This result is something that was highly expected, but the question that rises is why exactly it is happening. Is it a matter of lower fixation duration or less number of fixations? We showed that the median fixation duration does not change the second time of reading and this is observed for all print sizes, apart from the smallest letter, but still with no significant change. On the contrary, the mean number of fixations per sentence was found to be about one fixation less in the second time of reading in all print sizes. The lower number of fixations resulted naturally to smaller saccade amplitude, but the percentage of regressions was the same in both times of reading.

In agreement with the literature, the print size didn't affect reading performance in fairly large (and well visible) letters. The median fixation duration was relatively stable when text decreased from 0.9 logMAR to 0.2 logMAR. A statistically significant difference was found in fixation duration between letter size of 0.2 and 0.1 logMAR, with the change being more pronounced for smaller letters, down to -0.1 logMAR. Print size didn't seem to play any role in saccade amplitude either. When measured in number of characters, the saccade amplitude was relatively stable in all print sizes and in all conditions.

The contrast did not have an effect on fixation duration for large letters larger than 0.4 logMAR. In smaller latters, the effect was even more evident. The effect of contrast in the number of fixations is quite complicated. We saw that there is a decrease in the number of fixations in 10% contrast. However, as we have already mentioned, we used both Colenbrander reading cards, the normal one and the mixed contrast one. These two cards have exactly the same sentences. Their only difference is that half of them are in 10% contrast in the second card. The experiment was conducted with the normal card first and afterwards the mixed contrast card. That means that the contrast effect that we see in the graphs, also includes the learning effect.

We found that due to the learning effect the participants made on average one less fixation per sentence. A decrease of about one fixation was also observed in the contrast effect. We could therefore, attribute the effect found at low contrast letters to the learning effect.

The 10% contrast didn't really affect the saccadic characteristics. Neither the regression percentage nor the saccade amplitude changed because of the reduction of the contrast.

Luminance, similar, to contrast, affects eye fixation when reading, with the effect being more pronounced, since fixation duration was found increased even for the largest letters with a prominent increase in all print sizes. It's indicative that almost no participant could read at low luminance levels letters smaller than 0.3 logMAR. Again, we didn't find any effect of luminance on the number of fixations per sentence.

The percentage of regressions showed a decrease at low luminance levels. So did the saccade amplitude. At first glance, the decrease of the forward saccade amplitude is not in accordance with the stability of the number of fixations. However, there is an explanation for it. The number of fixations includes both the fixations after a forward saccade and a regression. The lower percentage of regressions at low luminance means higher number of forward fixations and this means in turn lower forward saccade amplitude.

The results of the comparison between the reading cards and the long text were quite clear. The median fixation duration was higher for the reading cards in all conditions. In high luminance it was 245 msec compared to 220 msec for the long text and 353 msec compared to 342 for the long text. Generally, the reading speed was higher in the long text. In high luminance the reading speed was 23.7 characters per second (c.p.s) for the reading card and 29.7 c.p.s for the long text, that is 25.5 % higher reading speed for the long text. In low luminance m c.p.s for the long text, that is 16.9% higher reading speed for the long text.

The characteristics examined provided information on the reading behavior, however we believe that examining the fixation duration distribution will allow a more detailed metric of eye movement patterns during reading and reading performance. By computing an ex-Gaussian analysis we managed to get just a quantitative measure of the distribution. The ex-Gaussian showed a very good fitting on the fixation duration distribution, as has been stated elsewhere, and is described by three parameters; μ, the mean of the normal distribution, σ., the standard deviation of the normal distribution and τ and mean and standard deviation of the normal distribution

The ex-Gaussian provided one more indication that reading the text twice, with a break of 5 minutes, doesn't have any effect on fixation duration. It isn't just the median of the fixation duration that stays the same. It's the whole distribution that showed a remarkable stability and all three ex-Gaussian parameters were almost the same in the two times of reading.

On the contrary, both the contrast and the luminance change showed an indicative effect. In 10% contrast, parameter μ increased by 34.5% and parameter σ also increased by 141%. On the other hand, parameter τ stayed the same. Likewise, at low luminance levels, parameter μ increased by 52.7% and σ increased by 186.7%. Again, parameter τ stayed intact.

Parameter μ was not affected by print size, when letters were relatively visible. As expected, print size effect was evident in different sizes in each condition. In 100% contrast it's evident from 0.2 logMAR, in 10% contrast from 0.4 logMAR and in low luminance from 0.5 logMAR. For this critical point and on, the parameter μ shows an increase that means a shift to the right of the distribution.

Parameter τ stays relatively stable in all print sizes and in all conditions. This stability was found in both texts and it was around the same value.

Finally, parameter σ shows a relative behavior with the parameter μ. In bigger letters there is no significant change, but from 0.4 logMAR the change is getting significant presenting an even bigger effect than μ.

11.2 Perspectives

Reading is one of the most common habits of people. This is why one of the most common complaints of young people and people with low vision is having difficulties in reading. Many reading cards have been presented in order to evaluate reading performance. However, there isn't any sophisticated method that can be used to evaluate in detail reading performance and diagnose any optical, neurological or psychological factor that causes the problem.

Usually some characteristics of reading behavior are evaluated, such as total reading time, reading speed and number of reading mistakes. However, these metrics cannot evaluate in detail reading performance. Using an infrared eye tracker we can see deeper in the reading procedure. Total reading time and reading speed consist of fixations and saccades. Analyzing characteristics of the fixations, such as fixation duration and number of fixations and characteristics of the saccades, such as percentage of regressions and saccade amplitude, we can understand exactly why the reading speed changes. For example, we saw that reading the same text for a second time makes us faster. This change in speed however, is caused by a decrease in the number of fixations and not a decrease in fixation duration. On the contrary, optical factors, such as contrast and luminance, affect the fixation duration and not the number of the fixations.

The ex-Gaussian analysis that we used, is a very precious tool for our understanding of reading behavior. Analyzing the fixation duration distribution, we have a deeper evaluation since we examine how the whole distribution changes and in which way. Ex-Gaussian parameters gave the quantitative view that was needed.

To our opinion, the combination of some standardized long texts with a proper analyzing method, like the one that we followed, will lead to a much better understanding of how several factors affect reading. We believe that further studies can work on distinguishing optical effects (contrast, luminance, print size, aberrations etc.) from cognitive (dyslexia, understanding problems etc.) and psychological and neurological factors (anxiety, autism, etc.)

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