Using Wavefront Sensing to Determine the Attributes of Microlenses in Stellest Glasses

Shirley Lidman
shirleylidman.sl@gmail.com

under the direction of
Assoc. Prof. Linda Lundström
M.Sc. Charlie Börjeson
Department of Applied Physics
KTH Royal Institute of Technology

Research Academy for Young Scientists
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Abstract

Refractive errors such as myopia, commonly known as nearsightedness, have become a common cause of vision problems affecting billions of people worldwide. In 2020, a new type of glasses with microlenses that could slow down myopia progression was launched by the optics company Essilor. In this study, the properties of the microlenses of these glasses and their effect on short-term vision were investigated to gain further insight on how myopia progression can be slowed down. The first part of the experiment utilized an optical system with a wavefront sensor to determine the properties of the glasses. The second part includes measurements with another wavefront sensor to determine the effect that the glasses have on image quality. A difference in power between the microlenses with a decreasing lens strength in the periphery compared to the foveal vision can be observed in the results. It is also concluded that the glasses affect peripheral vision by reducing the relative peripheral refraction.

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1 Introduction

The prevalence of myopia, also known as nearsightedness, has increased rapidly over the past years [1]. Myopia is thought to be caused by both genetic and environmental factors and is a common cause of vision loss affecting approximately two billion people across the globe. In thirty years, the number of myopic people in the world is estimated to increase to five billion. [2] Recently, Stellest glasses with lenses that have been hypothesized to prevent myopia progression were released by optics company Essilor [3]. This study investigates the properties of these glasses and their effect on human vision to determine how they can slow down myopia progression.

1.1 Theory

To understand the principles of wavefront sensing and optical aberrations, an introduction to methods and concepts such as the optics of the human eye and the function of wavefront sensing will be given.

1.1.1 The Human Eye

The visual field of the eye can be divided into foveal and peripheral vision. Foveal vision is responsible for the sharp central vision and. Peripheral vision is what the eye observes outside the point of fixation. When light reaches the eye, it passes through the different optical components and an image of the object is perceived. The point farthest from what a completely relaxed, emmetropic (normal visioned) eye can perceive as clearly focused is known as the far point of the eye and will be at infinity. To focus closer than at infinity, muscles in the eye contract, which is known as accommodation. If a relaxed eye can not focus light from infinity, it has a refractive error. One such error is myopia, where the far point is at a finite distance from the eye. This means that the eye only will be able to accommodate for objects closer than that distance and cannot see objects sharply if they are further away, as illustrated in Figure 1. [4]

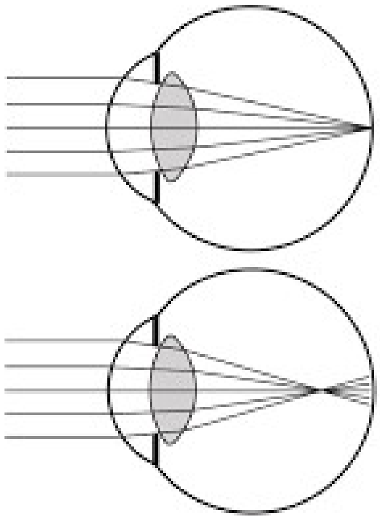


Figure 1: A representation of an emmetropic eye (top) and a myopic eye (bottom). [5]

1.1.2 Aberrations

An optical system, such as a lens, can have various aberrations, meaning that there are imperfections in the image quality produced by the lens. One common aberration in the human eye is defocus, which changes the location of the focal point in relation to the retina. Myopia is a type of defocus aberration. [4]

Spherical aberration is another aberration that will affect optical systems with spherical surfaces, which could result in blurry spots of what should have been a point of focus. It occurs when parallel rays are focused differently further away from the optical axis, making peripheral rays passing through the edge of the pupil focusing differently than rays passing through the optical center. [4]

Relative peripheral refraction is often used to compare the peripheral equivalent between different refractive error groups. It depends on the optical aberration field curvature and also the ocular shape. On average, emmetropes have a negative relative peripheral refraction, while myopic subjects usually have a positive relative peripheral refraction. [6]

1.1.3 Lenses

A lens is a refracting device that can change the direction of the rays passing through it. The two most common types of lenses are either convex or concave. Convex lenses cause the rays to converge toward the central axis. In contrast, a concave lens causes the incoming parallel beam to diverge from the central axis. This is shown in Figure 2. [7]

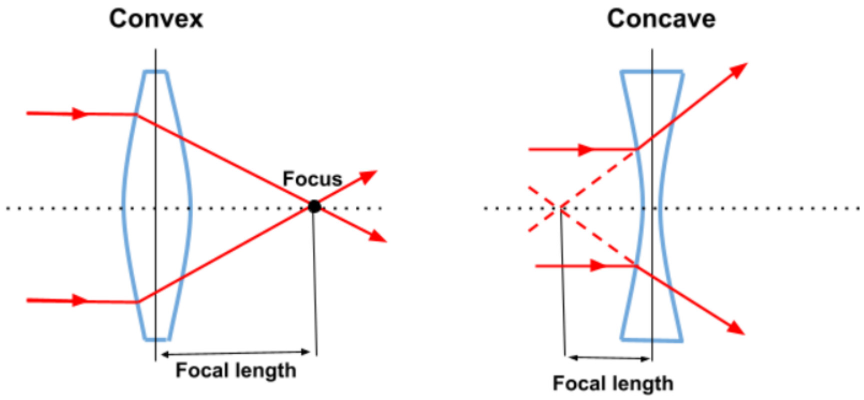


Figure 2: Examples of a concave, and convex lens.

As seen in Figure 2, the focal length is defined as the distance from the center of the lens to the focal point of the lens. It measures how strongly the lens converges or diverges light. The focal length can be calculated using Equation (1) known as the Gaussian lens equation or the lens maker's equation. [7]

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i} \tag{1}$$

It expresses the connection between the focal length f, the object distance s_o, and the image distance s_i. See Figure 3 for clarification.

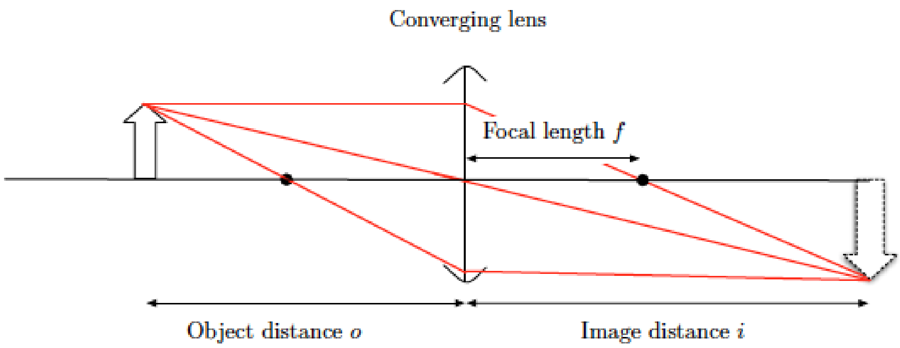


Figure 3: Defining object and image distance. [8]

The strength of a lens is determined by its focal length, which will affect how much light that can pass through the lens. The unit for lens power is given in diopters, defined as the inverse of the focal length.

The Magnification equation, as seen in Equation (2), defines the magnification M, by relating the ratio of the image height h_i, and the object height h_o with the ratio of the distance from the lens to the image d_i, and the distance from the object to the lens d_o. [7]

$$M = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \tag{2}$$

1.1.4 Wavefront Sensor

A wavefront is defined as a surface normal to the propagation of the rays at all points. Hence, parallel rays will have a perfectly flat wavefront. A wavefront sensor captures information regarding the wavefront of the rays, which can be transformed into aberrations of the optical system.

Different aberration types are described by how they affect a flat wavefront. When measuring wavefronts on a human eye, a weak laser beam is pointed at the eye, creating a dot on the retina. The retina will reflect light that exits the eye, generating a wavefront. In such a case, the wavefront will never be completely flat since the human eye always has various optical aberrations. [9]

The most common type of ocular wavefront sensor is the Hartmann-Shack wavefront sensor. It uses an array of small lenses called lenslets to focus the light in the wavefront on a detector. The shape of the wavefront is registered by the detector and can hence be reconstructed. A tilted wavefront hitting a lenslet, will cause shifts of focal points, which can be used to reconstruct the wavefront. [4]

1.1.5 Zernike Polynomials

Mathematically, a wavefront can be described with Zernike polynomials. These polynomials are a set of functions that are orthogonal over a unit hemisphere. They are often defined using polar coordinates (ρ, θ), where ρ is the radial coordinate and θ the azimuthal angle. The wavefront over a pupil can be described with Equation (3). [5]

$$W(\rho, \theta) = \sum_{m,n} c_n^m \, Z_n^m(\rho, \theta) \tag{3}$$

In this equation, Z is the Zernike polynomial, m the number of the polynomial of n order and c a coefficient. When analyzing the shape of a wavefront, there is a unique combination of Zernike polynomials for each wavefront and also each aberration. Thus, coefficients for every Zernike polynomial can be extracted, each coefficient representing the strength of the aberration. [5]

1.1.6 Dual Angle Open Field Wavefront Sensor

The Dual Angle Open Field Wavefront sensor uses two Hartmann-Shack wavefront sensors and can capture foveal and peripheral Zernike aberrations simultaneously. Being able to measure both foveal and peripheral Zernike coefficients at the same time is a huge benefit, since relative peripheral refraction of the eye, which consists of how the eye accommodates both in the periphery and the fovea, can be measured more accurately. The system can measure two horizontal visual field angles (the angle between them is 20°) on one eye and will be used in myopia research. [10]

1.1.7 Telescope

One way to reconstruct a wavefront is with a 4f-Keplerian telescope. This telescope has two convex lenses, with the focal lengths f_1 and f_2, that are placed at a distance of $t = f_1 + f_2$ from each other, seen in Figure 5. The eye will be placed at the length of f_1 away from one of the lenses and the wavefront sensor the distance of f_2 away from the other lens. Thus, the total length is $2f_1 + 2f_2$, explaining the name 4f-telescope. This telescope will create an image of the wavefront of the eye on the wavefront sensor. [11]

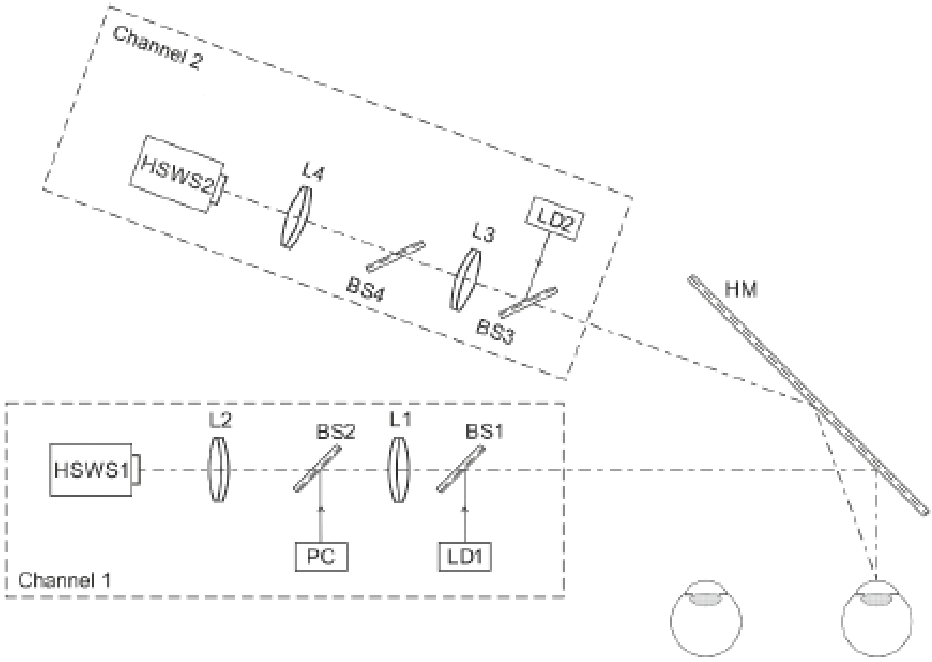


Figure 4: Schematic representation of the Dual Angle Wavefront sensor. PC - pupil camera, LD - laser, L - lens; BS - beam splitter, HM - hot mirror, HSWS Hartmann-Shack wavefront sensor. [10]

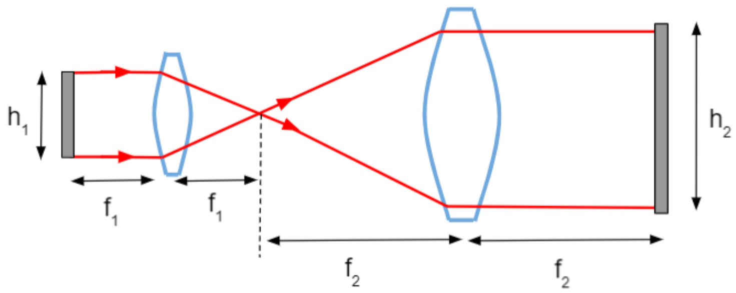


Figure 5: The 4f-Keplerian telescope.

1.1.8 ANOVA-test

An Analysis of Variance (ANOVA) is a widely used statistical method for hypothesis testing. It is used to find out if experimental results are significant or not. The one-way ANOVA-test determines whether there are any statistically significant differences between the means in a number of unrelated groups. [12] It calculates a F-statistic value and a P-value. The F-value is the variation between sample means divided by the variation within the samples. A higher F-value indicates variation in the means of the groups compared to the difference within the group. The P-value measures the probability that an observed difference in the results has occurred randomly. A lower P-value implies a greater statistical significance of the observed difference. [13]

1.2 Previous Research

Over the past years, evidence has been accumulated that wearing glasses with microlenses can be a way to slow down the progression of myopia [14]. In 2020, the ophthalmic optic company Essilor launched a new type of glasses called Stellest. The glasses featured microlenses that after one year of clinical trials show more than 60% stagnation in myopia progress on average compared to children wearing single vision lenses [3].

The Stellest lens has been designed with a technology called Highly Aspherical Lenslet Target (H.A.L.T.). The H.A.L.T. technology consists of aspherical lenslets spread on eleven rings. These lenslets are convex and can slow down myopia progression by preventing elongation of the eye, focusing the light in front of the retina instead of right on it. [15].

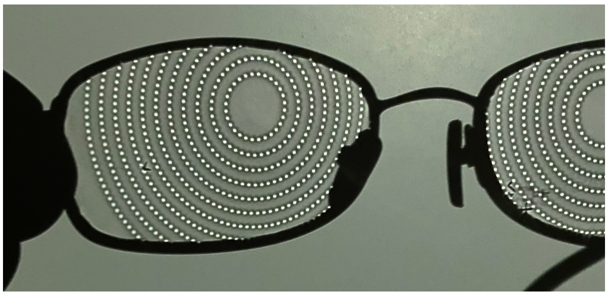


Figure 6: Shadow created by the Stellest glasses when illuminated with a small light source from far away, showing the micro lenses.

1.3 Aim of Study

The aim of this study was to understand how microlenses in Essilor's Stellest glasses worked by examining the properties of the glasses. More specifically, the purpose was to determine whether all microlenses have the same power by comparing Zernike coefficients for two aberrations of the eye, defocus and spherical aberration. It was also investigated how the lenses vary from each other by comparing the position of different microlenses on the glasses and their angle from the pupil, using regression analysis. The effect that the glasses have on the optical quality of the image on the retina was also examined in this study with the purpose of getting a better understanding of how myopia progression can be slowed down.

2 Method

The method was divided into two main parts. The first part was determining the two properties, defocus and spherical aberration, of the glasses by constructing an optical system using a wavefront sensor. The second part included measuring the effect the glasses have on image quality with a Dual Angle Open Field Wavefront sensor.

2.1 Constructing Optical System and Measuring Properties of Glasses

This part of the method consists of constructing an optical system that can be used to measure defocus and spherical aberration on Stellest glasses using a wavefront sensor.

2.1.1 Aligning reference light

The reference light was a weak laser, which was aligned using an alignment disk starting at the front of the rail and then moving it back to ensure that the beam was straight. Two polarization filters were used to reduce the effective power of the laser.

The next step was to align the microscope objective to focus the laser at a specific point. A pinhole was placed at the focus point of the microscope. To make the rays pass through the pinhole, a lens with a focal length of 100 mm was placed 100 mm from the pinhole, thus focusing the light from the pinhole.

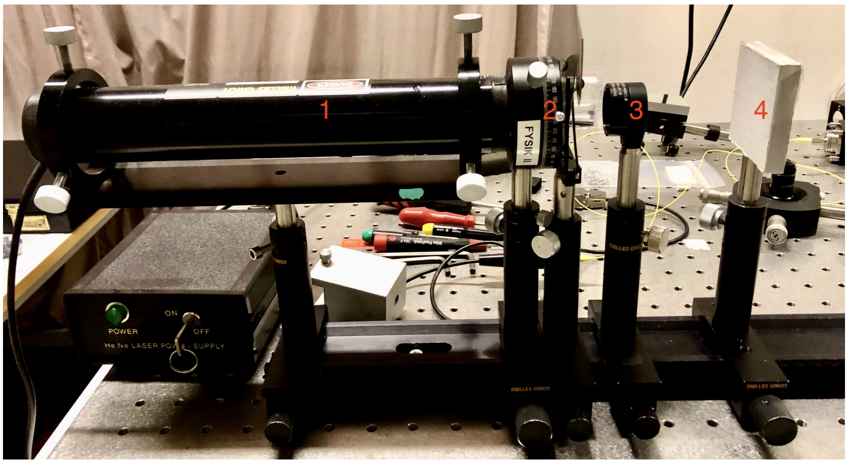


Figure 7: Aligning the reference light. The figure shows the laser (1), two polarization filters (2), the alignment disk (3), and the screen (4).

To ensure that the lens was a focal length away from the pinhole, four methods were combined. The first one was to measure the diameter of the spot that the laser made on a screen that was placed behind the lens using an aperture. Given the position of the lens and the implications of that, the size of the screen remained the same regardless of the distance between the spot and the lens.

The second method used a handheld telescope that was prepared by letting it focus at a great distance outside, thereby ensuring that the rays were parallel. Without changing the focus, the telescope was placed on the optical rail. If the rays were parallel, the pinhole would be in focus. Therefore, the placement of the lens was adjusted until it was focused. The third method used a shear plate, which shows parallel lines when the laser rays are parallel. The shear plate was placed behind the lens and the lens was adjusted slightly until the lines on the shear plate were parallel.

The last method included a wavefront sensor. It was connected to a program on the computer and placed behind the lens. Zernike coefficients for defocus were observed as the wavefront sensor was adjusted. When the coefficients showed zero, the laser would be focused at infinity. These four methods increased the reliability that the lens was aligned correctly. Next, the stand that the glasses would be placed on was attached to the optical rail.

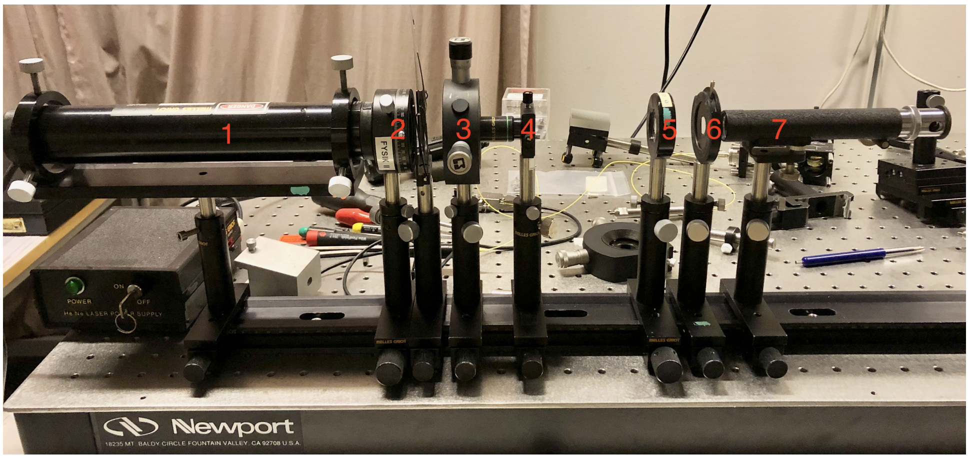


Figure 8: Using a handheld telescope to align the reference light. The figure shows the laser (1), two polarization filters (2), the microscope (3), the pinhole (4), the first lens (5), an aperture (6), and the handheld telescope (7).

2.1.2 Aligning the Telescope

The 4f-Keplerian telescope consisted of two lenses and the first step to align the telescope was to calculate the right focal lengths for the lenses to get the right magnification. The focal lengths were calculated to 140 mm and 50 mm, which were used to create a 4f-Keplerian telescope. To ensure that the lenses were aligned correctly, a shear plate and the wavefront sensor program was used. A piece of paper with a small hole was used instead of the glasses on the optical rail to ensure that the glasses were placed correctly. The position of the wavefront sensor was altered until the lens had no effect on the pupil size.

2.1.3 Testing Glasses

The glasses were placed in the stand on the optical rail so that the laser passed through the optical center of the left glass, where there were no microlenses. The size of the aperture, which in this case emulates a pupil, was set to 2.742 mm on the wavefront sensor, which is circa one mm on the glasses.

HASO, a computer program, showed images of the wavefront, which enabled the microlenses to be identified when the glasses were moved on the stand. The glasses were moved from the optical center to the first microlens on the nasal side and the Zernike coefficients for defocus and spherical aberration were noted. This was done seven times on the nasal side, one for each ring of micro lenses and was repeated three times. Next, the same procedure was done on the temporal side of the glass, this time consisting of eleven rings of microlenses. One measurement per ring was taken and the procedure was repeated three times.

2.1.4 Analyzing Data

The Zernike coefficients were plotted against the position of a microlens. The positions of the microlenses were calculated by measuring the distance from the optical center to the microlens. By using the positions of the lenses, the angle from the pupil to one microlens was calculated.

To determine the statistical significance of the result, an ANOVA-test was done, which obtained F-statistic values and P-values for defocus and spherical aberration.

2.2 Measuring Effect of Glasses on the Image Quality

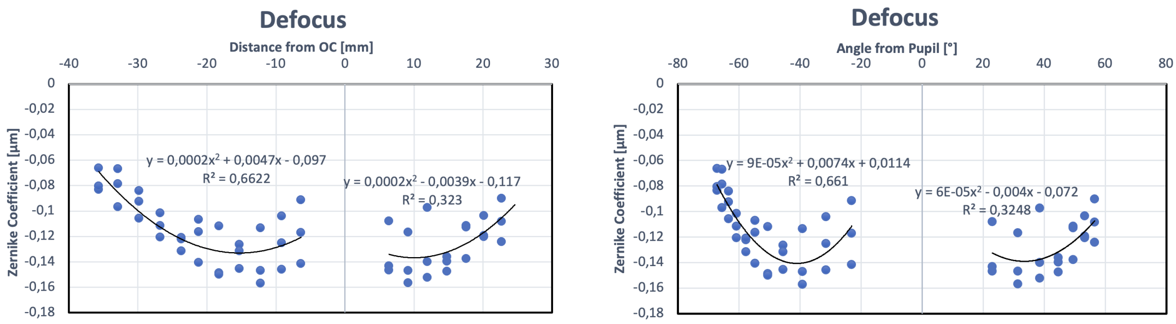
The Dual Angle Wavefront sensor was started and the lasers were set to approximately 0.33 mW. Subject 1 sat down in front of the wavefront sensor without glasses and looked at two crosses on a screen behind the sensor. The measurement was started and stopped after circa 30 seconds. This procedure was repeated a total of three times, after which subject 1 put on the glasses. Thereafter, the same procedure was repeated three times. The same procedure was repeated with subject 2. Zernike coefficients and pictures of the pupil were obtained from measuring the effect that the glasses had and were used in Matlab to calculate the relative peripheral refraction.

3 Results

The first part of the results includes observations of the properties of the microlenses regarding defocus and spherical aberration. The second part presents how the glasses affect relative peripheral refraction.

3.1 Properties of Microlenses

The Zernike coefficients in Appendix A for defocus were plotted in Figure 9. As seen in Figure 9, the values of the Zernike coefficients show a weak correlation regarding defocus. Both in a) and b), different microlenses have different Zernike coefficients depending on where the lenses are located on the glass.



(a) Lens distance from optical center

(b) Lens angle from pupil

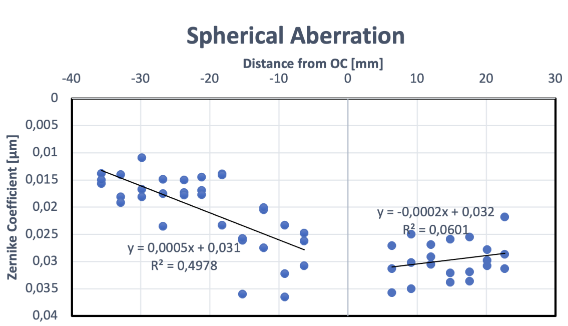
Figure 9: Defocus Zernike coefficients. Regression of quadratic formulas were done for the temporal and nasal side.

In Figure 10, the Zernike coefficients for spherical aberration can be observed. In similarity with Figure 9, Figure 10 also shows that there is a difference between the microlenses when looking at spherical aberration. The graph in Figure 10 is based on values in Appendix B.

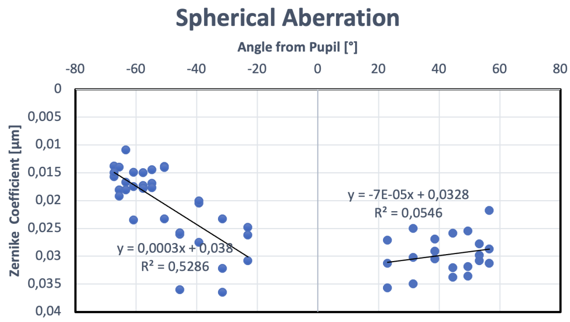
The F-statistic value and the p-value for defocus and spherical aberration were calculated with an ANOVA test. The results are presented in Table 1 and are based on values of standard deviation found in Appendix C.

Table 1: F-statistic value and p-value for defocus and spherical aberration obtained from the ANOVA test

Aberration	F-statistic value	p-value
Defocus	3.76821	0.0004
Spherical Aberration	7.87623	<0.0001



(a) Lens distance from optical center



(b) Lens angle from pupil

Figure 10: Spherical aberration Zernike coefficients. Linear regression was done for the temporal and nasal side.

As seen in Table 2, standard deviation means for defocus and spherical aberration were calculated. They are based on standard deviation values for each lens, found in Appendix D.

Table 2: Standard deviation means of Zernike coefficients for defocus and spherical aberration.

Aberration	Standard deviation mean
Defocus	0.012976883
Spherical aberration	0.003006456

3.2 Effect of Glasses on the Image Quality

The effect that the Stellest glasses have on the vision is observed in Figures 11 and 12 that were plotted using data in Appendix E. In Figure 11, two out of three measurements with glasses show higher peripheral refraction, which means a smaller difference in refractive error between fovea and periphery, since the value is closer to zero. The same applies to Figure 12, where three out of three measurements with glasses show a decrease in relative peripheral refraction compared to without glasses.

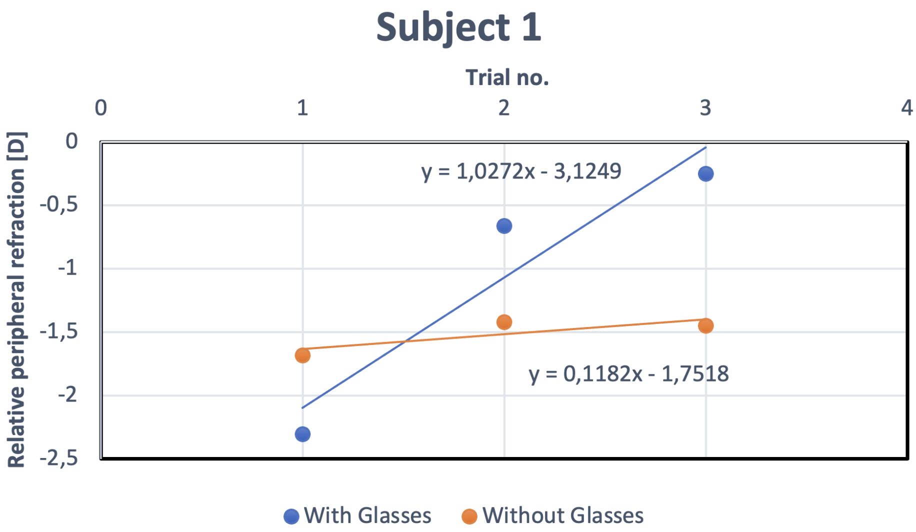


Figure 11: Relative peripheral refraction measured in dioptres with and without glasses for Subject 1.

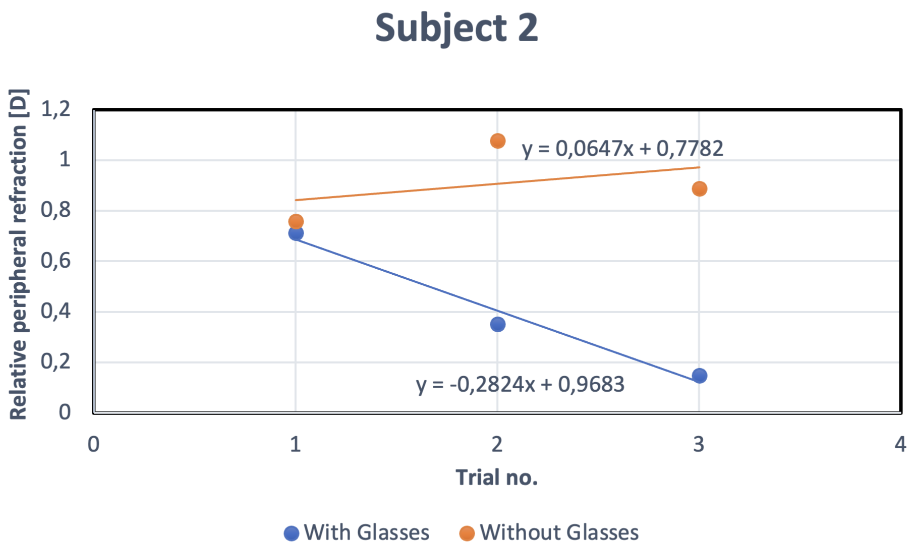


Figure 12: Relative peripheral refraction measured in dioptres with and without glasses for Subject 2.

4 Discussion

For the purpose of determining the properties of the Stellest microlenses, the results show that there is a difference in the power of the lenses when looking at both defocus and spherical aberration (p-value $<$ 0,01, seen in Table 1). The Zernike coefficients of defocus seem to be following a quadratic function. However, the low R^2-values in Figure 9 implies that the regression of the quadratic best-fit-line does not fit well to the actual data points.

Another observation regarding defocus is that the Zernike coefficients come closer to zero further out on the glass, both on the nasal and temporal side, suggesting that the lenses in the periphery are weaker than in the fovea. This can not be confirmed due to the high standard deviation mean for defocus seen in Table 2.

For the Zernike coefficients measuring spherical aberration, a lack of precision is observed. This can be explained using the low R^2-values seen in Figure 10, suggesting that the coefficients do not match the linear formula well.

What can be observed for both defocus and spherical aberration in the result, is that there is a difference between the power of the microlenses. This is supported by the F-statistic value in Table 1, which indicates that the variation between sample means and variation within the samples is high.

The results of the glasses' effect on the eyesight are that the peripheral refraction in most cases (5/6) shows a smaller value with glasses compared to without. Due to the number of measurements, no definite conclusion can be drawn from this part of the results besides that the glasses have an impact on the peripheral vision of the eye.

4.1 Further Studies

In future studies, it would be interesting to look at other Zernike coefficients for other aberrations to draw further conclusions regarding which properties that the microlenses have and how they can affect myopia progression. It would also be relevant to test the wavefronts of all microlenses and not only one on each row, to gain further insight into how and why the lenses are positioned the way they are on the glass. The lens position on the glass could both be used to understand how the lenses affect different parts of the periphery, but also how they can affect myopia progression. Further investigations of these glasses could include that the glasses are bent, which could be taken into consideration both when measuring the angle between the pupil and the microlens for data analysis and when investigating why they are bent the way they are.

4.2 Conclusion

The conclusion is that there are differences in lens power between microlenses on the glasses. Lenses further away from the optical center, with a larger angle from the pupil, were found to become weaker, although the findings were not statistically significant. The spread of values between the same microlenses when comparing Zernike coefficients makes it difficult to draw definite conclusions regarding the power of the lenses. In this study, the effect that the glasses have on image quality is that they reduce the relative peripheral refraction of the eye, but further studies need to be conducted to support this result.

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A Zernike Coefficients for Defocus

Table 3: Values of Zernike coefficients for defocus trial 1.

Lens no.	Lens position	Lens angle	Zernike coefficient-Defocus
1	-140	-67.20153979	-0.0663
2	-129	-65.47886884	-0.0969
3	-117	-63.29949806	-0.1058
4	-105	-60.73200479	-0.1115
5	-93	-57.67623943	-0.1223
6	-83	-54.66374792	-0.1164
7	-71.5	-50.54482949	-0.1487
8	-60	-45.55625223	-0.1265
9	-48	-39.20365314	-0.1469
10	-36	-31.45682336	-0.1252
11	-25	-23.0175618	-0.1416
12	25	23.0175618	-0.1467
13	36	31.45682336	-0.1468
14	47	38.61411056	-0.1523
15	58	44.58509377	-0.1474
16	69	49.54103518	-0.1127
17	79	53.31801537	-0.1205
18	89	56.52761185	-0.1242

Table 4: Values of Zernike coefficients for defocus trial 2.

Lens no.	Lens position	Lens angle	Zernike coefficient-Defocus
1	-140	-67.20153979	-0.0833
2	-129	-65.47886884	-0.0786
3	-117	-63.29949806	-0.0840
4	-105	-60.73200479	-0.1206
5	-93	-57.67623943	-0.1210
6	-83	-54.66374792	-0.1069
7	-71.5	-50.54482949	-0.1120
8	-60	-45.55625223	-0.1315
9	-48	-39.20365314	-0.1133
10	-36	-31.45682336	-0.1459
11	-25	-23.0175618	-0.0914
12	25	23.0175618	-0.1433
13	36	31.45682336	-0.1566
14	47	38.61411056	-0.1400
15	58	44.58509377	-0.1396
16	69	49.54103518	-0.1376
17	79	53.31801537	-0.1194
18	89	56.52761185	-0.0901

Table 5: Values of Zernike coefficients for defocus trial 3.

Lens no.	Lens position	Lens angle	Zernike coefficient-Defocus
1	-140	-67.20153979	-0.0805
2	-129	-65.47886884	-0.0670
3	-117	-63.29949806	-0.0925
4	-105	-60.73200479	-0.1015
5	-93	-57.67623943	-0.1314
6	-83	-54.66374792	-0.1407
7	-71.5	-50.54482949	-0.1500
8	-60	-45.55625223	-0.1454
9	-48	-39.20365314	-0.1570
10	-36	-31.45682336	-0.1040
11	-25	-23.0175618	-0.1169
12	25	23.0175618	-0.1081
13	36	31.45682336	-0.1168
14	47	38.61411056	-0.0974
15	58	44.58509377	-0.1361
16	69	49.54103518	-0.1115
17	79	53.31801537	-0.1036
18	89	56.52761185	-0.1082

B Zernike Coefficients for Spherical Aberration

Table 6: Values of Zernike coefficients for spherical aberration trial 1.

Lens no.	**Lens position**	**Lens angle**	**Zernike coefficient-Spherical Aberration**
1	-140	-67.20153979	0.0138
2	-129	-65.47886884	0.0140
3	-117	-63.29949806	0.0109
4	-105	-60.73200479	0.0149
5	-93	-57.67623943	0.0173
6	-83	-54.66374792	0.0169
7	-71.5	-50.54482949	0.0139
8	-60	-45.55625223	0.0261
9	-48	-39.20365314	0.0205
10	-36	-31.45682336	0.0365
11	-25	-23.0175618	0.0308
12	25	23.0175618	0.0313
13	36	31.45682336	0.0350
14	47	38.61411056	0.0269
15	58	44.58509377	0.0321
16	69	49.54103518	0.0336
17	79	53.31801537	0.0308
18	89	56.52761185	-0.0287

Table 7: Values of Zernike coefficients for spherical aberration trial 2.

Lens no.	Lens position	Lens angle	Zernike coefficient-Spherical Aberration
1	-140	-67.20153979	0.0157
2	-129	-65.47886884	0.0181
3	-117	-63.29949806	0.0167
4	-105	-60.73200479	0.0175
5	-93	-57.67623943	0.0178
6	-83	-54.66374792	0.0177
7	-71.5	-50.54482949	0.0233
8	-60	-45.55625223	0.0258
9	-48	-39.20365314	0.0275
10	-36	-31.45682336	0.0233
11	-25	-23.0175618	0.0248
12	25	23.0175618	0.0271
13	36	31.45682336	0.0302
14	47	38.61411056	0.0305
15	58	44.58509377	0.0338
16	69	49.54103518	0.0319
17	79	53.31801537	0.0298
18	89	56.52761185	0.0313

Table 8: Values of Zernike coefficients for spherical aberration trial 3.

Lens no.	Lens position	Lens angle	Zernike coefficient-Spherical Aberration
1	-140	-67.20153979	0.0150
2	-129	-65.47886884	0.0192
3	-117	-63.29949806	0.0181
4	-105	-60.73200479	0.0235
5	-93	-57.67623943	0.0150
6	-83	-54.66374792	0.0145
7	-71.5	-50.54482949	0.0141
8	-60	-45.55625223	0.0360
9	-48	-39.20365314	0.0201
10	-36	-31.45682336	0.0322
11	-25	-23.0175618	0.0262
12	25	23.0175618	0.0357
13	36	31.45682336	0.0250
14	47	38.61411056	0.0291
15	58	44.58509377	0.0259
16	69	49.54103518	0.0255
17	79	53.31801537	0.0278
18	89	56.52761185	0.0218

C Values from ANOVA Test

Table 9: Values from ANOVA test for defocus.

Group	N	Mean	Std. Dev	Std. Error
1	3	-0.0767	0.0091	0.0053
2	3	-0.0808	0.0151	0.0087
3	3	-0.0941	0.011	0.0063
4	3	-0.1112	0.0096	0.0055
5	3	-0.1249	0.0057	0.0033
6	3	-0.1213	0.0174	0.0101
7	3	-0.1369	0.0216	0.0125
8	3	-0.1345	0.0098	0.0057
9	3	-0.1391	0.0229	0.0132
10	3	-0.1250	0.0210	0.0121
11	3	-0.1166	0.0251	0.0145
12	3	-0.1327	0.0214	0.0123
13	3	-0.1401	0.0207	0.0120
14	3	-0.1299	0.0288	0.0166
15	3	-0.1410	0.0058	0.0033
16	3	-0.1206	0.0147	0.0085
17	3	-0.1145	0.0095	0.0055
18	3	-0.1075	0.0171	0.0099

Table 10: Values from ANOVA test for Spherical aberration.

Group	**N**	**Mean**	**Std. Dev**	**Std. Error**
1	3	0.0148	0.0010	0.0006
2	3	0.0171	0.0027	0.0016
3	3	0.0152	0.0038	0.0022
4	3	0.0186	0.0044	0.0025
5	3	0.0167	0.0015	0.0009
6	3	0.0164	0.0017	0.0010
7	3	0.0171	0.0054	0.0031
8	3	0.0293	0.0058	0.0034
9	3	0.0227	0.0042	0.0024
10	3	0.0307	0.0067	0.0039
11	3	0.0273	0.0031	0.0018
12	3	0.0314	0.0043	0.0025
13	3	0.0301	0.0050	0.0029
14	3	0.0288	0.0018	0.0010
15	3	0.0306	0.0042	0.0024
16	3	0.0303	0.0043	0.0025
17	3	0.0295	0.0015	0.0009
18	3	0.0273	0.0049	0.0028

D Standard Deviation Values

Table 11: Standard deviation of measurements of Zernike coefficients for defocus for each lens.

Lens no.	Standard deviation
1	0.00744
2	0.01230
3	0.00890
4	0.00780
5	0.00463
6	0.01423
7	0.01761
8	0.00799
9	0.01868
10	0.01710
11	0.02049
12	0.01745
13	0.01693
14	0.02352
15	0.00472
16	0.01203
17	0.00772
18	0.01393

Table 12: Standard deviation of measurements of Zernike coefficients for spherical aberration for each lens.

Lens no.	**Standard deviation**
1	0.0007846
2	0.0022376
3	0.0031169
4	0.0036012
5	0.0012193
6	0.0013597
7	0.0043848
8	0.0047392
9	0.0033980
10	0.0054969
11	0.0025630
12	0.0035113
13	0.0040836
14	0.0014817
15	0.0033951
16	0.0034874
17	0.0012472
18	0.0040086

E Effect of Glasses on Image Quality Values

Table 13: Values for subject 1 with glasses. RE stands for refractive error and RPR stands for relative peripheral refraction.

Trial	**Pupil size [mm]**	**RE fovea [D]**	**RE periphery [D]**	**RPR [D]**
1	1.75	-1.308033381	-3.551688278	-2.301896773
2	1.75	-1.444633392	-2.103831344	-0.6622827377
3	1.75	-1.425203424	-1.713706303	-0.2475294003

Table 14: Values for subject 1 without glasses. RE stands for refractive error and RPR stands for relative peripheral refraction.

Trial	**Pupil size [mm]**	**RE fovea [D]**	**RE periphery [D]**	**RPR [D]**
1	1.75	-1.259330649	-2.97666228	-1.682214084
2	1.75	-1.402105182	-2.792599609	-1.418100616
3	1.75	-1.302025375	-2.805210568	-1.445772159

Table 15: Values for subject 2 with glasses. RE stands for refractive error and RPR stands for relative peripheral refraction.

Trial	**Pupil size [mm]**	**RE fovea [D]**	**RE periphery [D]**	**RPR [D]**
1	1.75	-1.182087335	-0.4529591736	0.7123121
2	1.75	-1.130702522	-0.5998079858	0.3508853105
3	1.75	-1.349683358	-1.166378911	0.1475729787

Table 16: Values for subject 2 without glasses. RE stands for refractive error and RPR stands for relative peripheral refraction.

Trial	**Pupil size [mm]**	**RE fovea [D]**	**RE periphery [D]**	**RPR [D]**
1	1,75	-1,807187496	-1,056387327	0,7577143013
2	1,75	-1,970380319	-0,926769431	1,077895069
3	1,75	-2,176185498	-1,268714965	0,8871103833