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Optical Projection System Design for Both Distant and Near Eye Charts

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In this study, a digital eye chart optical projection system for distant and near vision examination was designed using the basic principle of geometric optics and a Snellen chart, which consists of four modules: an off-axis parabolic (OAP) mirror, a triplet lens, an liquid-crystal display (LCD), and a digital processing unit. Fifteen male subjects participated in the experiment, and their visual acuity data were recorded. The system shows the benefits of compactness, portability, and easy operation, in comparison with the traditional design. A detailed design process has been addressed in this paper.

1. Introduction

Taiwan is known as the kingdom of myopia; according to statistics, more than 63% of the population is myopic. During the COVID-19 pandemic, most people and students work at home, increasing the use of 3C products. Moreover, the myopic population is growing rapidly, especially the proportion of myopic children. In addition, with the recent promotion of AI products, eye vision problems will become worse.

As the population ages, presbyopia will become normal, which increases the need for vision examination and correction. The currently popular comprehensive refractor was originally used as an instrument to measure the function of extraocular muscles. Owing to the addition of a rotating mechanism of lenses, refractive examination has been added. The refractor can not only be used for refractive error examination, but also as an extraocular muscle examination machine, which is a basic examination tool for ophthalmic vision workers. It fits almost all the lenses used for examination in the optical trial lens set into the rotational wheel system, providing a more efficient and faster lens changeover in clinical operation than with a trial frame. With a knob, it rapidly switches to the lenses needed for the examination, making it ideal for complex subjective refractions. Since all the lenses in the refractor are closed, the optometrist does not have to worry about soiling the lenses. At present, the refractor, which is used for vision examination, requires

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a large space, so it is performed in an optometry room, and it is highly functional and requires professional personnel to operate.

In this study, we designed an innovative digital eye chart optical projection system for near and distant vision examinations, which is portable and easy to operate, and examinations can be easily performed anytime, anywhere.

2. Principle

The size of the image of an external object on the retina depends on the size sensation caused by it passing through the eye, and in general, the angle between the line spaces in front of the eye chart is very small if measured in radians, and its triangular tangent can be seen as equal to the angle, which is the concept of the viewing angle. Therefore, the perceived size of an external object depends on the size of the viewing angle corresponding to the external object. When the object is further away or the object is smaller, the viewing angle becomes smaller. The node points in the optical system are a pair of conjugate points with an angular magnification of +1, which are divided into the first node point of the object side and the second node point of the image side, and the direction of the light rays does not change after passing through the pair of node points. Since the distance from the retina to the second node is a constant for a particular eye, the subjective perception of the size of the external object is determined by the size of the viewing angle, according to the principle of trigonometric function. The viewing angle (α) of the eye is calculated as

$$\text{Viewing angle } (\alpha) = (h1)/(s1), \tag{1}$$

where the numerator $h1$ is the object height and the denominator $s1$ is the distance between the object and the first node point. This ratio is also equal to the trigonometric tangent of the angle between the top and bottom ends of the object and the first node point of the eye, when the viewing angle is small. Visual acuity is the ability of the eye to see and distinguish the smallest spacing between two objects, usually measured in terms of viewing angle. For the same small object, the smaller the viewing angle used, the better the subject's vision, so the reciprocal of the viewing angle is often used to indicate the vision. Clinically, according to different eye chart designs, there will be different expressions, and the test subjects are different, but their meanings are the same. In the Snellen fraction, the test standard distance (D) is used as the denominator and the actual test distance (d) is used as the numerator, which is expressed as

$$\text{Visual acuity } (V) = (d)/(D). \tag{2}$$

Snellen's eye chart typically shows eleven rows of capital letters, with the top row containing a single letter and the other rows containing feature letters that become progressively smaller. In the commonly used Snellen chart, the spacing between letters in each row is equal to the width of the letters in that row, the spacing between rows in adjacent rows is equal to the height of the letters in the smaller row, and the two-line spacing of the letter "E" is equal to the width of the letter line.

The size of the letters in the square is five times the width of the letter line that makes up the letters, and the square is at a viewing angle of five arc minutes at a specified distance, usually 6 m or 20 ft from the Snellen diagram to the subject, as shown in Fig. 1.(1–10) The Snellen fraction is converted into decimal form in the international standard eye chart, which is an arithmetic series and is recorded in decimals, such as 0.1–1.0 and 1.0–2.0. Since the eye chart in this study uses an optical system for projection, the design method is to achieve the projection size and distance in the distant and near eye chart on the basis of the viewing angle of one arc minute and the image formation of geometric optics. If the distances from the object to the first focal point of the lens and from the second focal point of the lens to the image are x_1 and x_2, respectively, for the focal length f of a thin lens in air, the distances are related by the imaging formula:

$$f^2 = x_1 * x_2. \tag{3}$$

The magnification (M) of the lens is the ratio of the sizes of the image and its corresponding object, or the ratio of the image to the distance from the object to the lens.(11–14)

3. Optical Design

The design process of the digital eye chart optical projection system includes various steps, which are briefly described as follows: the data collection and analysis of the eye chart, the determination of system specifications based on vision exam requirements, the type of selection of the projection optical system, the first-order design of the optical system according to the viewing angle of one arc minute, lens and merit function edit, and the optimization of the optical system. The flow chart of the digital eye chart optical projection system is shown in Fig. 2. The Snellen chart is designed on the basis of the viewing angle of each E letter for five arc minutes, and the optical projection system selects the eye chart commonly used in the optometry room for detailed analysis and planning. For example, a Snellen chart of 27.5 × 56 cm^2 size is used. A subject with normal vision (1.0) can see the 20/20 red line of the chart very clearly, as shown in Fig. 3.(15) The 20/20 red line has a total of eight letters and seven spaces, while it is blank on the left and right sides. The chart is placed 6 m in front of the subject. On the basis of the angle of view of each E letter for five arc minutes, the width of the 20/20 red line is calculated to be 13 cm, which is the same as the data from the eye chart. In addition to the above one-minute

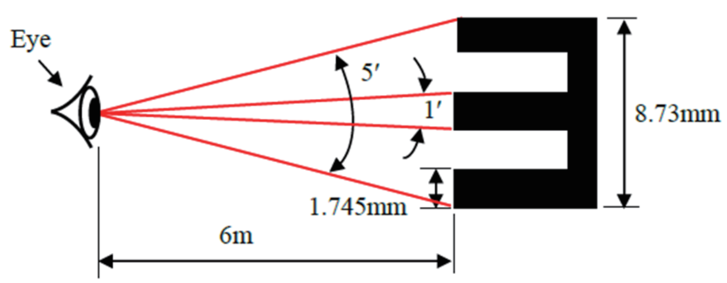

Fig. 1. (Color online) Letter E of Snellen chart at distance of 6 m.

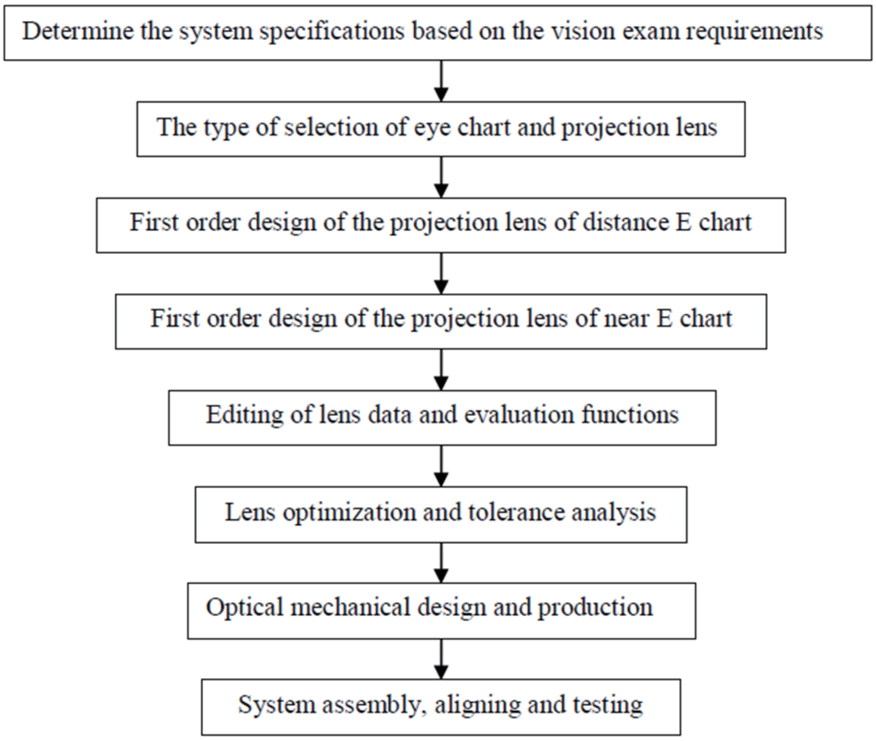

Fig. 2. Flow chart of digital eye chart optical projection system design.

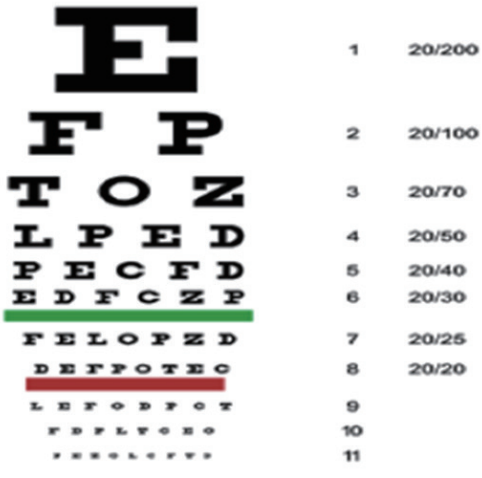

Fig. 3. (Color online) Snellen chart.(15)

viewing angle requirements, the convenience of handheld use of the system should also be considered. To reduce the size of the system, an off-axis parabolic mirror is used as a distant eye chart projection lens, as shown in Fig. 4. From the data obtained from the above analysis, it can be seen that when the focal length of the off-axis parabolic lens is 500 mm, the size of the eye chart is based on the angle of view of five arc minutes per letter and the requirement of

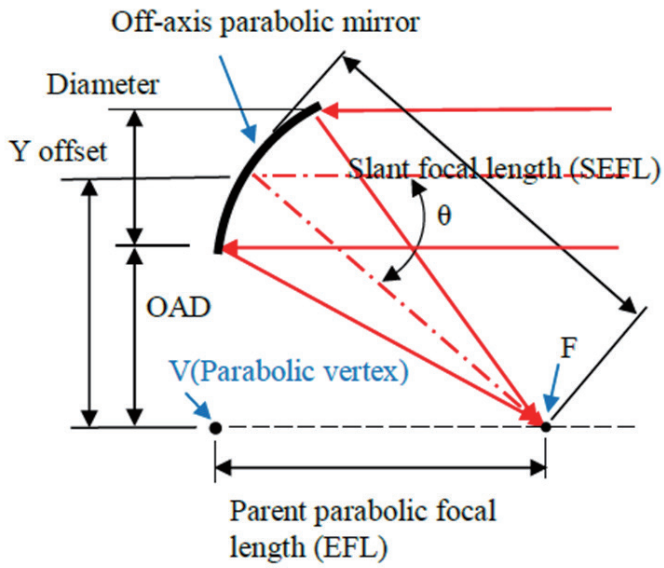

Fig. 4. (Color online) Schematic of off-axis parabolic mirror.

occupying eight letters and seven spaces on the 20/20 red line, and the size of the liquid-crystal display (LCD) screen is at least 11 cm. Assuming that the subject's normal visual acuity (1.0) has a focal length of 2.5 cm, a row of E letters 11 cm wide projects onto the retina with a width of 0.545 mm.

According to the specifications, the main optical parameters obtained from the first-order design results of the off-axis parabolic mirror are as follows: diameter, off-axis distance (Y offset), oblique effective focal length, parent parabolic effective focal length, and off-axis angle (θ), with values of 30 mm, 133.7 5 mm, 516 mm, 506 mm, and 15°, respectively. The design method of the digital near eye chart is to place the LCD within the focal length range of the triplet lens to form an enlarged virtual image that is visually seen by the subject. The first-order optical parameters of the triplet lens are the focal length of 60 cm and the image distance of 40 cm according to the visual acuity test conditions. After calculation with the imaging equation, the object distance and magnification are 24 cm and 1.32, respectively. The system is used for both the distant and near eye chart projections, and according to the first-order design results of the above two optical systems, the distance d between the two focal points of the triplet lens and the off-axis parabolic mirror in the horizontal direction is 17 cm, as shown in Fig. 5. In addition, the projection size of the near vision chart is based on the five-arc-minute viewing angle of each letter E. The focal length of the triplet lens is determined by the imaging equations. Finally, the reference practice eye is used for calibration and fine-tuning.

4. System and Experimental Results

The system includes four modules: an off-axis parabolic mirror, a triplet lens, an LCD, and a digital processing unit, as shown in Fig. 5. The optical projection lens of the distant E chart is an off-axis parabolic mirror, and the near E chart optical projection modules use a triplet lens. The

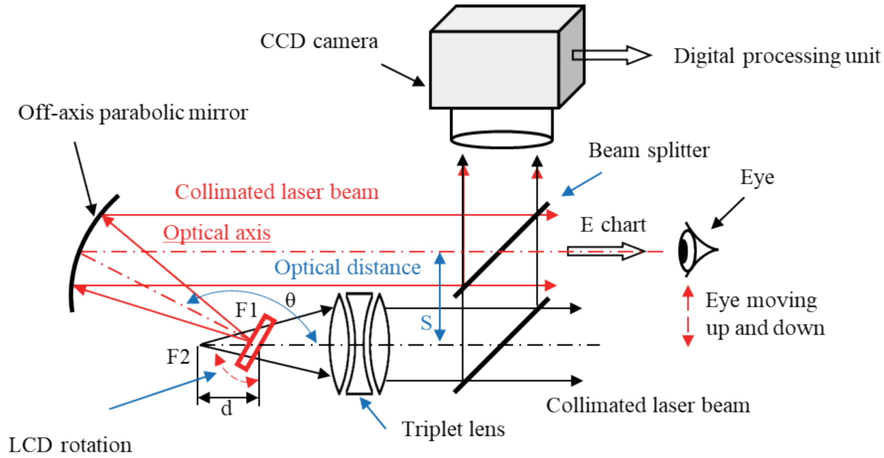

Fig. 5. (Color online) Digital eye chart optical projection system.

focal points of the two optical projection systems are not at the same point, but are located on the same horizontal axis and are separated by a certain distance *d*. The LCD is placed at the focus (F1) of the off-axis parabolic mirror and the object point (O2) of the triplet lens. F1 and O2 overlap, displaying a series of E letters on the eye chart. The included angle between the input optical axes of the two optical projection systems is the angle θ, and the output optical axes are parallel to each other and separated by a distance S in the vertical direction, where θ is 15°. The LCD is mounted on a precision rotating stage and placed at the focal point F1. It can rotate the θ angle and be used with the optical projection system for both distance and near vision examination, as shown in Fig. 5. The digital processing unit is responsible for system control, data processing, and video recording. The LCD is remotely controlled via a digital processing unit to display a series of E letters for the distant and near eye charts. LCD selection must consider screen size, pixel format, brightness, contrast, and panel chromaticity. The relevant specifications of the LCD are as follows: a screen size of 10.9 cm, a pixel format of 480 × 272, a brightness of 350 nits, a contrast of 350:1, and a panel chromaticity of x 0.31 and y 0.33. In addition to the black-and-white eye chart, combined with a color vision test, the color selection of the LCD is mainly the three monochrome colors RGB.

RGB is known as the three primary colors of light. The colors on an LCD screen are a mixture of red (R), green (G), and blue (B). When these three colors overlap, an infinite number of colors can be produced, with values ranging from 0 to 255. When all the components are 0, it is pure black, and when all the values are 255, it is pure white. Thus, when colors are added with more time, the brighter they will be, and RGB is also known as an additive color system. When used in a hue test, the subjects will be given blocks of different colors. The optometrist will ask the subjects to arrange them in color order, from red to purple. If the items cannot be arranged in the correct order, the subject may have some kind of color vision deficiency.

To match the actual use of optometry, it can be evolved into two types, namely, the monocular eye chart projection device and the binocular eye chart projection device. The arrangement method is briefly described as follows.

The optical projection systems of the distant and near eye charts are combined into one unit and arranged up and down or left and right. This structure is called a monocular eye chart optical projection device, as shown in Fig. 6. An X-cube prism is placed vertically in front of the distant and near output beams of the monocular eye chart projection device, and the output beam will be divided into three beams (left, right, and center). The left and right beams are symmetrical relative to the central beam, and the distance between them is set to the interpupillary distance between the two eyes, as shown in Fig. 7. The three parallel beams are produced by the combination of an X-cubic prism and two plane mirrors. The left and right light beams are deflected by 90° by a plane mirror tilted at 45° and projected to the subject, thus forming two sets of identical monocular eye chart projection devices. The distant and near eye charts can be generated alternately. This is similar to the monocular eye. The largest difference between chart projection devices is that this structure is called a binocular vision chart projection device. The optical properties of the X-cube lens used in this study are that the reflectance and transmittance of visible light wavelengths are both 80%. The optical material used in the X-cube prism is BK7 glass, the angle tolerance is 10′, and the surface flatness is $\lambda/10$, where λ is 530 nm.

This system has three operating modes: distant vision exam, near vision exam, and relaxation. The relaxation mode is implemented before the near vision test. A beam splitter tilted at 45° is placed in front of the eye for splitting light. The E chart in front can be seen through the beam

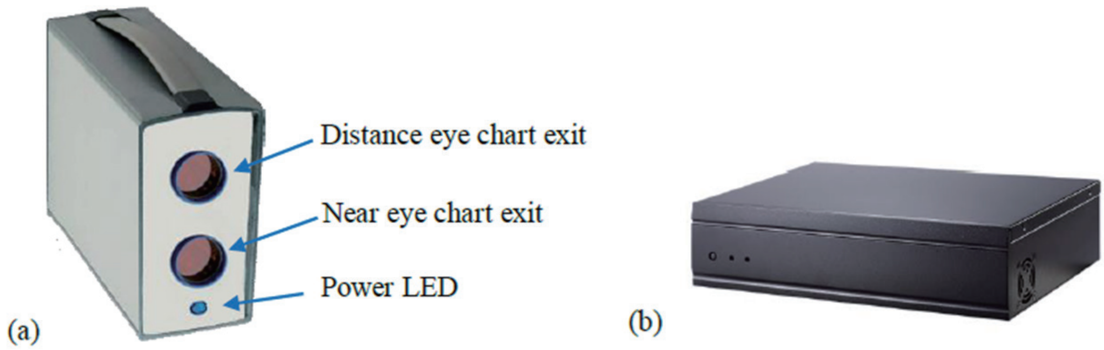

Fig. 6. (Color online) Monocular eye chart optical projection device: (a) optical projection systems of distant and near eye charts and (b) digital image processing unit.

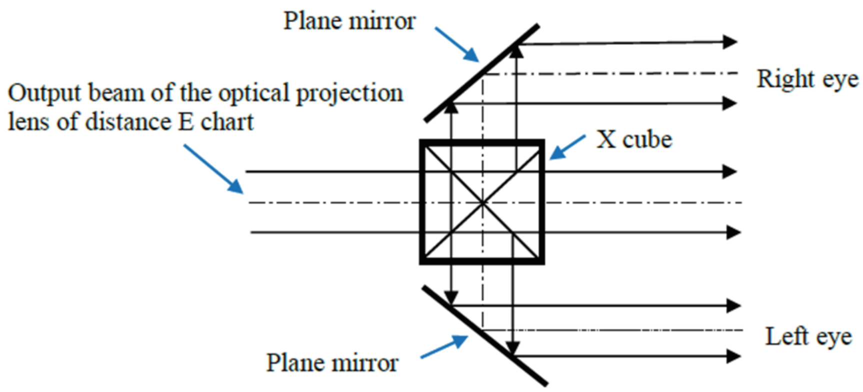

Fig. 7. (Color online) Schematic of partial components of binocular eye chart projection device.

splitter. The camera on the side of the eye can capture the E chart through the reflection of the beam splitter. The CCD camera connected to the digital processing unit is used to monitor the eyes, as shown in Fig. 5. When looking at the E chart, the subject can use a mouse to operate the sequence size E letters of the distant and near E charts by himself or the optometrist. When both the playback software and the mouse are controlled by the digital processing unit, the subject can confirm the starting and ending positions of the E chart on the LCD by pressing the buttons during the test.

In the monocular visual test, the shielding device is used to shield the other eye during the monocular visual test. After the preparation of each optical component, the optoelectronic module and optomechanical component are completed, and the system assembly and alignment are carried out immediately. The five parallel laser beams used for optical axis alignment of the optical system are distributed in the upper, lower, left, right, and center of the circular fixture, parallel to each other, and located in the same reference plane as shown in Fig. 8.

The system alignment process includes the following six steps, as shown in Fig. 9, which are briefly described as follows:

(1) According to the system design, we confirm the relevant position and spatial attitude of each optical component and determine the preliminary setup. The projecting system and the optical alignment device with five parallel lasers are placed on the optical table, and the five parallel lasers are directed towards the off-axis parabolic (OAP) mirror.

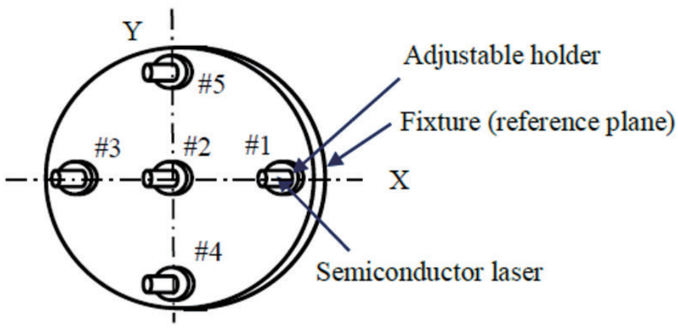

Fig. 8. Schematic of optical alignment device with five parallel lasers.

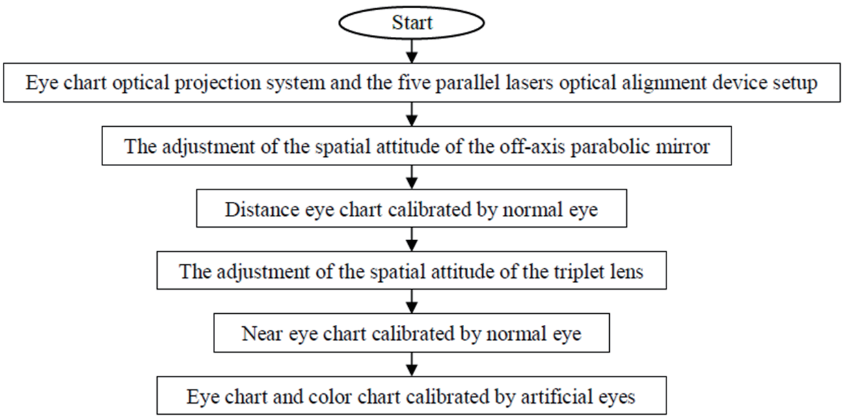

Fig. 9. Flow chart of system alignment.

(2) The optical alignment device with five parallel lasers is used to align the spatial attitude of the OAP mirror, such as adjusting the *x* and *y* directions, so that the central laser is aligned with the optical axis of the OAP mirror, and the surrounding four lasers after passing through the OAP are focused at a point with the central laser.
(3) The LCD is placed at the focus point of the OAP, and the E letter of the sequence is played, which is viewed by a person with normal eyes to confirm the spatial attitude accuracy of the OAP mirror alignment.
(4) Furthermore, five parallel lasers are used to align the spatial attitude and focus of the triplet lens, and the focus of the triplet lens is coincided with the focus of the OAP mirror.
(5) When a series of E letters are played on the LCD, the image projected through the triplet lens is very clear, and the system obtains the best alignment effect.
(6) The E fonts on the distant and near eye charts are calibrated through reference practice eyes, and the decimal range of the Snellen chart is 0.2–1.5. Table 1 shows the conversion tables for distant acuity and near visual acuity, and the diopter values are estimates. As for the color chart, if the colors are not differentiated, a spectrometer is used for correction.

Usually, after measuring the naked visual acuity of the subject using a Snellen chart, a comprehensive phoropter and a trial lens are used to determine the highest positive power and best visual acuity of the eyes. Therefore, the eye chart measurement is only used as a preliminary visual acuity. Although the diopter listed in Table 1 in step (6) is an estimate, it does not affect the effect of fitting glasses. The spherical diopter of the reference practice eye device used in this study was adjusted between +4D and –5D to simulate different refractive errors. + degree is used to correct farsightedness and − degree is used to correct myopia. The reference practice eye consists of a CCD camera, an aperture with adjustable diameter, nine pieces of trial lens, a lens slot, and a retractable lens housing, as shown in Fig. 10. The images captured by the CCD camera are directly sent to the digital processing unit for data processing. The size correction method for the E letters projected by the digital eye chart optical projection system is calibrated using the trial lens of various diopters in the reference practice eye. The digital processing unit remotely controls the LCD, which plays the E letter continuously and the E font in order from the

Table 1
Conversion table for representation of distant acuity and near visual acuity.(16–21)

Conversion table for distant visual acuity		Conversion table for near visual acuity	
20/20-based Snellen	Diopter (Decimal)	at 40 cm	Diopter (Decimal)
20/400	−4.00	20/20	1.00
20/300	−3.50	20/30	0.67
20/250	−3.00	20/40	0.50
20/200	−2.50		
20/150	−2.00	20/60	0.33
20/100	−1.50	20/80	0.25
20/70	−1.25	20/100	0.20
20/60	−1.00		
20/50	−0.75	20/200	0.10
20/30–40	−0.5		
20/25	−0.25		
20/20	0.00 normal eye		

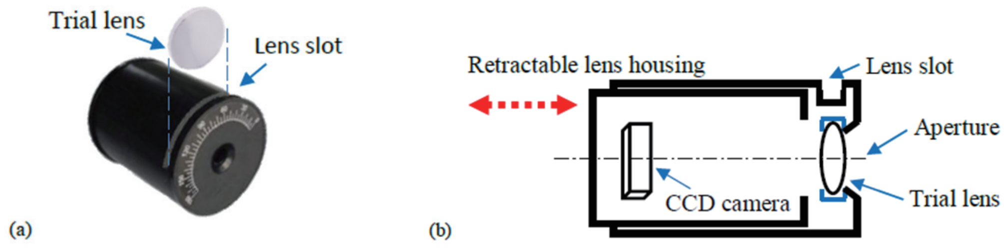

Fig. 10. (Color online) Schematic diagram of reference practice lens: (a) external parts and (b) internal component configuration.

largest to the smallest. The corresponding E letter can be found in the 20/20-based Snellen field in Table 1 for each trial lens with different diopters. In a trial lens with a diopter, the letter E should be clearly visible when the LCD shows the corresponding letter E. If it is not clear, we use the program to fine-tune it. This digital eye chart optical projection system must be corrected after a period of use, such as half a year. The calibration process is to sequentially examine the size of the 20/20-based Snellen E letter with each audition and further fine-tune it until the E letter can be clearly seen. The calibration results of the distant eye chart are listed in Table 2. The calibration results of the near eye chart are the same as those of the distant eye chart and will not be listed again.

In this study, participants were required to have myopia and no eye disease, and had been trained for optometry testing using the digital eye chart optical projection system prior to the test. A total of 15 male subjects participated in the experiment, aged between 30 and 40 years old, and most of them used American 21 steps for optometry before the experiment. The visual acuity of all the 15 male subjects who participated in the experiment was 0.8. The 15 male subjects were tested using the digital eye chart optical projection system of this study. Each subject was tested five times, and the average of the five times is listed in Table 3. The test results produced three groups of subjects with four, seven, and four, and test data of 0.9, 0.8, and 0.7, respectively. After the experiment, by comparing the optometry data of the American 21 steps, the refraction data measured using the digital eye chart optical projection system in this study deviated greatly, and the subjects reported that the glasses using the American 21 steps optometry data were indeed more comfortable.

The projected E letter may be slightly deformed, showing that aberrations exist in the projection optical system, and the resolution of the next generation of new products needs be improved. Some of the test subjects may not be comfortable with the projection equipment, and the field of view being not sufficiently large is one of the reasons, which needs to be improved. The overall system design should be more user-friendly and accurate.

This innovative design is portable, digitalized, and compact, which are its advantages. The visual acuity can be obtained by the subject response, which is suitable for normal people with refractive errors and people with disabilities. The traditional design used in optometry and the innovation design are compared in Table 4.

Finally, the two optical projection lenses of the far and near eye chart are set as a unit, arranged in the vertical direction, projecting the distance eye chart above and the near eye chart

Table 2
Calibration sheet.

20/20-based Snellen	Diopter of trial lens (Decimal)	Corresponding E letter clarity
20/400	−4.00	OK
20/300	−3.50	OK
20/250	−3.00	OK
20/200	−2.50	OK
20/150	−2.00	OK
20/100	−1.50	OK
20/70	−1.25	OK
20/60	−1.00	OK
20/50	−0.75	OK
20/40	−0.5	OK
20/25	−0.25	OK
20/20	0.00	OK

Table 3
Test data of visual acuity of 15 subjects.

Subject no.	Data	Subject no.	Data	Subject no.	Data
1	0.9	6	0.8	11	0.8
2	0.9	7	0.8	12	0.7
3	0.9	8	0.8	13	0.7
4	0.9	9	0.8	14	0.7
5	0.8	10	0.8	15	0.7

Table 4
Comparison of characteristics of traditional and innovative optometry designs.

Design	Characteristic			
	E letter generation method	Device usage	Visual acuity confirmation	Subject under test
Traditional design	LCD projected or posted E or C chart	Fixed space and measurement distance of 5 or 6 m	Subject guided by optometrist	Normal subject with refractive errors but no eye diseases
Innovative design	Optical image	Portable; eyes are placed on exit pupil of optical system	Subject responds by himself	Normal subject with refractive errors and subject with disabilities but no eye diseases

below, also known as the monocular eye chart projection device. Two sets of identical monocular eye chart projection devices are symmetrically left and right side by side, and a set of binocular eye chart projection devices is integrated.

5. Conclusions

An innovative design of an optical projection system for both distant and near eye charts has been implemented. The system consists of four modules, which are an off-axis parabolic mirror, a triplet lens, LCD, and a digital processing unit. Fifteen male subjects participated in the experiment, and their visual acuity data were measured. The system is compact, portable, and easy to operate, and examination can be easily performed anytime, anywhere, which are its advantages. In the future, the resolution of the optical system of this device will be improved, a large amount of data can be collected, and AI technology can accelerate the practical application of this innovative design.

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