Subjective and Objective Eye Tracking Test Results of Commerical VR Products

Tao He*, Zhengyu Wang*, Gunaghang Mei**, Shunli Zang**, Tianwen Hou**, Chaohao Wang, Lei Zhao***, Xiaochen Zhou****
***GravityXR Electronics and Technology Co.Ltd., Ningbo, Zhejiang, China**
****Yongjiang Laboratory, NingBo, Zhejiang, China**

*****Co-corresponding author: xczhou@gravityxr.cn, lei-zhao@ylab.ac.cn**

Abstract

We conducted spatial accuracy tests on virtual reality products with eye-tracking capabilities, and provided two test methods, a subjective eye-tracking test with volunteers and an objective eye-tracking test using a high-precision human eye simulation device. By comparing the test results, we found that the objective spatial accuracy test better reflects the performance of the eye tracking system, and that the high-precision human eye simulation device can provide a strict true value of the eye gaze direction and is a stable system that simulates the real human eye gaze. In addition, the spatial accuracy of eye tracking is more superior under the condition of appropriate eye relief distance, and the relative position of the eye tracking module to the eyeball also affects the spatial distribution of the gaze point and thus the magnitude of the spatial accuracy.

Author Keywords

Eye tracking; Spatial Accuracy; Gaze Direction; Eye Relief; Virtual Reality.

1. Introduction

In recent years, the rapid commercialization of Virtual Reality(VR) devices has made Head-Mounted Displays (HMDs) more accessible to consumers. VR technologies have advanced significantly, transforming industries such as gaming[1], healthcare[2] and manufacturing[3]. A crucial innovation in VR devices is eye-tracking technology[4, 5], which monitors and records eye movements to determine where users are looking. This technology is critical to improving user interaction, enabling natural and intuitive gaze direction-based control, optimizing VR device display performance through point-of-gaze rendering[6], and enhancing immersion and realism by aligning virtual content with the user's gaze direction.

With the introduction of VR devices equipped with eye tracking systems and features, such as Apple Vision Pro, Pico 4 Pro Eye, Quest Pro, etc., the eye tracking method used by these VR devices is a Pupil-Centered Corneal Reflection(PCCR) algorithm[7, 8] consisting of multiple infrared LED light sources and an infrared camera. The corneal reflection method measures light reflected from the surface of the eye to determine the gaze point and eye position. The pupil tracking method utilizes infrared light sources and a camera to capture the pupil's trajectory and infer the direction of gaze. Of paramount importance is the recognition that the accuracy and precision of data derived from all eye-tracking devices are contingent upon the successful execution of calibration procedures [9].

Eye-tracking systems provide a rich source of information on real-time human visual attention and cognition, and understanding human visual attention is critical for many applications in computer vision[10], psychology[11], sociology, and human-computer interaction[12]. Eye tracking accuracy is important in studies that use tiny gaze stimulation targets, such as reading studies where regions of interest are in close proximity to each other, neurological studies[13], and gaze input systems[14].

There are fewer studies on the eye tracking accuracy of VR products[15, 16], and the accuracy and precision provided by manufacturers are usually calculated under ideal conditions, which may invalidate experimental results or conclusions[17, 18, 19]. In addition to this, most tests on eye tracking accuracy usually invite volunteers to participate, and human eyes are accompanied by micro eye movements when gazing at a target object, as well as physiological behaviors such as blinking and saccades[20, 21] of eyes caused by eyestrain in volunteers, and the fact that the relative positions of the real eyeballs and the eye tracking module are not the same for each volunteer while wearing the VR device may result in an inaccurate eye-tracking accuracy test to be inaccurate. Therefore, we used a set of high-precision human eye simulation equipment to objectively test the eye tracking accuracy of VR products. We found that the use of this equipment can well avoid the above problems arising from real human eyes, and is an objective eye tracking test method that better describes the accuracy and precision of the device's eye tracking system.

2. Experimental Setup

As shown in Figure 1 is a high-precision human eye simulation device, this device mainly contains two parts, which are the artificial eye and the multi-axis artificial eye control system. The device can simulate the gaze direction of the real human eye, and can be set with different kappa angles, as well as the simulation of the real human eye movement trajectory, such as smooth pursuit, saccades, etc. The artificial eye is based on the real human eye structure as well as optical properties, and detailed simulation of the human eye structure from eye size, pupil, iris, cornea, etc. is carried out. The multi-axis artificial eye control system realizes precise control of the movement of the artificial eye, with an accuracy of 0.01° of rotation angle, a range of 90° of rotation in the horizontal and vertical directions, and a maximum speed of 700°/s. In addition to this, the inter-pupillary distance of the artificial eye can also be controlled. We used this device to test the objective spatial accuracy of eye tracking on VR devices.

In addition, we invited seven volunteers to join us in the

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experience of the VR product and the subjective testing of the spatial accuracy of eye tracking. All of these volunteers were middle-aged males, with an age distribution of 25-40 years old, and none of them wore eyeglasses or contacts during the test.

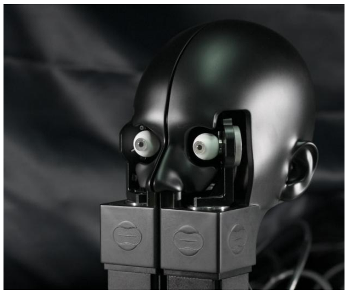

Figure 1. High-precision human eye simulation device for use in objective eye tracking spatial accuracy testing.

3. Software Setting

Before conducting the eye tracking accuracy test, the positions of all test target points need to be defined. We set up a total of 37 target test points, as shown in Figure 2, first defined the right-angle coordinate system and spherical coordinate system, the origin O is the center of the binocular line, the gaze direction and the Z-axis angle is the polarity angle θ, and the projection in the XOY plane and the X-axis angle is the azimuth angle φ. All the target test points are located in the same plane, which is perpendicular to the Z-axis and is 5 m away from the origin, and one target test point is located in the polarity angle $\theta = 0°$, and 12 target test points are located at $\theta = 20°$, evenly distributed in φ every $30°$. In addition to this, there are 12 target test points each for $\theta = 10°$ and $\theta = 30°$, which are not plotted in Figure 2.

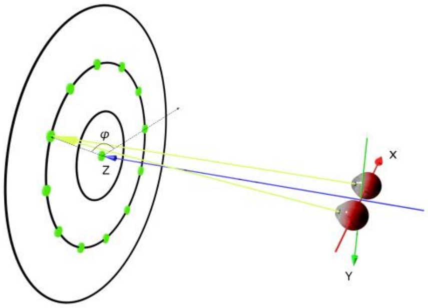

Figure 2. Eye tracking spatial accuracy global test coordinate system definition, and test target point location distribution. Only the center and the 12 target points at $\theta = 20°$ are shown(green points); the locations of a total of 24 target points at $\theta = 10°$ and $20°$ are not plotted.

We obtained eye tracking gaze direction data through the SDK provided by the VR product manufacturer. In the objective eye-tracking test, we need to write a program to make the artificial eye gaze at the target test points, and gaze at each target test point in a fixed order, with θ and φ both ranging from smallest to largest, and set the gaze dwell time. In the subjective eye tracking test, we developed an application using Unity software that has a simple 3D scene with a gaze object with a cross in the center that moves between 37 target test points in the order described above.

4. Procedure

Subjective and objective eye tracking tests are fundamentally similar in terms of the testing process, and the main steps are as follows:

(1) Adjust the relative position between the eyeball and the VR equipment, usually the pupil of the eyeball is at the exit pupil of the optical lens of the VR equipment, so that the content of the virtual scene can be clearly seen.

(2) Eye tracking calibration, following the calibration program prompts to make the eye gaze at the calibration point, is required to successfully complete the calibration.

(3) For eye tracking spatial accuracy tests, the eyes gaze at the target test points for a period of time, and all target test points are completed in sequential order.

(4) Collecting and saving eye tracking gaze direction data.

We recalibrate the eye tracking algorithms for VR products if the prerequisites of the test are changed, such as changing volunteers in subjective tests, adjusting the value of eye relief in objective tests, etc.

5. Methods

Accuracy quantifies the average offset between the actual gaze direction and the true target direction, and precision quantifies the ability of the eye tracker to reliably reproduce a given result, i.e., the reproducibility of the test results.The direction of view fed back by the VR device is the test value, and the true value of the direction of view in the subjective test is the direction of the eyeballs to the target test point, whereas the true value in the objective test is the direction in which the artificial eye is actually rotating to gaze at the target test point . We calculated the angular difference between the test value of gaze direction and the true value for each sample of data as shown in Equation (1). To take into account the uncertainty of each sample, the angular offset of each sample needs to be calculated. The overall accuracy of the eye tracking system is then determined by averaging all offset angles as shown in Equation (2).

$$\theta_i = \arccos\left(\frac{\vec{v_t} \cdot \vec{v_r}}{\| \vec{v_t} \| \| \vec{v_r} \|}\right) * 180 / \pi \tag{1}$$

$$\theta_{\mathrm{Offset}} = \frac{1}{\mathrm{n}} \sum_{i=1}^{\mathrm{n}} \theta_i \tag{2}$$

The estimation of precision usually involves two common methods. One method is to measure the standard deviation (SD) of the sample data, as shown in Equation (3), and the other is to calculate the root mean square (RMS) of the angular distance between consecutive sample data. In this paper, SD values are used to assess the precision of eye tracking.

$$\mathrm{SD} = \sqrt{\frac{1}{\mathrm{n}} \sum_{i=1}^{\mathrm{n}} (\theta_i - \theta_{avg})^2} \tag{3}$$

6. Results

Eye tracking objective gaze direction data can be obtained by high-precision human eye simulation equipment, as shown in Figure 3, which demonstrates the results of the spatial distribution of the gaze points of products A, B, and C. We only plotted the results of the spatial distribution of gaze points for $\theta = 0°$, $\theta = 10°$ and $\theta = 20°$. Compared to Product B, the spatial distribution results of Products A and C at almost every test target point are closer to the ground truth(the center of the black cross) of the gaze point , while at the same time, the gaze point test results of Product B are more discrete.

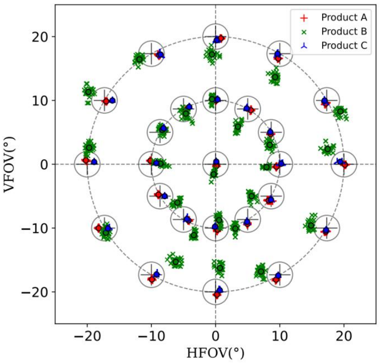

Figure 3. Spatial distribution of objective eye-tracking gaze points for products A, B and C. Results are shown for $\theta = 0°$, $10°$, and $20°$ and φ uniformly distributed at every $30°$. The center of the black cross is the ground truth of the test target point.

We invited seven volunteers to participate in subjective eye-tracking spatial accuracy tests for Products A and B. Each volunteer underwent pre-test training and all successfully completed eye tracking algorithm calibration, and the results are shown in Figures 4 and 5. From the results of Product A, the accuracy and precision are getting worse with increasing θ (larger FOV) and the accuracy of eye tracking varies between volunteers, which may be related to the differences in the eye structure of the volunteers as well as the positional attitude of the VR device when worn. Similarly from the results of Product B, the subjective accuracy of different volunteers is different, and the accuracy difference is very small at different θ angles. The reason for this is mainly that the subjective accuracy and precision of Product B is a bit worse than Product A.

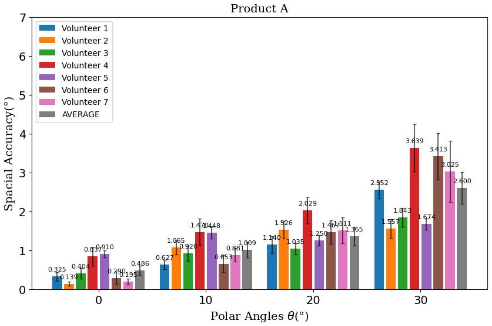

Figure 4. Subjective spatial accuracy of eye-tracking for Product A.

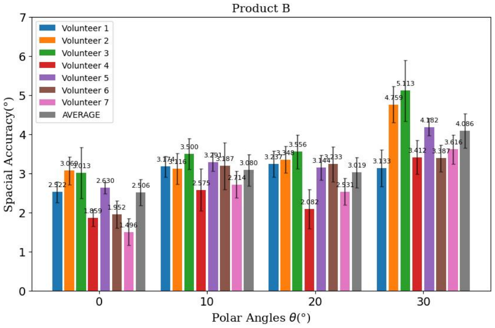

Figure 5. Subjective spatial accuracy of eye-tracking for Product B.

After getting the subjective and objective spatial accuracy of eye tracking, we summarize it at the same θ angle, as shown in Table 1. From the table, we can summarize that the eye tracking performance of products A and C is better. Comparing the subjective and objective test results, we find that both have the same point, as the polarity angle increases, the spatial accuracy also increases. In addition, there are also points of difference in that the accuracy and precision obtained by both methods are slightly different, which is very interesting to think about. We speculate that there are the following reasons, in the subjective test, the eyes of the volunteers will be accompanied by some physiological behaviors, such as displacement of the eyeballs, blinking caused by visual fatigue, etc., when they are gazing at the target point. The eyeballs of different volunteers have different eye structures from each other and the artificial eye, with individual variability. The relative position and rotation of the eyeballs to the VR device are also difficult to control consistently in subjective tests. For the above speculated reasons, we found the eye tracking original line-of-sight direction data and drew the curve functions corresponding to $\theta = 20°$ and $\varphi = 180°$, $210°$, $240°$, $270°$ and $300°$ for a total of five test target points.

Table 1. Spatial Accuracy in VR Devices

Spatial Accuracy(°)		Product A		Product B		Product C
		Obj.	Sub.	Obj.	Sub.	Obj.
$\theta = 0°$	Mean	0.296	0.448	1.603	2.381	0.427
	SD	0.056	0.121	0.475	0.332	0.032
$\theta = 10°$	Mean	0.516	1.009	2.013	3.080	0.495
	SD	0.059	0.197	0.410	0.396	0.041
$\theta = 20°$	Mean	0.675	1.415	2.918	3.019	0.707
	SD	0.075	0.241	0.484	0.390	0.081
$\theta = 30°$	Mean	1.054	2.538	3.707	3.961	1.558
	SD	0.067	0.406	0.661	0.440	0.272

As shown in Figure 6, it can be seen that there are “spikes”(Red dotted box) in the subjective curve and that the objective curve is smoother. The “spikes” do not always appear at each test target, but the subjective curve has “burrs” (roughness) at each test target. These phenomena must be related to the subjective human factors of the volunteers, and we found that the volunteers would have eye physiological behaviors such as blinking and saccades in the process of gazing at the target point. When there is a wide range of saccades, there will be "spikes" on the curve, and the micro eye movement when gazing at the target point will cause "burrs" on the curve. Comparing volunteers No. 3 and No. 4 in the subjective test, the height of the "spikes" and the roughness of the "burrs" are different, which is related to the structure of the volunteers' eyes, and these are inherent and unavoidable behaviors of the human eye.

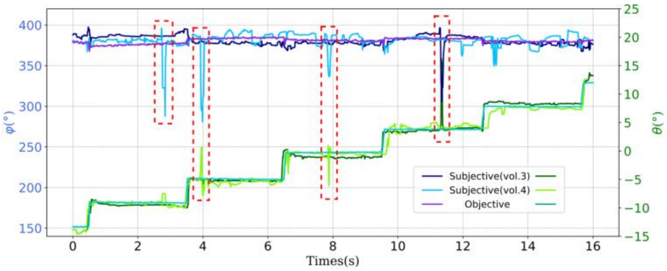

Figure 6. The blue and green lines show the subjective and objective azimuth and polarity angle test results for product A at the target points $\theta = 20°$, $\varphi = 180°$, $210°$, $240°$, $270°$ and $300°$, respectively.

The "spikes" caused by wide-area hopping are produced by volunteers suddenly looking in other directions while gazing at the target object, which are not the real data at the test target point, and their amplitudes in θ and φ are usually large, which will have a serious impact on the accuracy of the eye-tracking. Therefore, this part of the data should be discarded when calculating the spatial accuracy and precision, but the "burrs" caused by micro-movements of the eyeballs cannot be removed by simple data processing.

In order to gain a deeper and more detailed understanding of the effect of the aforementioned micro eye movement on the test results, we selected a test target ($\theta = 20°, \varphi = 210°$), removed the data generated by the wide range of hopping vision, and plotted curves to compare the two, as shown in Figure 7. It can be visualized that the objective curve is much smoother, while the subjective (Vol.3&4) results are mixed. We first calculated the mean values of the individual curves, which yielded SD of 1.01°, 2.42°, and 0.24° for subjective Vol. 3, Vol. 4, and objective tests at azimuth angle φ, corresponding to peak-to-peak(P-P) values of 7.24°, 11.18°, and 1.13°, respectively. Similarly, at polarity angle θ, the SD was 0.22°, 0.68° and 0.07° with P-P values of 1.09°, 2.86° and 0.30°, respectively. By comparison, we found that the dispersion of the subjective results was much larger than the objective ones, as well as that the dispersion of the test results of Vol. 3 and Vol. 4 was different in the subjective tests, indicating that the magnitude of micro eye movements when gazing at the target was also different for different volunteers. Finally, we calculated the spatial accuracy and precision at this test target point, and the accuracy for Vol. 3, Vol. 4, and the objective were 0.95°, 1.36°, and 0.34°, respectively, and the precision SD was 0.25°, 0.67°, and 0.10°, respectively.

From the above, it can be concluded that the micro eye movements of the human eye will have a certain impact on the eye tracking test, and the objective eye tracking accuracy and precision are smaller than the subjective test results. In addition, in the subjective test, each volunteer wears the VR device in a different position, whether the relative position of the eyeball and the eye tracking system will affect the spatial accuracy of eye tracking test results in the subjective and objective tests, so we carried out the relevant tests. In the objective test, we fixed the VR device on a six-axis motion platform and adjusted its rotation in the X, Y, and Z-axis directions and displacement in the X-axis direction to obtain the spatial distribution of the eye-tracking gaze point.

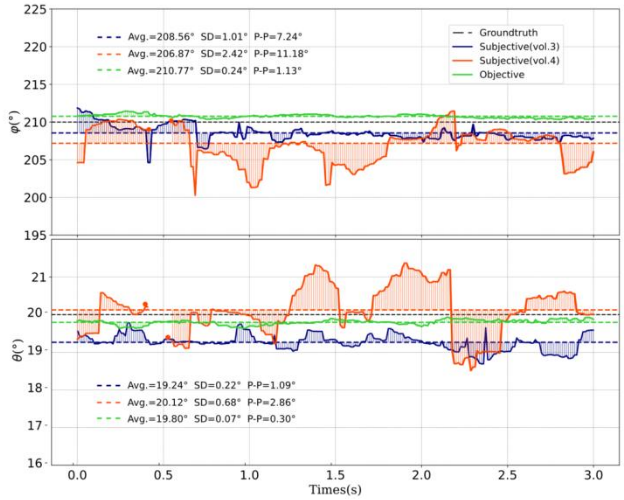

Figure 7. At $\theta = 20°$ and $\varphi = 210°$, the blue and red curves are the difference between the subjective and objective eye tracking raw data and the ground truth, respectively.

Because its center of rotation is not easy to determine, we only rotationally adjusted a very small angle, with a total of 12 target test points located at $\theta = 20°$, $\varphi = 0°, 30°, 60°... 330°$. From the Fig. 8, we can find that as long as the bit position of the VR device changes, i.e., the relative position and rotation of the VR device and the eye tracking system change, the spatial distribution of the gaze points will also change accordingly, which ultimately leads to changes in the spatial accuracy of eye tracking.

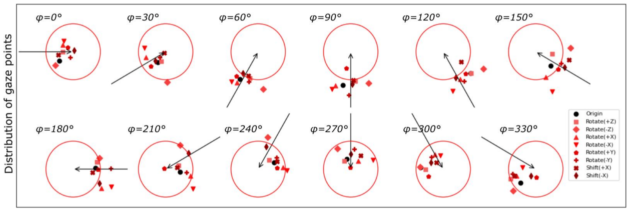

Figure 8. Spatial distribution of objective eye tracking gaze points. Polarity angle $\theta = 20°$, each point is the mean of all sample points for that test, black arrows indicate the location of the test target point, and the red circle has a radius of 87.3 mm (Gaze depth = 5 m).

The many independent variables mentioned above that change the relative position and rotation between the eye and the VR device are not conducive to evaluating the exact extent of the effect of such factors on the accuracy of eye tracking, so we investigated the effect of the vertical distance between the eye and the optics of the VR device (i.e., Eye Relief (ER)) on the experimental results. As shown in Fig. 9, the variation curves of spatial accuracy with ER are plotted at different polarity angles, and it can be seen that the spatial accuracy of eye tracking is minimized at ER=15 mm, which indicates that a superior performance eye tracking experience can be obtained by using the VR device at this position. As ER decreases or increases, the accuracy decreases, and the shape of the curve in the figure resembles a “smile” curve.

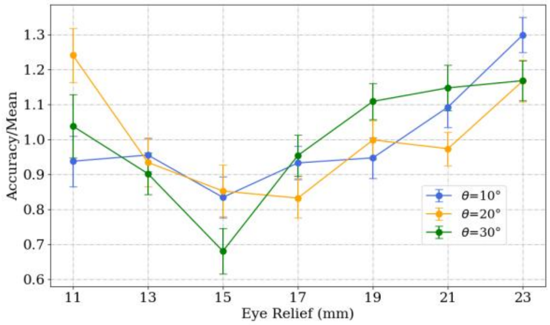

Figure 9. Curves of eye tracking spatial accuracy with eye relief at $\theta\ =\ 10°$, $20°$ and $30°$ for Product A.

7. Discussion

In this paper, we conducted objective eye tracking spatial accuracy tests on several VR devices with human eye tracking systems using high precision human eye simulation equipment, and we also invited volunteers to participate in subjective eye tracking tests. We obtained subjective and objective eye tracking test results, and the accuracy of different VR devices is different, and of course the accuracy obtained by different volunteers is also different. By comparing the subjective and objective test results, we found that there are three main reasons for the differences in the accuracy obtained by the two test methods. First, from the point of view of the physiological behavior of the human eye, large saccades can be excluded through data screening, but small eye movements when gazing at the target object are inevitable and have an impact on the eye tracking test. Second, differences in the relative position to the eyeball when using VR equipment also affect the spatial distribution of gaze points. Finally, there are multiple factors in subjective testing, such as differences in eye structure and the size of the target object gazed at by different volunteers.

As shown in Fig. 10, we compared the subjective and objective eye-tracking accuracy test results of Product A under $\theta\ =\ 20°$ condition, and the accuracy difference between the two is $\Delta\ =\ \theta_{Sub.} - \theta_{Obj.}$. According to the analysis above, Δ =0.740 ° it is mainly caused by three aspects, which are the micro eye movements of the physiological behavior of the eye, the relative position between the VR device and the eye, and other factors such as the structure of the eye and the size of the target object. First, we calculated and analyzed the mean SD value of 0.382° caused by micro eye movements for 12 test target points at $\theta\ =\ 20°$ for each volunteer, removing the instability of the eye tracker itself, i.e., subtracting the SD value of 0.075° from the objective results, so that tiny eye movements caused an error of 0.317°. Second, we indicated the effect of the relative position of the eye to the VR device by the change in ER, which caused an accuracy error of 0.185° when ER = 13~19(±1mm) mm. Finally, there are various factors in the subjective test, such as structural differences between eyes and the size of the gaze target object.

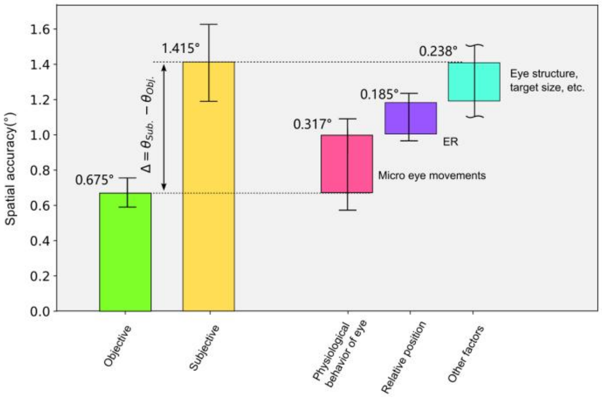

Figure 10. Analysis of the reasons for the discrepancy between subjective and objective eye-tracking test results for Product A at $\theta\ =\ 20°$.

8. Conclusions

In this paper, we demonstrate the spatial accuracy of subjective and objective eye tracking for VR devices on the market, and the eye tracking systems of Products A and C outperform Product B. Comparison of subjective and objective eye-tracking test results revealed that the accuracy values became larger as the field of view angle increased, and the volunteers in the subjective test were accompanied by ocular physiological behaviors when gazing at the target point, which had a greater impact on the test results, and thus this part of the gaze direction data needed to be excluded. In addition, there are also micro movements physiological eye movement behaviors that lead to poor precision, and such eye movement behaviors are unavoidable in the subjective test. The relative position of the eye to the VR device, such as ER, can also cause differences between subjective and objective results, and these differences also include other factors such as the structure of the eye, the size of the gaze target, and so on.

However, in objective eye tracking tests using a high precision human eye simulation device, which can provide the ground truth of gaze direction, as well as having a fairly stable artificial eye system, the aforementioned eye extensive and micro eye movements do not occur at all, and the relative position of the eye to the VR device can also be accurately controlled, which allows for a better assessment of the accuracy and precision of eye tracking in VR devices. Finally, we found that the spatial accuracy of eye tracking is smaller under proper eye relief, which also gives a new direction to combine the optical system and eye tracking system of VR devices for design.

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