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Study on Artificial Imaging at The Peripheral Retina Region*

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Abstract **Objective** For people with impaired central vision, novel artificial optical devices can provide access to simplified images by projecting them onto retina regions out of the macula, thus allowing them to utilize peripheral vision to perceive information. We investigate perceptual characteristics of peripheral visual field and provide clues for the design of implantable optical artificial vision devices. **Methods** We propose an experimental environment for investigating perceptual characteristics of peripheral vision, in which pattern stimuli of symbols, numerals, and Chinese characters are applied to the subjects, with variables including the size, the color combination, the eccentricity, and the motion controlled. The relation between perceptual capability and the variables are analyzed using graphical methods. **Results** The perceptual capability declines as the eccentricity increases, forming two appreciable trends, and it is significantly influenced by color combination and size. **Conclusion** Variable combinations with considerable perception rate are provided. The results may promisingly act as a reference for the implantation of artificial optical devices in eyes, the development of color symbol codes for special communication, *etc*.

Key words implantation, macula, peripheral vision, image identification, symbol, text & color
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With the development of various man-machine integration technologies, artificial vision has become a hot field. However, currently most artificial visualization techniques, either external devices or internal implanted devices, mainly focused on the macula region. A retina contains cone cells and rod cells for visual sensation[1]. The macula is the central region for human vision where cone cells have a high intensity, and around the macula the cone cell density decreases sharply. However, the density of rod cells peaks outside of the macula region and then decreases slowly. The macula region in the retina of an adult has a diameter around 5.5 mm, and an area about 24 mm^2, but rod cells distribute in an area forty times of the macula (Figure 1a, b) [2]. Therefore, the peripheral vision can be generated in a much larger area of the retina and provide the brain plenty of useful optical information of the environment[3-5].

In daily life, weakness and age-related macular degeneration may result in losing the capability of reading, driving, face recognition, *etc*. To solve this serious problem, we have proposed an "optical projection device in eye"[6-7], which could project optical images onto the curved hemispherical retina, especially the out-of-macular region. It is expected that such a device would help people who are suffering from macular degeneration to partly restore visual capacity and thus recover the capacity of reading, driving, *etc*.

Yet the characteristics of peripheral vision has not been fully invested. Previous studies have addressed detailed features of the peripheral color vision mechanisms as compared to the foveal

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mechanisms. The effects of light adaptation, color detection, discrimination thresholds, activity of L-M and S-(L+M) channels (short-wave S-cones, with peak sensitivity at ~430 nm; middle-wave M-cones with peak sensitivity at ~530 nm; and long-wave L-cones with peak sensitivity at ~560 nm), resolution thresholds, *etc*., have been studied[8-15]. Rozhkova *et al*.[16] measured the entire range of eccentricity and obtained comprehensive data on the general characteristics of peripheral color vision. They found that when presented with color-tested stimuli in the peripheral visual field (with the eccentricity of 25°−95°), participants perceived the peripheral stimuli clearly and vividly. In most cases, participants tended to choose the central stimulus that was most similar to the peripheral test stimulus. Feng *et al*.[17] showed that character and radical recognition had peripheral inversion effects at the eccentricity of 6.2° and 12.2°. Still, recognition rate of inverted stimuli was higher than that in random case. Sun *et al*.[18] measured the perception time for peripheral visual stimuli at large eccentricities. The results showed that the larger the eccentricity, the longer the perception time. Chanceaux *et al*.[19] investigated the recognition capability for letters, numerals, symbols, and shapes in peripheral vision, and discussed the triple correlation among the eccentricity, stimulus type and visual field. For instance, they found that symbol and shape stimuli showed similar effects of eccentricity in both visual fields, while the performance of letter and numeral stimuli depended more on the horizontal position in a string. Despite limited insight into the characteristics of peripheral vision, current research has also practically focused on the application of peripheral visual perception in terms of art, optical illusions, *etc*[20].

In this work, we investigated the capacity and characteristics of peripheral vision in terms of color combination, pattern (shapes, numerals, and Chinese characters), object movement, *etc*. We made both qualitative and quantitative analyses of visual characteristics, such as the dependence of eccentricity and color combination. Some new features were found, *e.g*., Chinese characters were recognized better than numerals in a larger peripheral region. The results of this work may offer a solid foundation for artificial optical devices implanted in eyes. They may also offer some clues for virtual reality (VR) and augmented reality (AR) technologies, or alternative optical encodings[21].

1 Experimental setups

The experiments were performed in a quiet dark room. The participants were all healthy Chinese college students with an average age of 22. Chinese was their first language and English was the second. All participants achieved visual acuity in the naked eye or corrected vision of 1.0.

As shown in Figure 1c, a participant sits still in front of a wide dark screen (4.5K, resolution 4 480 × 2 520, working at 60 frames per second). The screen is 30 cm away from the participant. The edge of the screen was about 60° away from the straightforward direction of the eyesight. A small bright white cross pattern was fixed in the center of the screen to mark the central point of the field of view. The eccentricity of the object displayed in the screen, hereinafter referred as θ, was defined as the offset angle of the stimulus to the straightforward direction of eyesight, as shown in Figure 1c. During all the trials, the participants were required to keep their head position straightforward, and to focus their eyesight onto the central cross pattern all the time. In some experiments, 6 pieces of solid screens were set in front of the participants, arranged in a semicircular shape, and the stimuli were projected to the screen by a digital projector fixed closely on top to the participant's head.

All the patterns and texts used in the recorded experiments were presented using programs based on PsychoPy[22]. The participants used testing keyboard to pick their answers, and therefore the reaction time and the correctness of answers were recorded simultaneously.

For each category of patterns, the participants needed to complete 10 sets of trials, where each set was consisted of 20 trials. A 30 s resting time was applied between two sets of trials. It took around 20 min for one category of testing pattern, and each participant needed to spend 3 h completing all the categories for his or her peripheral vision capability.

By changing the eccentricity of the stimuli, we systematically tested the identification accuracy, reaction time, recognition capability, *etc*., for a variety of categories for patterns and texts in the peripheral vision.

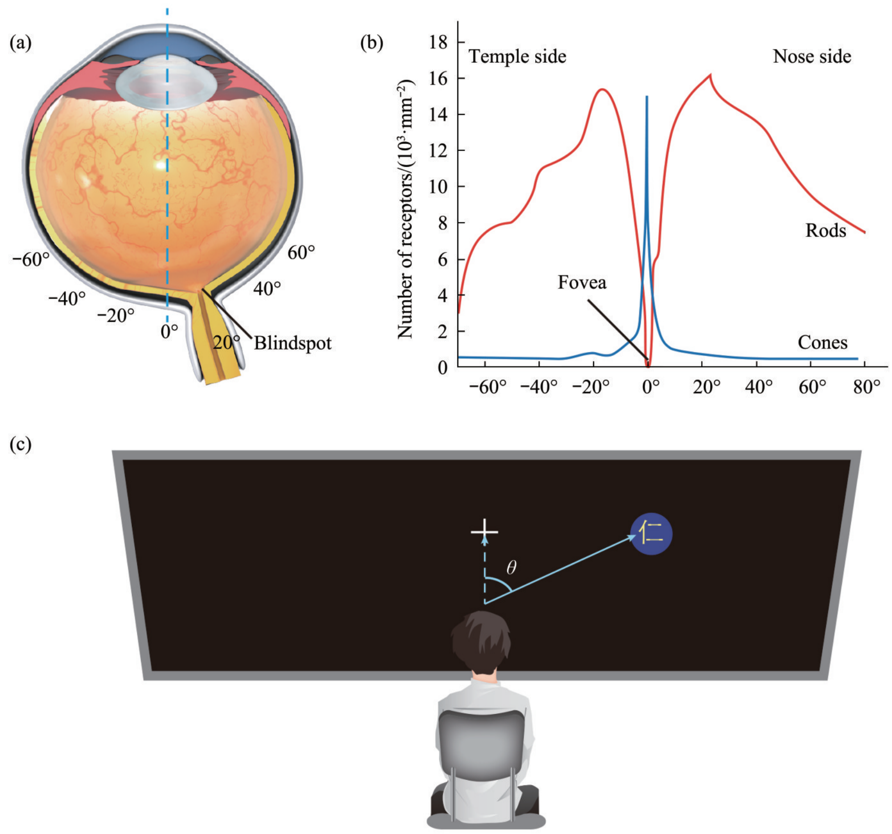

Fig. 1　Features of an eyeball and the experimental setup

(a) Schematic structure of an eyeball. (b) Density distributions of cone cells and rod cells along the retina. (c) Illustration of experimental setup of this work.

For instance, to measure the visual sensitivity and accuracy for the color combination of patterns, the objects were designed as Chinese characters of one color embedded in a solid circular of another color. Chinese characters with similar structures were chosen, such as the "left-right" structured "什", "仁", "化". To make choices, the participants needed to stroke keys of 1, 2, 3 on the testing keyboard.

To measure the visual sensitivity and accuracy for numerals and Chinese characters with different size at various eccentricities, in addition to randomly chosen colors, color combinations such as green patterns on red background, yellow or white patterns on blue background, blue patterns on white background, were chosen for double-confirmation tests, as it had been proven that the participants were most sensitive to these color combinations. Numerals with similar shapes, 8, 9, 0, *etc*., were most frequently used in these tests.

To measure the visual sensitivity and accuracy for moving or blinking objects in the peripheral visual field, we designed colored arrow patterns, and let them move in different ways including rotating, moving, blinking, *etc*., to compare them with stationary arrows.

In part of the experiments, such as the comparison for sensing numerals and Chinese characters, the eccentricity of the stimuli was chosen among 5°, 7°, 9°, 11°, 13°, 15°, 17°, 19°, 21°, 23°, 25°, 27°, 29°, 35°, 45°, 55° along the horizonal direction. For the rest experiments, the eccentricities were randomly chosen for figuring out unexpected phenomena. For the investigation on the symmetry of peripheral vision around the macula, 200 different positions in a rectangular lattice were chosen for the experiment.

2　Results

2.1　Symmetrical characteristics in peripheral vision between the left and right, upper and lower regions

We first generally checked the symmetry in recognition of patterns in a wide range of peripheral vision. For each set of experiment, 200 testing points were uniformly displayed or projected in the screen.

Figure 2 presented a typical result. The task for participants was to recognize the pointing direction of a short bar in a white background circle, either from up-left to down-right, or from right-up to left-down, as shown in Figure 2a. The parameter plotted in Figure 2b was the reaction time for recognizing the pattern and diving the answer, where the color bar showed the reaction time from 0.5 s to 1.5 s. The horizontal eccentricity corresponds to θ as defined in Figure 1c, and the vertical coordinate corresponds to the eccentricity along the vertical direction with the same ratio. The data in Figure 2b were the averaged values taken from one participant.

The horizontal eccentricities from −5° to −45° were corresponding to the reaction of the participant's left eyesight, and the angles from 5° to 45° were corresponding to the reaction of the participant's right eyesight. The results showed that, in a roughly circular region with eccentricity of 30°, the average reaction time was less than 1.0 s. And this reaction time got longer at higher eccentricity.

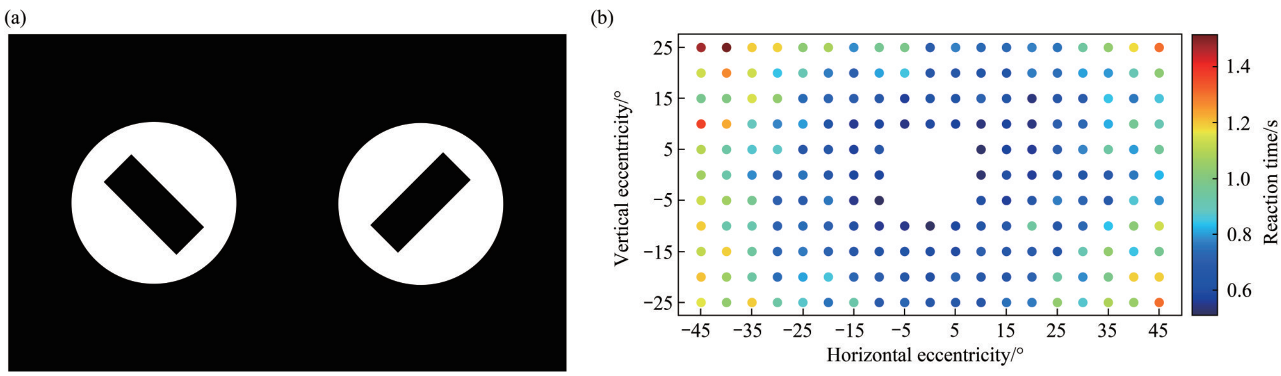

Fig. 2 The reaction time for recognizing a direction pattern presented in different special locations of the peripheral vision field

(a) The pattern for testing. (b) The average reaction time for the pattern showing at different screen positions with varied eccentricity in both horizontal and vertical directions.

We further analyzed the symmetrical characteristics of peripheral vision from the raw data. Shown in Figure 3 was a smoothed contour pattern map after performing linear interpolation for the raw data. The central region was not tested therefore leaving a square hole. Despite the measurement errors occurred in limited tests, generally the left and right eyesight, upper and lower eyesight, both appeared symmetric.

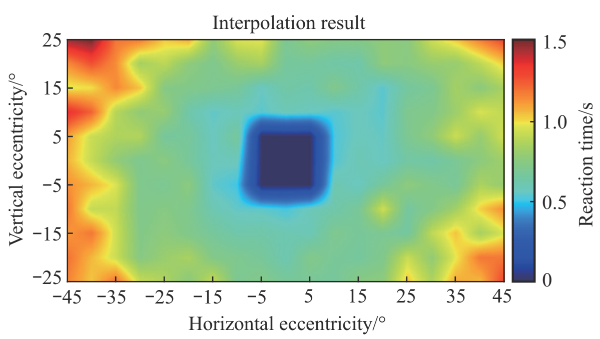

Fig. 3 The contour pattern map of the raw data of reaction time after performing linear interpolation

Therefore, in the rest experiments, we mainly tested the capacity of peripheral vision at the right eyesight and changed only horizontal eccentricity.

2.2 Recognition sensitivity for different color combination in peripheral vision

We measured the recognition sensitivity for patterns and texts with different color combinations in the peripheral vision by displaying patterns or texts with one color in a small circular background of another color.

Figure 4a showed a typical set of testing patterns. Here 5 columns of background circles were colored in blue, red, yellow, green, and white, respectively. Chinese characters such as "什" (shown in Figure 4a) was embedded in the same position of each circle but presented in varied color. Each testing stimulus were displayed in the screen with changing eccentricities, and the recognition accuracy of the embedded word (Chinese character) was recorded. Figure 4b presented the average results for the yellow characters on blue background, and white characters in yellow background. For the former, the yellow on blue combination, an accuracy over 80% was recorded even at the eccentricity of 25°. While for the latter, the white on yellow combination, it decreased quickly after eccentricity larger than 10°.

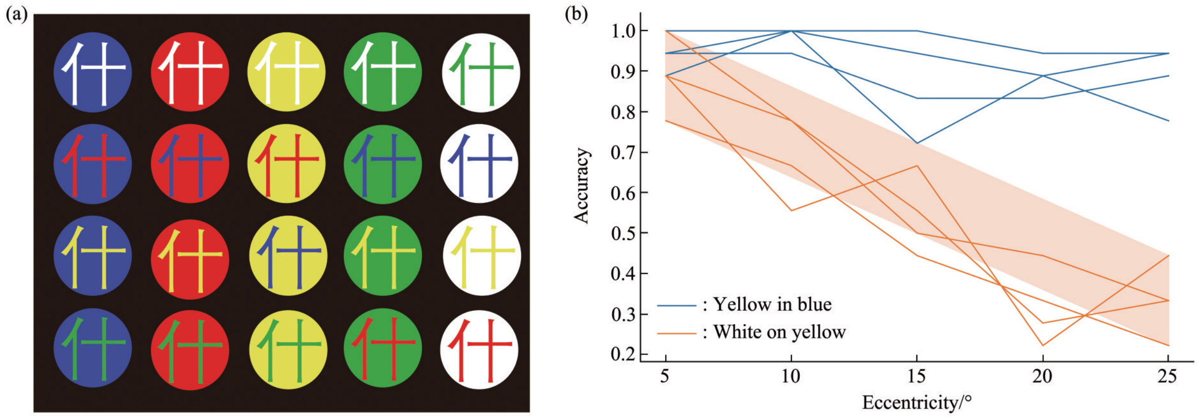

Fig. 4　The measurement results for the recognition sensitivity for patterns with varied color combinations

(a) The patterns used in the tests. (b) The accuracy results of 4 participants. Typical results showing the recognition accuracy for yellow words on blue background (top lines, highlighted with blue shadow) were remarkably higher than those of white words on yellow background.

Figure 5 summarized a statistical table for the average experimental results taken from the 4 participants. It showed that the yellow on blue combination, an accuracy over 80% was recorded. While for the latter, the white on yellow combination, the overall accuracy was less than 60%. Among a variety of color combinations, those patterns or words having blue, red backgrounds received the highest recognition accuracy. Meanwhile, blue and red patterns were also easier to identify than the rest colors. This might be attributed to the sensing properties of widely distributed rod cells in the retina, as shown in Figure 1a.

It is worthy of further detailed studies for more color combinations in the full spectrum of sensible color of eyes.

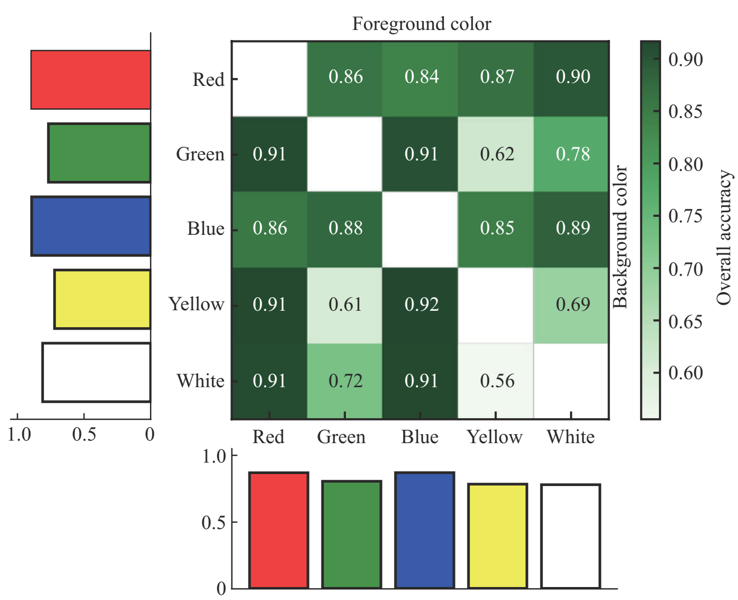

Fig. 5　The average measurement results for the recognition sensitivity for different color combinations

2.3 Recognition sensitivity for size and text meaning in peripheral vision

As expected, objects with larger size received better identification accuracy. Figure 6 presented a set of testing results. The three rows of patterns displayed in the screen, as typically shown in Figure 6a, corresponded to eccentricities of 2.5°, 4.0° and 6.0° to eye. The color combinations used were white on blue, yellow on blue, blue on white and yellow on red, respectively. The testing results were plotted in Figure 6b. When displayed at small eccentricities, *e. g.*, less than 10°, the difference was not remarkable. At big eccentricities, *e. g.*, more than 25°, larger patterns received much higher recognition accuracy. The quantitative results plotted in Figure 6b might offer valuable base for estimating the maximum number of words or other meaningful text in the design of inner optical projection devices in eye.

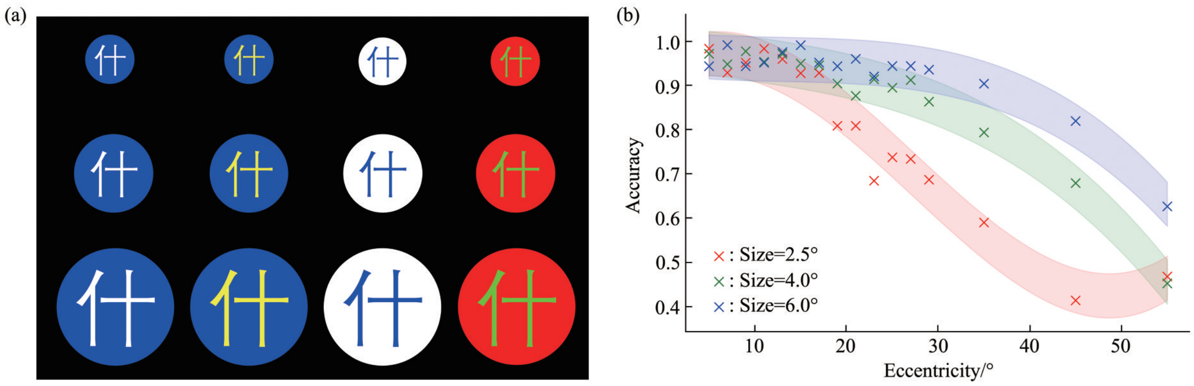

Fig. 6 Sensitivity of peripheral vision to Chinese characters with varied sizes

(a) From top to bottom, typical patterns used in the tests, corresponding to eccentricities of 2.5°, 4.0° and 6.0°, respectively. (b) Measurement results of recognition accuracy for different patterns with these varied sizes over changing horizontal eccentricities from 5.0° to 55.0°.

Similarly, we measured the color effect for numerals in the peripheral vision, as typically presented in Figure 7. Figure 7a plotted three rows of numeral patterns displayed in the screen, corresponding to eccentricities of 2.5°, 4.0° and 6.0°, and Figure 7b showed the experimental results.

We noted that, for the same pattern size, different color combination caused different trends of decreasing recognition accuracy for Chinese characters and for numerals. For instance, with the same combination of green on red, the participants had higher recognition accuracy for Chinese characters but much lower accuracy for numerals. It needed further investigations to reveal the underlying mechanism.

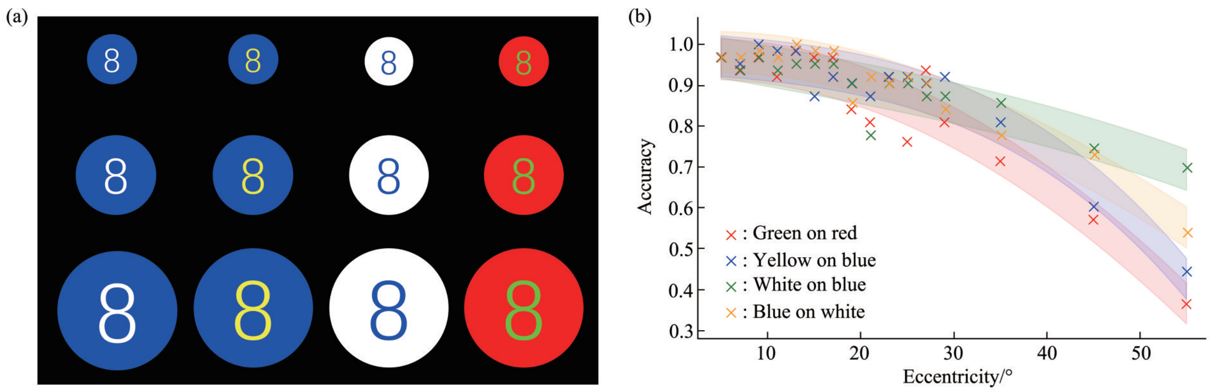

Fig. 7 Sensitivity of peripheral vision to numerals with typical color combinations

(a) Three rows of numeral patterns displayed in the screen, corresponding to eccentricities of 2.5°, 4.0° and 6.0°. The 4 columns showed different color combinations of these patterns. (b) Experimental results of recognition accuracy for the patterns displayed at varied horizontal eccentricities in peripheral vision.

2.4　Difference in recognition sensitivity for Chinese character pattern and numeral patterns

We investigated and compared the recognition capacity in peripheral vision for Chinese characters and numerals. Figure 8a plotted some object patterns used in the experiments, where three Chinese characters "什", "仁" and "化", as well as 3 numerals, 8, 9 and 0, were embedded in circular backgrounds. These three Chinese characters had the same "left-right" structure thus they were not easy to identify in blur images. Similarly, the three numerals were also easy to confuse in blur images. Different color combinations, such as white on blue, yellow on blue, blue on white and yellow on red, *etc*., were applied in different trials. These color combinations were chosen for double confirmation as receiving the highest sensitivity as previously measured and discussed. All the testing objects had the same size in the screen.

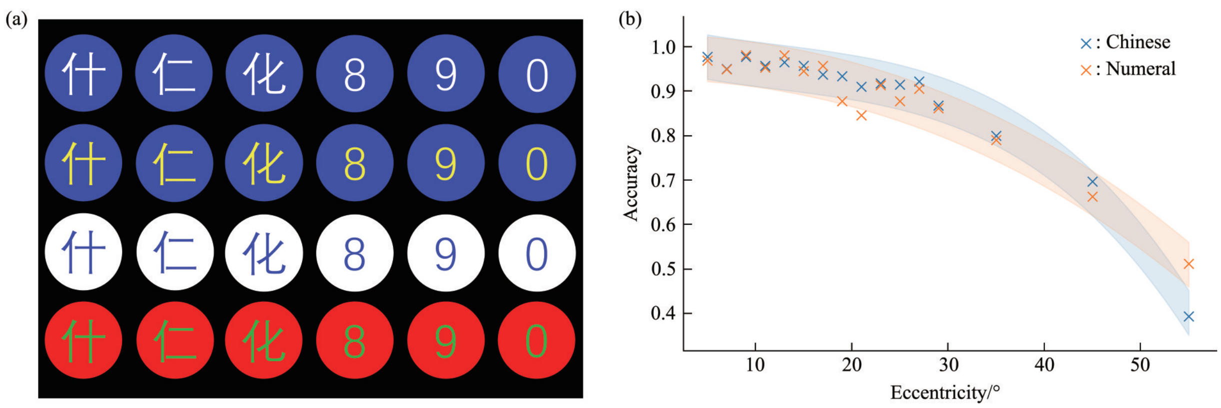

Fig. 8　Comparison between Chinese characters and numerals

(a) Some object patterns used in the experiments, where 3 "left-right" structured Chinese characters "什", "仁" and "化", as well as three numerals, 8, 9 and 0, were embedded in circular backgrounds, with varied color combinations. (b) The measurement results for the patterns shown in (a) at various eccentricities, taken from 8 participants.

Figure 8b plotted the testing results. It was interesting that in the moderate eccentricity in the range of 15°−45°, the participants showed a slight but distinguishable higher recognition accuracy for the chosen Chinese characters than for the three similar shaped numerals. This might attribute to the learning and reading habits of the participants in this work. Yet it might be universal. Previously, Feng *et al*. [17] studied the perception capacity of Chinese characters at eccentricity of 6.2° and 12.2°, and concluded that Chinese characters might offer serval structural criterions for identification. Wong *et al*.[23] suggested that longtime experience in book reading could resulted in unique identification capacity. All these might lead to a higher recognition capacity in peripheral vision for Chinese characters than numerals which have simple outer shapes.

2.5　Sensitivity to moving or blinking objects in peripheral vision

Consistent to previous reports, our experiments also showed that people were sensitive to moving or blinking objects in the peripheral visual field. Figure 9 presented part of the testing results. Listed in Figure 9a were some different ways of changing patterns used in the experiments, *i. e*., rotating, moving, blinking, irregularly positioning, respectively. For instance, in one trial, the "rotating" object rotated periodically within 5°, while the "moving" object was designed to move left and right. The "irregular" object was set to change its position randomly in certain range.

Figure 9b plotted the testing results. The participants were requested to tell the direction of the arrow. In general, the trends showed that the sensitivity for moving or blinking objects was higher than that for stationary ones within the eccentricity of 45°. After that, the recognition accuracy dropped quickly with increasing eccentricity.

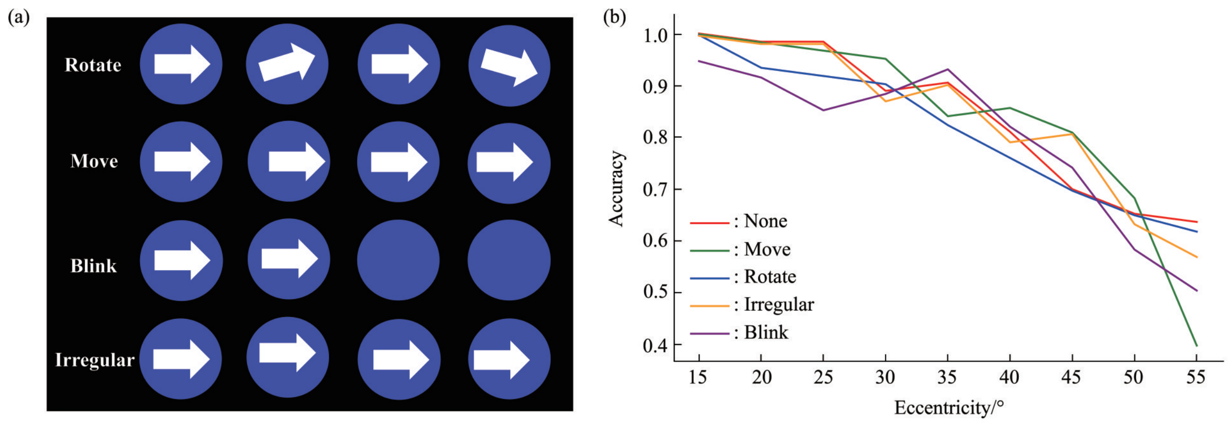

Fig.9 Sensitivity of peripheral vision to patterns with different changing styles

(a) Some different changing patterns used in the experiments, including rotating, moving, blinking, and irregularly positioning ones. (b) The accuracy results of different changing patterns at various eccentricities.

3 Discussion

The foregoing experimental results implies a declination of recognition rate starting from the eccentricity of 10°. Furthermore, as the eccentricity continues to increase, the plot stages into another part with a larger slope, which is appreciably influenced by color combination and size. Since a defect of recognition rate can lead to a dangerous scenario caused by misjudgment, to acquire rapid and accurate recognition in peripheral vision, original images should not be used without handling. Conversely, graphical instructions in form of symbols, simple letters, *etc*., are preferred in such application. This paper explores possible combinations of such instructions, demonstrating that larger patterns enjoy a higher recognition rate though with a decrease in information. Meanwhile, patterns that have intuitive implications such as arrows outperform intricately structured characters. In practice, characters with simple structures could be taken into consideration, but it is recommended to enlarge the distance between each pair of symbols.

The pupil of a human eye has a regular diameter of 2−5 mm. Therefore, although after the pupil the lens has a focusing function for incident lights, the major imaging mechanism of an eye is the “pinhole imaging” mechanism[1].

Considering that, the retina layer has a hemispherical shape. As a result, only in its central region, *i. e*., the macular region, external lights are precisely focused, which offers a high intensity of pixels for clear optical images. Meanwhile, in the large area regions outside of the macula, the quality of optical images decreases rapidly, causing much lower cognition capacity in peripheral vision of the brain.

The proposed “optical projection device in eye”[6-7] is capable of projecting images precisely onto the curved hemispherical retina in or out of the macula. At each part of the retina where rod cells exist with density over certain threshold, even at large eccentricity, clear images might be created in the visual cortex. Therefore, the novel device has a potential to remarkably enhance the cognition capacity of the peripheral vision. To confirm it, further investigation is necessary.

4 Conclusion

In this paper, we measured the sensing characteristics for symbols, texts, numerals, colors and moving objects in peripheral vision. We found that, in the visual field with eccentricity less than 15°, the recognition capabilities for numerals and Chinese characters were at the similar level. However, when the eccentricity was in the range of 15°−45°, the peripheral vision had a remarkable better recognition accuracy for Chinese characters than for numerals. This interesting result supported the previous argument of Wong *et al*.[23], that it might be attributed to the reading habits for Chinese characters and books (where dozens of characters appeared at the same time in the central and peripheral region) built up during their education trainings of the participants. In the peripheral vision, symbols with varied color combinations caused varied visual recognition. For instance, in general the participants were most sensitive to yellow text symbols embedded in blue background. Yet for numerals, they seemed most sensitive to white numerals embedded in blue background. For small eccentricities, motion of the target did not affect much of the recognition accuracy. But in the eccentricities in the range of 25° −45° , movements of the stimuli resulted in higher recognition accuracy than stationary ones. All the tests showed that, for stimuli located in the regions with eccentricity larger than 45°, the recognition accuracy in peripheral vision dropped steeply.

The results of this work offered quantitative basis for the development of artificial visual devices implanted in the eyes that project optical images and texts onto peripheral retina regions outside the macula. Furthermore, this work might trigger attentions to the detailed imaging mechanisms in peripheral vision, both the optical mechanism of the physical eyeball and the cognitive mechanism of the visual path in neural systems.

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视网膜周边视野人工成像研究*

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摘要 **目的** 对于中心视力受损的人群，新型人工视觉系统可以将简化后的图像投射到视网膜上黄斑区以外的区域，从而帮助他们利用周边视觉感知信息。本文探究周边视野的感知特征，为植入式光学人工视觉系统的图形编码设计提供依据。**方法** 设计了探索周边视野感知特征的实验环境，向被试施加符号、数字、汉字的图案刺激，并控制刺激的大小、颜色组合、偏离角度、运动情况。用图形化的方法分析感知能力与各变量的关系。**结果** 周边视野的感知能力随偏离角度增大而下降，其趋势分为两个阶段，且受颜色组合、大小的影响明显。**结论** 研究结果提供了感知识别率较高的变量组合，为人工视觉系统的光学投影、眼内光学植入装置、特殊通信彩色符号编码开发等“人机结合”新技术提供重要的实验依据。

关键词 植入，黄斑，周边视觉，图像识别，符号，文本和颜色

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