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Research Letter

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Temporal Changes in Convergence Distance and Level of Eye Fatigue during Video Viewing on a Smartphone

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Abstract In recent years, ophthalmic problems such as asthenopia and strabismus due to watching videos on smartphones have increased, particularly among the younger generation. A smartphone can be operated with one hand regardless of posture. Consequently it is possible to use a smartphone at a closer distance than the usual near-sighted working distance (40-30 cm) for long periods. This may be the cause of the problems described above. In this study we aim to investigate the control of eye movements during viewing of a video on a smartphone. The video features intense two-dimensional images with depth information. The gaze of both eyes was measured, and the convergence distance was examined. Six university students participated in the study. They were asked to watch a 15-minute video on a smartphone, during which their eye movements were measured. During the experiment, the participants watched a self-made "video moving through a 3-D maze." For each viewing distance, the convergence distance was calculated based on the intersection of the eyes' gaze. In some instances, the viewing distance and the convergence distance did not match when watching the video, suggesting that the mismatch could lead to eye strain and strabismus.

Keywords: gaze point, convergence distance, fatigue level, strabismus.

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1. Introduction

An increase in incidence of acute esotropia has been observed in recent years, particularly among younger age groups. Acute esotropia is believed to be associated with prolonged viewing of screens on smartphones, tablets, computers, and gaming devices [1–3]. However, the exact mechanism of its development remains unclear. In Japan, a nationwide study on the relationship between digital device use and the onset of acute esotropia was initiated in 2018 [4]. Individuals with difference in visual acuity between two eyes or with strabismus need to take care when watching 3D images [1]. We are increasingly watching videos on our smartphones as part of our daily life, creating a visual environment that differs from our traditional visual experience. Therefore, it is conceivable that the potential stress on the eyes is increasing. Even individuals with no medical issues have reported more pronounced symptoms of eye fatigue during 3D viewing, resulting in difficulty to maintain a continuous gaze [5]. In viewing videos with continuously moving contents for long periods of time, it is speculated that maintaining convergence with the moving stimuli may be difficult.

Previous research on eye gaze analysis using smartphones has focused on studies of users viewing trends on social media websites [6] and analysis of specific gaze patterns related to autism spectrum disorder [7]. Most of these studies focused on still images or videos with relatively gentle movements on smartphone screens. Unlike previous approaches, in this study, we conducted gaze analysis focusing on videos with violent movements, for which controlling the gaze is considered to be particularly difficult. This new approach is expected to be an important step in exploring the limitations and possibilities of gaze analysis.

Therefore, we focused on the individual differences

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in controlling the eye position and the subjective fatigue during smartphone video viewing by visually normal adults. The changes in gaze points of both eyes over time were analyzed to examine the variations in convergence distance. The aim was to provide insights that may contribute to the prevention of eye stress.

2. Methods

2.1 3D maze Video

Six university students (participant A to F; 5 males and 1 female aged 23.0 ± 0.1 years) participated in the experiment. The participants had visual acuity of 1.0 or better, with no manifest strabismus or ocular motility disorder, and unremarkable ocular history. During the experiment, t watched a 15-minute virtual 3D maze video, as depicted in **Fig. 1**. The video was created using the Unity game engine (Unity Software Inc.). The participants did not have control over the vehicle (the lower cube in **Fig. 1**), but only observed the object as it navigated through the maze and the background images for the entire 15 minutes.

In recent times, the visual environment for young people has been characterized by a significant amount of time spent watching videos on smartphones. Even with 2D contents, there is frequent use of techniques that alter the speed of movement between the foreground and background, creating a perception akin to 3D visuals. We hypothesized that this may be a contributing factor to strabismus. Therefore, for this experiment, we created videos that emulate this effect and investigated the response of the participants.

The experiment was performed in accordance with the Declaration of Helsinki and was approved by the ethics research committee of Niigata University of Health and Welfare (No. 18689-210720), and Niigata University (No. C2022-0103). Informed consent was obtained from all the participants prior to their participation.

2.2 Visual task

An eye movement measuring device (SiB Eye Tracking Core+, Japan) was used to measure the gaze points on an iPhone 11 smartphone, which has dimensions of 150.9 × 75.7 mm and resolution of 1792 × 828 pixels, as shown in **Fig. 2a**. The measurement frequency was 60 Hz. Typically, maintaining a viewing distance of 300 mm or more is recommended when reading a book. For this experiment, two viewing distances were tested: 200 mm (representing the typical distance when people use their smartphones) and 400 mm (the control distance). The viewing distances of 200 mm and 400 mm are, respectively, the distance used when composing emails on a smartphone and the distance used when using a desktop computer. Before the experiment, in order to determine whether the participants had sufficient accommodative power for near vision, we confirmed that they could recognize the 1.0 visual target on a near vision chart at both 200 mm and 400 mm.

A participant wore an eye movement measurement device and sat in front of a table on which a smartphone fixed on a phone holder was placed. The smartphone was placed at the same level of the eyes, and the surrounding was covered with a black curtain at the left, right, and front.

The task assigned to the participant was to watch a 3D maze video for 15 minutes at different viewing distances. We collected precise gaze points by tracking the movement of the eye using a jaw-receiving stand. After the experiment, the participant was requested to assess their fatigue level. Although a jaw-receiving stand was used in the measurement, the results of this experiment can be extended to daily activities because people do not move their faces when they use smartphones in daily life.

The participant's perception of fatigue was measured using a 10-point scale: 0 for no fatigue, 1-3 for slight fatigue with sustained energy, 4-6 for moderate fatigue with reduced concentration, 7-8 for significant tiredness and difficulty concentrating, 9 for extreme tiredness impairing task performance, and 10 for complete exhaustion preventing any activity.

2.3 Data Analysis

We conducted an analysis of the right and left gaze

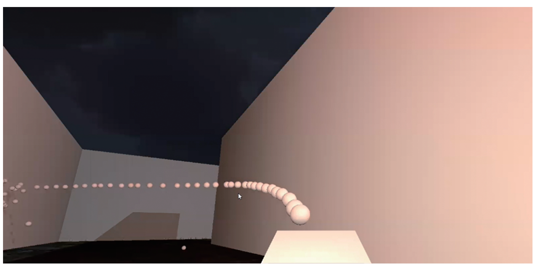

Fig. 1 Screenshots of the 3D maze video.

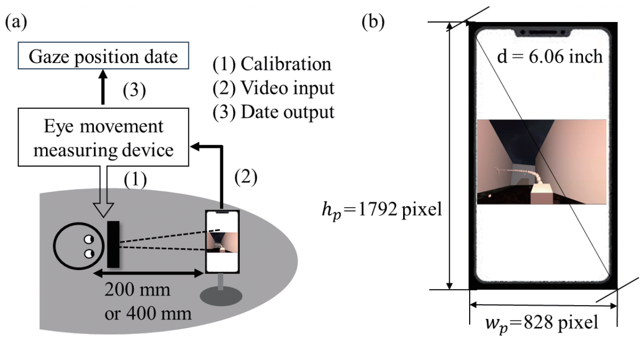

Fig. 2 (a) Experimental environment, (b) converting pixel measurements to millimeters; conceptual diagram.

points as well as the inter-pupillary distance (IPD). The eye movement measuring device used in the experiment measured the gaze points in pixels and the IPD in millimeters. Therefore, we had to convert the pixel measurements to millimeters based on the distance between the gaze points, as shown in **Fig. 2b**.

$$\mathrm{PPI}=\frac{\sqrt{{w_p}^2+{w_p}^2}}{d} \quad (1)$$

For the iPhone 11 with resolution of 1792 × 828 pixels, the diagonal size, denoted 'd,' is 6.06 inches. Consequently, the pixel density was calculated to be 326 pixels per inch (PPI) from Eq. 1. As 1 inch is equal to 25.4 millimeters, 1 pixel was calculated to be approximately equal to 0.0779 millimeters.

First, we calculated the distance $r(t)$ at time t between two gaze points on the smartphone using Eq. 2, where $x_R(t)$, $x_L(t)$, $y_R(t)$, and $y_L(t)$ are the horizontal positions of the right and left eyes and the vertical positions of the right and left eyes, respectively, in millimeters.

$$r(t)=\sqrt{\{x_R(t)-x_L(t)\}^2+\{y_R(t)-y_L(t)\}^2} \quad (2)$$

Figure 3a shows the temporal waveform of $r(t)$ of participant A (viewing distance = 200 mm). The pattern is similar to that of $X(t) = |x_R(t) - x_L(t)|$, as shown in **Fig. 3b**, but not to that of $Y(t) = |y_R(t) - y_L(t)|$, as shown in **Fig. 3c**. Similar results were obtained from the other participants. Therefore, we adopted $X(t)$ as a substitute for $r(t)$ to evaluate the convergence distance.

When the left gaze point was measured on the left side and the right gaze point on the right side, the convergence distance at time t, $d_c(t)$, was greater than the viewing distance, $d_v(t)$, as shown in **Fig. 4a**. In this case, i.e., $d_v(t) > d_c(t)$, the similarity of the two triangles of **Fig. 4a** yields the following equation,

$$d_c(t):\mathrm{IPD}/2=\{d_c(t)-d_v(t)\}:X(t)/2$$
$$\Leftrightarrow\ d_c(t)=\{d_v(t)\mathrm{IPD}\}/\{\mathrm{IPD}-X(t)\}. \quad (3)$$

On the other hand, when the convergence distance, $d_c(t)$, is smaller than the viewing distance, $d_v(t)$, as shown in **Fig. 4b**, i.e., $d_v(t) > d_c(t)$, the similarity of the two inverted triangles yields the following equation,

$$d_c(t):\mathrm{IPD}/2=\{d_v(t)-d_c(t)\}:X(t)/2$$
$$\Leftrightarrow\ d_c(t)=\{d_v(t)\mathrm{IPD}\}/\{\mathrm{IPD}+X(t)\}. \quad (4)$$

If $X = 0$, i.e., the convergence distance is equal to the viewing distance, we can verify the equality, $d_c(t) = d_v(t)$, from Eqs. 3 and 4.

Here, we explain the distinction between **Figs. 4a and 4b** (Eqs. 3 and 4, respectively). **Figure 4a** indicates that when viewing the video, the participant is watching an object in the video using only the dominant eye. Typically, our eyes are naturally turned outward, with the right eye facing right and the left eye facing left (considered the default state). When we focus on an object, both eyes converge inward to focus on the same point. However, it can be challenging to align both gazes to the same point when the viewing distance is relatively short. In such case, the dominant eye focuses on the object, while the other eye remains turned outward in the default state.

Conversely, **Fig. 4b** shows that when viewing the

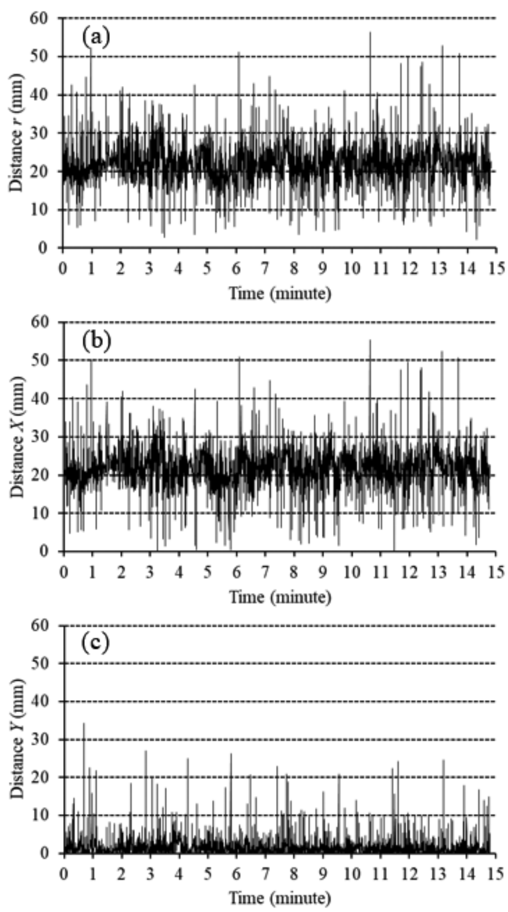

Fig. 3 Temporal waveforms of (a) distance r, (b) distance X, and (c) distance Y.

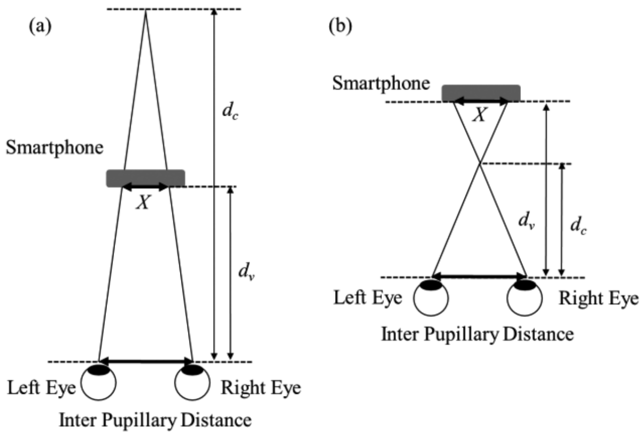

Fig. 4 The relationship between the convergence distance (d_c), the viewing distance (d_v), the inter-pupillary distance, and the distance X measured from the left to the right eye. (a) When $d_c > d_v$. (b) When $d_c < d_v$.

video, the participant is watching the object with both eyes. This increases the possibility of the participant hyper-focusing on the same object, especially when fast-moving images are involved, which can lead to eye fatigue. Prolonged exposure to such condition may increase the risk of the eyes developing internal strabismus.

3. Results

The difference in convergence distance for participant A is shown in **Fig. 5**. The two sets of data represent the data for viewing distances of 200 mm (red) and 400 mm (blue). In the experiment, participant A had convergence distances shorter than the viewing distance of 200 mm. There was a state of excessive convergence during the viewing time, indicating poor control of the eye position.

When participant C was viewing the video at a viewing distance of 200 mm, the convergence distance showed an initial downward trend for one minute, with the overall convergence distance being consistently below 200 mm (**Fig. 6**). For the viewing distance of 400 mm, the convergence distance decreased from 600 mm to less than 300 mm within a span of five minutes, and then remained below 400 mm.

For participant D, the viewing distance was equal to the convergence distance for the first minute (**Fig. 7**). After one minute, the convergence distance was longer than the viewing distance for various scenarios, and there was significant fluctuation in the values.

For participants B, E, and F, the convergence distance was equal to the viewing distance throughout the entire experiment. The convergence distances of participant F are shown in **Fig. 8**.

The participants' eye fatigue levels at two viewing distances are shown in **Table 1**. Considering that control of eye position can cause eye fatigue, the interquartile range (IQR), which is the difference between the third and first quartiles by statistical evaluation of the time series, is also shown.

4. Discussion

In this experiment, we set the viewing distances at 400 mm and 200 mm. The accommodative effort (strain) of the crystalline lens of the eye when focusing on objects at 400 mm was calculated to be 2.5 D, while it was determined to be 5 D at 200 mm. The participants in this study were in their twenties, and their accommodative capacity easily exceeds 10 D. Consequently, fatigue of the crystalline lens can be safely disregarded at both 400 mm and 200 mm. In other words, accommodative fatigue related to near vision of the eye (crystalline lens) can be excluded. Furthermore, the fact that their near vision acuity was 1.0 confirms that these participants possess ample accommodative capacity.

However, the videos that aimed to express depth

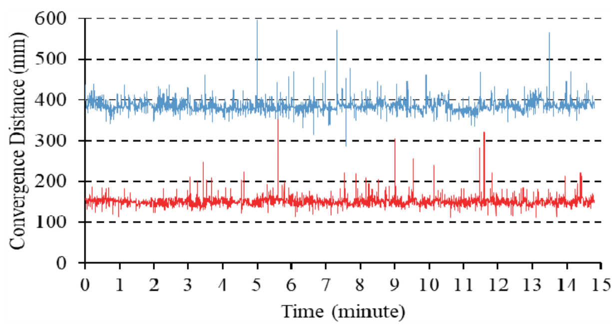

Fig. 5 Convergence distances of participant A for viewing distances of 200 mm (red) and 400 mm (blue).

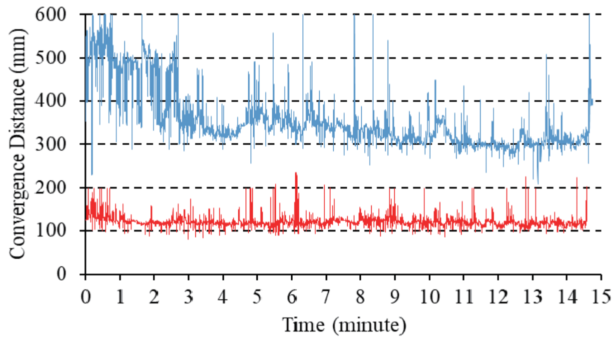

Fig. 6 Convergence distances of participant C for viewing distances of 200 mm (red) and 400 mm (blue).

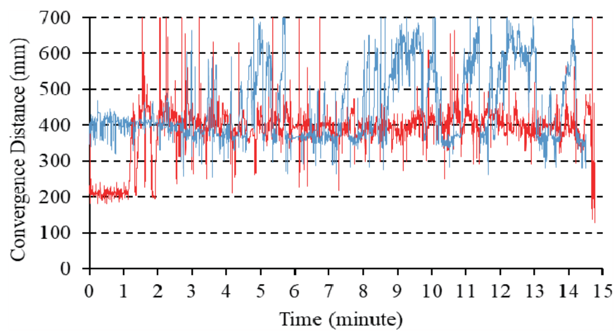

Fig. 7 Convergence distances of participant D for viewing distances of 200 mm (red) and 400 mm (blue).

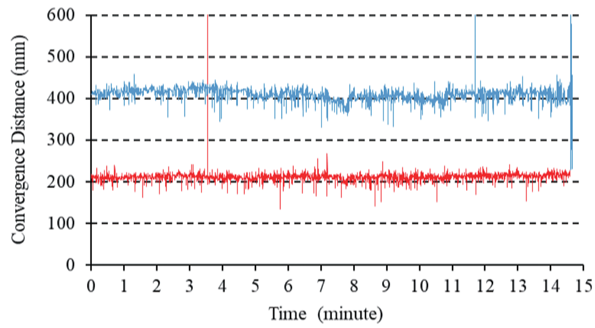

Fig. 8 Convergence distances of participant F for viewing distances of 200 mm (red) and 400 mm (blue).

(pop-out, depth) on the small two-dimensional screen of a smartphone were considered to be strong visual stimuli. There were individual variations in convergence distance among the 6 participants who watched the same video.

Participant A (**Fig. 5**) experienced stronger eye fatigue due to mismatch between the viewing distance and the convergence distance. In this case, both the 200 mm and 400 mm viewing distances had shorter convergence distances, requiring additional accommodation effort. Moreover, the gaze was directed towards the screen, while the actual image was positioned further away, which required the brain to fuse this disparity [1]. This likely contributed to the increased sense of fatigue. Participant C (**Fig. 6**) had a shorter convergence distance (approximately 100 mm) compared to the viewing distance (200 mm) from the beginning of the experiment. It would be difficult to create a 100 mm pop-out effect unless it was due to binocular disparity generated by the 3D images [8]. The low level of eye fatigue would suggest that one eye was deviated inward and the other eye was in a monocular viewing state. Participant D (**Fig. 7**) had longer convergence distances for both 200 mm and 400 mm viewing distances within 1 minute of starting the experiment, indicating that one eye was deviated outward and the other eye was in a monocular viewing state. In this participant, the level of eye fatigue was also low. It has been reported that intermittent exotropia tends to lead to monocular viewing [9]. Participants B, E and F (**Fig. 8**) had convergence distances that matched the viewing distances, indicating good control of the eye position.

This study reveals that inconsistency between the convergence distance and viewing distance arises when viewing videos that aim to create a sense of depth on a two-dimensional screen. Of the 6 participants, 2 were in a monocular viewing state. This highlights the need to pay attention to the strength of visual stimuli on smartphones.

Controlling the eye position can cause eye fatigue. Fluctuations in the eye position are reflected in fluctuations in the convergence distance calculated from Eqs. 2 and 3. Therefore, the small fluctuations in the convergence distance measured in participant F (convergence distance $\simeq$ viewing distance at 200 mm) imply that the eye fatigue is also relatively small (fatigue level 3 as shown in **Table 1**). On the other hand, for example, the relatively large fluctuations in the convergence distance measured in participant A (convergence distance $<$ viewing distance at 200 mm) suggest that the eye fatigue is also large (fatigue level 9 in **Table 1**). In fact, the IQR values are 7.56 mm for participant A and 6.28 mm for participant F. As indicated in **Table 1**, this tendency is not observed in all the participants in this study. We need data from many participants to verify statistically the relationship between the fatigue level and IQR.

Table 1 Eye fatigue level and IQR (mm) of individual participants. Asterisk signifies that the convergence distance is equal to the viewing distance.

Participant	d_v = 200 mm		d_v = 400 mm	
	Fatigue	IQR	Fatigue	IQR
A	9	7.56	7	12.24
B*	6	10.65	5	9.67
C	4	9.22	5	56.57
D	4	39.19	3	175.16
E*	3	7.46	2	15.08
F*	3	6.28	3	15.49

5. Conclusion

When watching videos for long periods of time on small screens such as smartphones, with images moving both right and left, and up and down, the mismatch between the viewing distance and the convergence distance increases and this hinders binocular vision. Trying to equalize the viewing and convergence distances gives rise to eye fatigue, and this can cause acute esotropia. In this paper, we measured the variations in convergence distance of participants when watching 15-minute long videos and evaluated these variations. One-half of the participants were unable to match the convergence distance with the viewing distance. The current visual environment with smartphones demands more precise and sophisticated binocular vision function. We plan to increase the number of experimental participants and statistically verify the validity of the present results.

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