The Comparison of the Eye-Tracking Characteristics among the Subjects with Different Visual Field Loss

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Abstract: Glaucoma is a disease that causes optic nerve damage and loss of the field of vision. It is characterized by an inability to see part of the visual field, or blurring of the visual field, as if by a mist. We therefore took static visual field measurements in individuals with unimpaired vision and those with glaucoma, both confirmed in standard visual acuity and visual field ophthalmological examinations, and then compared gaze movements during driving simulations. In this experiment, EMR-9 and EMR-8 eye mark recorders (NAC Image Technology Inc.) were used for eye tracking. All gaze points during driving were measured, and the ellipse containing 95% of the measured points was drawn. Among participants with glaucoma, the area of the ellipse containing 95% of gaze points was relatively small, indicating that they could only see a narrow range. While this range also widened on the course with colliding vehicles for the glaucoma participants, the increase was not as large as that for unimpaired participants.

Key Words: driving simulator, gaze point, glaucoma, eye tracking, visual field.

1. Background and Objectives

Glaucoma is a disease that causes optic nerve damage and loss of the field of vision. It is characterized by an inability to see part of the visual field, or blurring of the visual field, as if by a mist. A diagram of a typical view for someone with glaucoma is shown in Fig. 1.

Aoki et al. [1] performed age-matched analysis of the accident rate of people with glaucoma, and compared subjects based on three levels of severity. They found that 10 of 29 subjects with advanced glaucoma had previously had accidents, while only two with primary or intermediate level glaucoma had previous accidents, which indicates a significantly higher accident rate among those with advanced glaucoma. This demonstrates a need for quantitative assessment of the effects of the field of view of the driver on the accident rate.

Recently, studies have started focusing on the shift of gaze points while driving and the association with accidents. One study analyzed the relationship between sleepiness and shift of gaze points and investigated how to apply the results to safe driving initiatives, for example with alerts during driving [2]. However, previous studies have primarily examined only people with unimpaired vision, and few studies have focused on gaze movement in individuals with defects in their field of vision. Moreover, the few studies that did examine individuals with impaired vision did not perform specific tests to confirm a normal ophthalmological visual field. Thus, the possibility exists that the subjects in these previous studies had impaired visual fields.

One study showed that drivers perform compensation actions such as increasing saccade movement when they cannot determine driving conditions, for example when surrounded by many vehicles [3]. Based on these previous findings, it can be speculated that drivers who cannot determine driving conditions due to a visual field defect might also perform similar compensation actions. However, there have yet to be any studies that have specifically examined the types of such actions taken by such subjects.

We therefore took static visual field measurements in individuals with unimpaired vision and those with glaucoma, both confirmed in standard visual acuity and visual field ophthalmological examinations, and then compared gaze movements during driving simulations.

2. Methods

2.1 Subjects

Visually unimpaired participants were adults who showed no abnormalities in general eye tests, had 20/20 corrected vision, were confirmed to have unimpaired visual field measurements when using the Humphrey visual field analysis program 24-2, had at least five years of driving experience, and drove an automobile regularly. Anderson-Patella criteria that are regularly used in the clinical field were used to determine whether or not the visual field was normal.

The glaucoma participants were diagnosed by an ophthalmologist using the Anderson-Patella criteria and did not have any other ophthalmologic diseases or motor disorders that would affect driving. Similar to visually unimpaired participants, participants with glaucoma were adults with 20/20 corrected vision, had visual field measurements performed by
Humphrey visual field analysis program 24-2, had at least five years of driving experience, and drove an automobile regularly.

To facilitate attachment of the eye monitor, participants who professed being able to drive without correction with glasses performed the tasks without glasses, and those who could not do so performed the tasks while wearing their glasses.

2.2 Driving Simulator

The simulations were performed using driving simulation software for persons with glaucoma, manufactured by Honda Motor Co. (HONDA Safety NAVI Glaucoma edition, right-side steering wheel, accelerator, brake pedal, and laptop computer for control; Fig. 2).

Participants could not operate the steering wheel themselves, and could only operate the accelerator and brakes. The driving speed was set so that it did not exceed a certain speed limit even with the accelerator fully engaged. Two driving courses were created.

2.2.1 Course A

This course comprised a long and straight road, the first half with two lanes on each side (speed limit of 50 km/h) and the second half with one lane on each side (speed limit of 30 km/h). Similar to a regular road, the simulation program was equipped with traffic lights and had other vehicles driving along it. Participants were instructed to drive as they normally would. Vehicles came at them from outside the frame and also suddenly veered towards them from within the frame of the screen (Figs. 3 and 4). The participant was required to avoid collision by hitting the brakes.

2.2.2 Course B

As in Course A, participants were only able to operate the accelerator and brakes. Steering and turning along the course were controlled automatically. This course comprised route A and route B. In route A, there were no other vehicles to collide with the participants’ car. Route B included other vehicles that could potentially collide with the participants’ car; therefore, the participant was required to avoid collision by hitting the brakes. Control of the car, the shape of the driving course, and the landscape were identical in routes A and B.

2.3 Measurement of Gaze Points during Driving (Eye Tracking)

In this experiment, EMR-9 and EMR-8 eye mark recorders (nac Image Technology Inc.) were used for eye tracking. These devices recorded the gaze points of the participants’ left and right eyes while filming the view from the driver’s seat shown on the simulation screen with the EMR recorder’s visual field camera. The sampling rate was 30 frames per second. The EMR-9 and EMR-8 recorded the coordinates on images captured with the visual field camera at 60 Hz and 30 Hz, respectively. EMR-dFactory eye mark analysis software (nac Image Technology Inc.) was used to analyze gaze points.

For eye tracking, the participant was fit with the EMR device, and the program was calibrated to ensure that right and left gaze movement was being measured correctly. Next, the participants performed driving simulation and their gaze points were measured.
2.4 Analysis

2.4.1 Course A

All participants were given an explanation of the experimental protocol prior to starting the study, and provided informed consent in writing. A total of 117 unimpaired individuals and 75 individuals with glaucoma drove through Course A. All gaze points during driving were measured, and an ellipse containing 95% of the measured points was drawn. The area of the ellipse and length of the major and minor axes were compared. The Wilcoxon rank sum test was used to test the significance of the difference between the area of the ellipse and length of the major and minor axes with unimpaired individuals and individuals with glaucoma. All analyses were performed with the statistical program JMP10.0 Pro (SAS Institute). The EMR-9 was used for this experiment, and the results are shown in box-and-whisker plots. The details of box-and-whisker plot are shown in Fig. 5.

2.4.2 Course B

A total of six unimpaired individuals and four individuals with glaucoma who provided informed consent in writing drove through Course B. Three-dimensional histograms were created using all the gaze points of the participant. The height of the bottom 50% of the total area under the histogram curve was labeled \( H \), and \( H/n \) was divided by the total number of gaze points, \( n \), to find \( H/n \), an indicator of the dispersion of gaze points. The Wilcoxon rank sum test was used to test the significance of the difference between the \( H/n \) values of routes A and B with unimpaired individuals and individuals with glaucoma. Similarly, the Wilcoxon rank sum test was used to test the significance of the difference between reduction rate between \( H/n \) values of routes A and B with unimpaired individuals and individuals with glaucoma. All analyses were performed with the statistical program JMP10.0 Pro. The EMR-8 was used for this experiment. The results are shown in the box-and-whisker plot.

3. Results

3.1 Course A

Participants who could not be measured and those who did not complete the course were excluded from analysis. As there were few younger participants with glaucoma in this study group, participants younger than 40 years of age were also excluded from analysis. After exclusions, 68 participants with an unimpaired visual field and 60 with glaucoma remained and underwent analysis. Those with mild glaucoma had a mean MD (Mean Deviation) of -9.24, with a maximum and minimum of 1.41 and -28.16, respectively. The results indicate there was a wide range of severity of the visual field defect in the glaucoma participants and that 60% of the participants had experienced at least one accident. Examples of gaze point distribution for unimpaired participants and participants with glaucoma are shown in Figs. 6 and 7, respectively.

Each black dot represents one gaze point, and the gray ellipse is the smallest ellipse that contains 95% of all gaze points. Figure 8 shows the comparisons of the area and length of the major and minor axes between the unimpaired and the glaucoma participants. Among participants with glaucoma, the area of the ellipse containing 95% of gaze points was relatively small, indicating that they could only see a narrow range. Although the length of the minor axis did not differ greatly from that of the unimpaired participants, the major axis was shorter for those with glaucoma as compared to those with unimpaired visual fields. This finding is characteristic of the vision in subjects with glaucoma. Participants with glaucoma were divided into those with a mild visual field defect, indicated by a mean score of 18 [dB] or higher for the Humphrey visual field sensitivity, and those with a severe visual field defect, indicated by a mean score of less than 18 [dB]. The results of the comparisons of the area and the length of the major and minor axes are shown in Fig. 9.

The results showed a smaller area under the ellipse for both individuals with mild and severe visual field defects, which indicates that even those with a mild visual field defect have a different way of seeing as compared to the unimpaired individuals. In addition, the major axis was shorter for both individuals with mild and severe visual field defects compared to the unimpaired participants, which shows a particularly reduced range.
Fig. 8 Differences in eye movement between unimpaired participants and participants with glaucoma (from the top: area of the ellipse containing 95% of the gaze points, length of the major axis of the ellipse containing 95% of the gaze points, and length of the minor axis of the ellipse containing 95% of the gaze points).

3.2 Course B

None of the participants had any difficulty measuring gaze points and all were able to complete the course, and thus all participants were included in the analysis. Figure 10 shows the histogram for one of the participants. The height of the bottom 50% of the total area under the histogram curve was labeled H, and H was divided by the total number of the gaze points, n, to find H/n, an indicator of the dispersion of gaze points. H/n values are shown in Fig. 11.

For all the participants, the H/n values were smaller for the course with colliding versus without colliding vehicles, with the distribution also indicating a wide range of gaze points. In the case of the course without colliding vehicles, the median value of H/n for the unimpaired participants was larger than that for the participants with glaucoma. On the other hand, in case of the course with colliding vehicles, the median value of H/n for the unimpaired participants was smaller than that for the participants with glaucoma. Figure 12 shows the difference between the reduction rate between H/n values of routes A and B with unimpaired individuals and individuals with glaucoma. For the H/n rate of change, there was a median decrease of 26.6% for the unimpaired participants and 12.5% for the participants with visual field defects, with the difference being statistically significant (p < 0.01). Among the unimpaired participants, there was a widening for the range of gaze points on the course with colliding vehicles. While this range also widened on the course with colliding vehicles for the glaucoma participants, the increase was not as large as that for unimpaired participants.

4. Discussion

The results of the present study clearly showed that the range of gaze points was narrower for participants with glaucoma than unimpaired participants (Fig. 8).

Studies have found that driving becomes increasingly dangerous as the range of visual field defects grows, although individuals with mild visual field defects can drive safely [6]. In the...
Fig. 9 Differences in eye movement between unimpaired participants, participants with a mild visual field defect, and participants with a severe visual field defect (from the top: area of the ellipse containing 95% of gaze points, length of the major axis of the ellipse containing 95% of gaze points, and length of the minor axis of the ellipse containing 95% of gaze points).

In the present study, the range of eye movement was narrower among participants with mild visual field defects (Fig. 8). This may present a danger during driving. Moreover, the range of lateral gaze movement was narrower even among participants with mild visual field defects (Fig. 9). Depending on the type of danger (for example, vehicles veering in from the side), it is possible that even those without primary visual field defects may encounter danger.

In Course B, comparisons of participants with and without visual field defects on the course without colliding vehicles showed that participants with glaucoma moved their eyes as a compensating action to obtain visual information about the visual field defect area, resulting in a wider gaze range compared to unimpaired participants (Fig. 11). It is possible that unimpaired individuals can drive safely without shifting their gaze greatly and only continue to view the direction of travel ahead. In the course that contained the colliding vehicles, the range of gaze movement increased for both types of participants. The
appearsance of colliding vehicles could create a more complex situation, and thus, could lead to a heightened awareness of the potential collisions. The above results were consistent with the finding of a previous study that saccade movement increases in complicated environments [3].

Figure 11 shows, in the case of the course without colliding vehicles, the median value of $H/n$ for the unimpaired participants was larger than that for the participants with glaucoma, and in case of the course with colliding vehicles, the median value of $H/n$ for the unimpaired participants was smaller than that for the participants with glaucoma. That means unimpaired participants keep their eyes stable during the course without colliding vehicles, but begin to move their eyes when they become aware of the possibility of colliding with vehicles. In the case of the course without colliding vehicles, participants with glaucoma move their eyes over a wider range than unimpaired participants. One reason for this would be their restricted visual fields. That is, the visual defects in participants with glaucoma are scattered about the visual field, so they need to move their eyes to maintain a clear driving view.

5. Conclusion

In the study described in this paper, with the course that was used first (Course A), we presented a mixture of two courses: a straight course with no cars veering toward the simulation car, and a scene where cars veered toward the simulation car and collisions were likely to occur. In comparing the distribution of gaze points during driving on both courses, we found that participants with glaucoma had a narrower range of gaze points.

When we compared driving simulation performance among participants on Course B, which included routes comprising only scenes in which no cars veered toward the simulation car, we found that in scenes where no cars veered toward the simulation car, participants with glaucoma had a broader range of gaze points than those with unimpaired vision.

In comparisons of driving when there were cars veering toward the simulation car and a possibility of a collision, and scenes with no cars veering toward the simulation car and no possibility of a collision, the results of the present study showed that participants with unimpaired vision and those with glaucoma had different ranges of gaze points. Compared to individuals with unimpaired vision, individuals with glaucoma had a narrower range of gaze points when collisions were possible and a broader range of gaze points when no collisions were possible.

References


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