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Estimation of Mental Workload Using Saccadic Eye Movements in a Free-Viewing Task

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***Abstract*—This study proposes a new method to automatically estimate a person's mental workload (MWL) using a specific type of eye movements called saccadic intrusions (SI). Previously, the most accurate existing method to estimate MWL was the pupil diameter measure [1]. However, pupil diameter is not practical in a vehicle driving environment because it is overly sensitive to brightness changes. A new method should be independent from environment brightness changes, robust in most driving environments, and accurately reflect MWL.**

This study used SI as an indicator of MWL because eye movements, including SI, are independent from brightness changes. SI are a specific type of eye-gaze deviations. SI are known to be closely related to cognitive activities [2], [3]. This means that SI may be also closely related to MWL.

Eye movements were recorded using a non-intrusive eye tracking camera, located 550 mm away from a participant. Participants were instructed to move their eye gaze to examine a highway driving scenery picture. In the data set of the recorded eye movements, our new algorithm detected SI and quantified SI behavior into a SI measure.

Participants were also engaged in a secondary N-back task. The N-back task is a popular task used in cognitive sciences to systematically control a MWL level of participants. In our results, all 14 participants exhibited more SI eye movements when their MWL level was high compared to when their MWL level was low. Moreover, our results showed that the SI measure was a more accurate measure of MWL than the pupil diameter measure.

This finding indicates that MWL of the person can be estimated by observation of SI eye movements. This new method has a wide range of applications. One of them is to predict a person's MWL, thus predicting when a person is capable of driving a vehicle in a safe or dangerous manner.

I. Introduction

A typical vehicle today uses a one-way command line: the driver alone judges the current states of both the driver and the vehicle and controls the vehicle. Future cars are expected to have two-way command lines; vehicles also estimate the current states of the driver and the vehicle and change their behavior accordingly. One of the states that the future vehicle automatically estimates is the capability of the driver in terms of mental workload.

Mental workload (MWL) is a concept that indicates how mentally/cognitively busy a person is. For example, when a driver is talking on a cell-phone or with a passenger, traffic accident risk increases four times [4]. This is considered to be a result of the increased MWL that the drivers were imposed with the conversation either with the passenger or on the phone [4]. Conversation can consume a large amount of cognitive resources and may leave only a small amount of cognitive resources, not enough for safe driving.

Quantifying MWL is difficult partially because MWL of a person is fluctuating every second. Currently, there exist no reliable methods to accurately quantify MWL in real-time in a driving environment. A reliable method to quantify MWL could detect a moment of unsafe driving or unsafe operation of other machines. Once this state of the operator person is detected, preventive actions can be taken to reduce the likelihood of accidents.

The aim of our research is to develop a system to automatically quantify MWL in real-time with a non-intrusive device, such as an eye-tracking video camera. This present study was run in an experiment room and not in a vehicle mock-up model. However, this study used a non-intrusive eye tracker and demonstrates the peculiar eye movement pattern (i.e., saccadic intrusions) that was consistently observed only when high MWL was imposed. Using this involuntary physiological response of the eye, this study attempts to estimate the person's MWL.

II. Eye Movements

A. Types of Eye Movements

Eye movements in general can be categorized in two groups: fixations and saccades. Fixations are a general group of eye movements that function to examine a visual scene in one area. One fixation can last from 200 ms (0.2 sec) to several minutes. Saccades are another general group of eye movements that shifts a gaze fixation location from one place to another. One saccade can last only 20 to 200 ms, with a fast velocity at 50 eye angular degrees/sec or faster. In this article, saccades are called 'regular saccades' to specifically differentiate them from other kinds of saccadic eye movements such as microsaccades and saccadic intrusions which are explained in a later paragraph. In everyday life, humans alternate between a regular saccade and a fixation repeatedly. Our interest in this study is eye-gaze deviations during fixations.

During fixations, the eye does not remain perfectly still. Rather, when a person is staring at one fixation target, the eyes are constantly moving. These movements in an 'apparent'

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fixation are called fixational eye movements. A fixation or fixational eye movements can be subdivided into smaller categories such as tremors, slow drifts, microsaccades, and saccadic intrusions (SI). Fig. 1 shows an example of fixational eye movements on the horizontal axis of the eye for 7 seconds while the eye was fixating at a stationary target. This example includes the first three kinds of fixational eye movements (tremor, slow drifts, and microsaccades), but no SI.

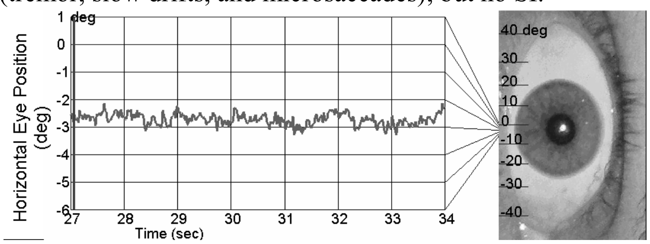

Fig. 1. Typical horizontal eye movements while fixating at a stationary dot, showing the three main kinds of fixational eye movements, such as tremor, slow drifts, and microsaccades. No saccadic intrusions are observed in this example.

B. Saccadic Intrusions (SI)

Saccadic intrusions (SI) are a specific type of eye movements, usually considered to be a sub-type of fixational eye movements. One episode of SI is usually a round trip from a gaze fixation point; the gaze deviates from the original fixation point, and then quickly returns. Fig. 2 shows some examples of SI during a fixation. There are at least six episodes of SI in Fig. 2.

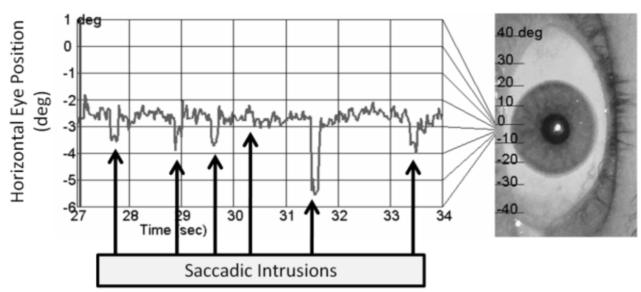

Fig. 2. Examples of saccadic intrusions (SI). Although the eye was fixating at a stationary dot, the eye gaze deviated from the fixation point with round-trip movements.

There are several characteristics of SI [5]. Typically, each episode of SI has a series of eye movements making a rectangular pulse, seen in Fig.2. That means the small gaze shifts away and then back to the original fixation in a fast and jerky (i.e., saccadic) manner. That deviation has certain amplitude, ranging from 0.4 to 4.1 deg of visual angle [5]. SI have the largest amplitudes among fixational eye movements. The second largest type of fixational eye movements are microsaccades, having amplitudes of 0.4 deg or smaller.

Each SI has a dwell time, the plateau of the rectangular pulse. A dwell period ranges from 60 to 870 ms [5]. SI occur only on the horizontal axis of the eye, rather than the vertical or the torsional axes. Also SI are conjugate; both eyes synchronically move in the same directions at the same time. All of the SI examples identified in Fig. 2 satisfy all of the above conditions.

C. Saccadic Eye Movements

This study uses at least three kinds of saccadic eye movements: microsaccades, saccadic intrusions, and regular saccades. Saccade means that a movement is fast, jerky (sudden start and sudden stop), and ballistic (straight movement from the beginning to the end of the movement). All the three types of saccadic eye movements in this article (microsaccades, SI, and regular saccades) are fast, jerky, and ballistic.

There are differences in these three types of the saccadic eye movements. While a regular saccade functions to shift gaze location from one place to another, microsaccades and SI usually do not ultimately change gaze direction. They keep the gaze as it was, so that the eye can keep staring at the same visual scene. To differentiate SI from microsaccades, amplitude is one of the major factors. SI are much larger movements than microsaccades.

D. Saccadic Intrusions and Mental Workload

SI are related to cognitive activities. Several studies have reported that SI were related to visual attention and auditory attention [2], [3]. Our group's research extended their idea from attention to MWL. Our previous studies [6], [7] have reported that each of the eight or more participants showed more SI when they were engaged in a high MWL task than in a low MWL task. However, our previous studies confined eye movements using a stationary dot fixation task. This previous task allowed the participants to have only fixational eye movements without having regular saccades. Our present study used another task that allowed regular saccades to occur, so that eye movements were more similar to normal driving conditions, and therefore allowed us to determine whether this new method to estimate MWL would be useful in a normal driving situation.

III. Experiment Procedure

A. Purpose of This Study

The purpose of this study is, first, to demonstrate that our automatic algorithm can detect SI in eye movement data where both fixational eye movements and regular saccades co-exist. Second, this study aims to demonstrate that SI and MWL level are correlated, so that it is possible to estimate MWL using these eye movements.

B. Experiment Devices

Fig. 3 shows one scene of a pilot experiment. The experiment setting consists of the Tobii eye tracker with the computer monitor, a chin rest, computer speakers, and a computer keyboard. The Tobii monitor was located approximately 550 mm away from the participant. The Tobii 1750 eye tracker has the temporal resolution at 50 Hz (recording eye data every 20 ms). Also, the Tobii's spatial resolution is high enough for this study. Although the absolute spatial resolution is as crude as 0.5 deg, the relative spatial resolution is as accurate as 0.02 eye angular degrees or finer on the horizontal and vertical axes of the eyes. Unfortunately, the Tobii is not the finest eye tracker, rather, it is a relatively more crude eye tracker in terms of both the spatial and temporal resolutions for examining the characteristics of eye movements. Nonetheless, SI are relatively easy to observe even with a low-resolution eye tracker like the Tobii since SI are the largest eye movements among fixational eye movements. Also, the successful detection of SI using the Tobii in this study makes it promising in the future to develop an inexpensive device to detect SI.

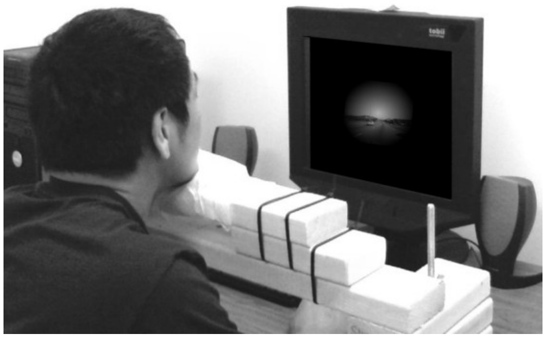

Fig. 3. Experimental scene including the Tobii eye tracker. The Tobii with the embedded video cameras in the computer monitor frame can track eye movements in a non-intrusive manner to the participant's body even without a chin rest.

The Tobii can also record eye movements of the two eyes at the same time, and the pupil sizes of the two eyes. Pupil diameter is known to be a good indicator of MWL [1], [8]. A chin rest was used to confine head movements. Although the Tobii usually does not require a chin rest to record eye movements, our experiment used a chin rest so that we could make sure that the recorded eye deviations were derived certainly from the eye movements, not from the head movements or anything else. The computer keyboard was used for the MWL task.

C. Experiment Tasks

This study used a dual task: an auditory N-back task to control MWL level and a free-viewing task to control the eye movements.

The auditory N-back task played the pre-recorded voice of a one-digit number (either 'one', 'two', 'three', or 'four') approximately every 3 seconds from the computer speakers. The task required the participant to remember the order of the number presentation, and to judge if the currently presented number was the same as another number presented N events before. The 1-back task is the easiest, and a higher N-back task (3- or 4-back task) is very challenging, thus adding more MWL on the participant. The majority of the participants (10 out of 14 participants) performed the 1, 2, and 3-back tasks as low, medium, and high MWL tasks. The 3-back task was not challenging enough for the other 4 participants; they did 1, 3, and 4-back tasks for L, M, and H conditions.

The free-viewing task was shown on the computer screen (Fig. 4). A stationary picture was chosen from a set of highway driving scenes on a sunny day in Boston. These highway driving scenes were obtained from an image database, called the LabelMe project at MIT's CSAIL (computer science and artificial intelligence laboratory) [9]. The participants were asked to move their gaze to examine the still picture. Each picture was shown for one trial (approximately for 60 sec), and only shown once to each participant.

Fig. 4. Example of a driving scene picture used in the free viewing task. Participants were asked to move their gaze, so that this study could test our new algorithm to detect SI in a set of moving eye data.

After each trial of the dual task, the participants rated their perceived difficulty level toward the dual task. The VAS (visual analogue scale) on the scale of 0 to 100 was used.

D. Participants

Sixteen college students participated in the study for a part of their general psychology course credit. Two were removed from the data analyses for the following reasons. One participant's correct rate of the N-back task was lower than 60%, and it was assumed that the person's MWL level was not systematically controlled enough. Another participant was removed due to the Tobii computer stopping in the middle of the experiment, and the eye data being incomplete. The other 14 participants' data were used for the analyses. There were 10 females and 4 males, the age range was from 18 to 21 years old. Six were using their contact lenses, one was using the eye glasses, and the other 7 used no correction.

E. Procedure

Participants first received an explanation of the experiment. After agreeing with the explanation, they signed the consent form. They practiced the dual task of the auditory N-back task and the free-viewing task. Each practice trial took approximately 1 minute, and each participant practiced about 15 trials. During the practice trials, the correct rate of the N-back task was recorded, and the difficulty level was adjusted for each participant in two ways; the inter-stimuli-interval (ISI) and the N levels. The correct rate of the highest possible N-back task that the participant could do was adjusted between 80 and 90 % of the N-back performance accuracy, so that we know that the high N-back task was challenging enough for the participant. The ISI was adjusted to a longer or shorter interval depending on the practice trial performance. Also, the N level was adjusted depending on their performance. Once the ISI was determined using the highest N-back task for that participant, that exact ISI was used for the other, lower N-back tasks (e.g., 1 and 2-back tasks) for that person. The range of the ISI was from 2400 ms to 4600 ms in the 14 participants.

After the practice trials, the Tobii eye tracker was calibrated for each participant's eye movements. This took about 1 minute. Then, Tobii started recording the eye data.

There were 12 trials for the recorded experiment in each participant. Each of the three MWL levels (low, medium, and high MWL) had 4 trials. The order of the 12 trials was pseudo-randomized.

It took approximately 50 minutes from the consent form to the end of the 12 trials. The eye strain level was asked every 15 minutes, so that the experimenter could stop the experiment if the participant was experiencing discomfort. However, no participants complained of experiencing high eye fatigue or significant discomfort.

IV. Algorithm to Detect Saccadic Intrusions

A. *General procedure of the Algorithm*

The author developed an algorithm to detect saccadic intrusions (SI) in a set of the eye data that Tobii recorded every 20 ms. In the first step, the algorithm categorized the eye movements into two groups; fixational eye movements and regular saccades. In the second step, the algorithm detected gaze deviations during the fixational eye movements. In the third step, the algorithm detected gaze deviations that matched the characteristics of SI and quantified this SI behavior into a SI value.

B. *Step 1: Detecting Fixational Eye Movement Sections*

The purpose of this study was to determine whether SI behavior would increase as MWL increased. Since SI are observed only in fixational eye movements, this algorithm first categorizes eye movements into two groups; regular saccades and fixational eye movements.

A regular saccade was defined as a sudden gaze shift of 1 deg of visual angle or larger in the two dimension plane (horizontal and vertical), in which the gaze shift stayed in the new gaze location and did not return to the previous gaze location for at least 1000 ms. The time length of 1000 ms was determined to differentiate SI from regular saccades, since a SI can dwell at a deviated location for up to 870 ms. If the gaze comes back to the previous gaze location within 1000 ms, that eye movement pattern is a candidate to be coded as a SI rather than a regular saccade. An example of detecting regular saccades is shown in Fig.5.

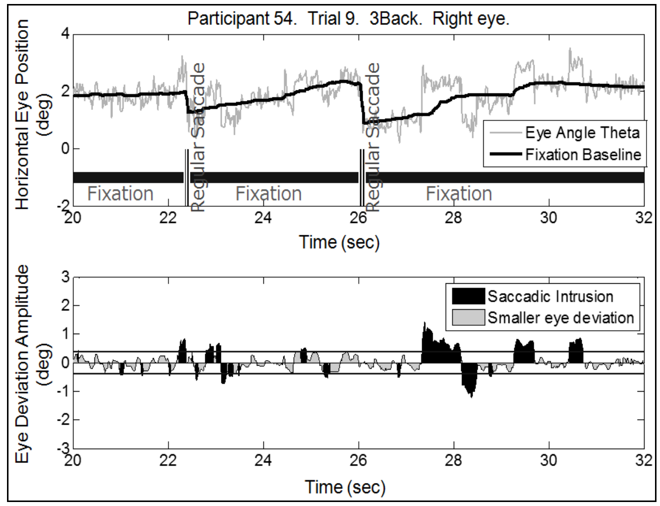

Fig. 5. Example of horizontal eye movement data and the example results of our algorithm. In the upper graph, our algorithm detected regular saccades (or gaze shifts).

The light gray line shows the horizontal eye movements for 12 seconds. At the 22.4 and 26.1 second marks, regular saccades (i.e., gaze shifts) are detected. There are other apparent gaze shifts at the 27.3, 28.2 second marks and later. However, these were classified as SI, not regular saccades, since these gaze shifts went back to the previous gaze locations within 1000 ms. After eliminating regular saccades, the other eye movements that were not regular saccades were considered to be fixational eye movements. In the later steps (Steps 2 and 3), gaze deviations were searched for during these fixational eye movement periods.

C. *Step 2: Gaze deviations in Fixational Eye Movements*

Gaze deviations during fixational eye movement periods were detected in Step 2. These gaze deviations were candidates for SI. Gaze deviations were defined as deviations from a fixation baseline. A fixation baseline was calculated using a median score of a 2 second moving window. An example of a fixation baseline is drawn in Fig. 5 (the black line in the upper graph).

The difference between the fixation baseline (the black line) and the horizontal eye angle theta (the gray line) was the gaze deviation from the fixation baseline. The gaze deviation was drawn in the lower graph in Fig. 5. Both the gray and black areas are gaze deviations.

D. *Step 3: Detection of Saccadic Intrusions*

Out of all the gaze deviations during the fixational eye movement periods, only gaze deviations that matched SI characteristics were classified as SI. SI should shift their gaze with a fast movement (saccadic movement), with a large amplitude at 0.4 deg or larger, with a dwell time ranging from 60 to 870 ms, and shift their gaze back to the previous gaze location within that dwell period. In the lower part of Fig. 5, examples of SI that met all the criteria above are colored in black. The other gaze deviations are colored in gray, labeled as smaller eye deviation.

The black area indicates the detected SI behavior within the eye movement data. The detected SI behavior was quantified in a single value as a SI value. The average amplitude in the evaluation period for a trial represents the SI behavior as a SI value in the unit of deg/sec.

V. Results

A. Assumption of MWL with Subjective Rating

Before looking at the results of saccadic intrusions (SI), we wanted to make sure that mental workload (MWL) was imposed in three levels since it was the independent variable of the experiment. Fig. 6 shows the results of subjective ratings by each participant. Each bar represents the average rating of four trials. All 14 participants perceived that the high MWL task was the most difficult, as planned. MWL seemed to be systematically controlled.

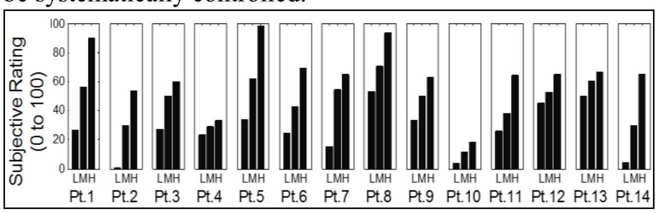

Fig. 6. Subjective rating scores. The three bars in each participant represents the average rating for each of the three mental workload levels (Low, Medium, and High), showing that the High MWL task was perceived as the most difficult. This shows the MWL levels were controlled well.

B. Assumption of MWL with N-back Performance

Also, the control of the three MWL levels was assured with the N-back task performance. Fig.7 shows that the higher N-back task was performed with the poorest scores in almost all participants. This indicates that participants received more MWL with a higher N-back task, as planned.

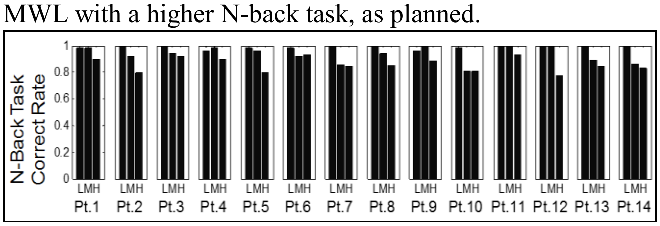

Fig. 7. N-back task's performance. The high mental workload task (usually the 3-back task) had the lowest score in each participant, showing that the highest MWL was imposed in High MWL condition, as the experiment designed.

C. SI Results of One Sample Participant

Fig. 8, 9, and 10 show some sample eye data of the three MWL levels in one sample participant, #12, who showed the average results among the 14 participants. Fig. 8 shows an example result in the low MWL condition. The horizontal eye angle theta (the gray line) did not deviate much from the fixation baseline (the black line). This shows that there were not many SI (the black area) detected in the lower block in Fig. 8.

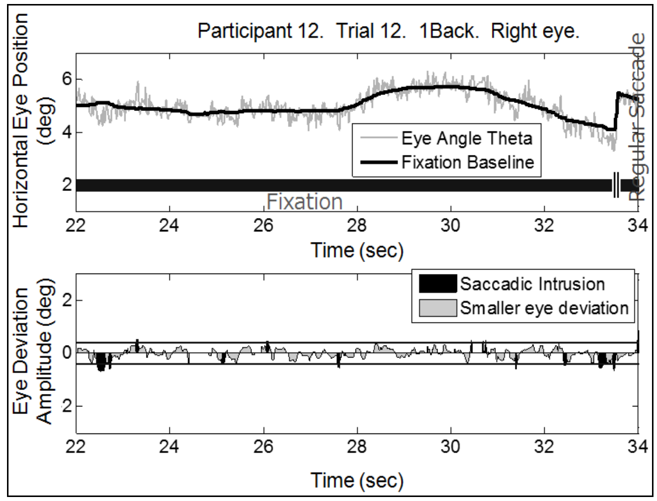

Fig. 8. Sample eye movement data on the Low mental workload task. There seems almost none saccadic intrusions observed.

Fig. 9 shows an example result in the medium MWL condition. The eye angle theta deviates from the fixation baseline only for a limited period of time, resulting in some SI (the black area) being detected, especially around the 27 second mark.

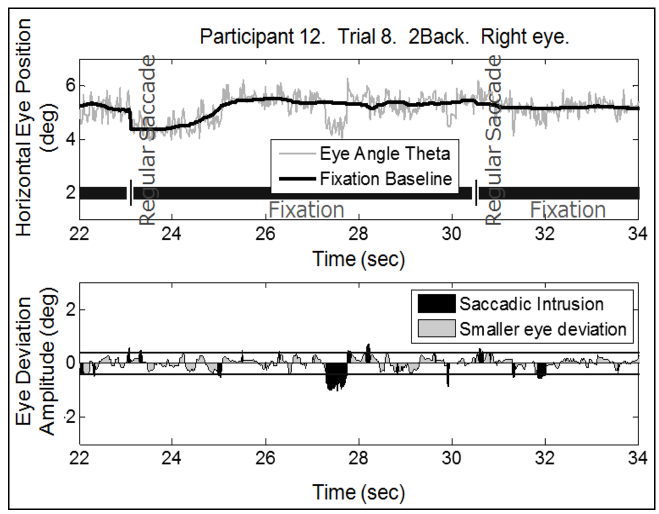

Fig. 9. Sample result of the horizontal eye movement data on the medium mental workload task. There are some saccadic intrusions observed. A large SI is observed at the 27 second mark.

Fig. 10 shows example results in the high MWL condition. The horizontal eye angle theta deviates frequently from the fixation baseline. SI (the black area) are observable almost every second.

The examples illustrated in Fig. 8, 9, and 10 demonstrate the typical pattern of SI gaze behavior with sudden round-trip eye deviations from the fixation baseline. These examples show more SI in a higher MWL task.

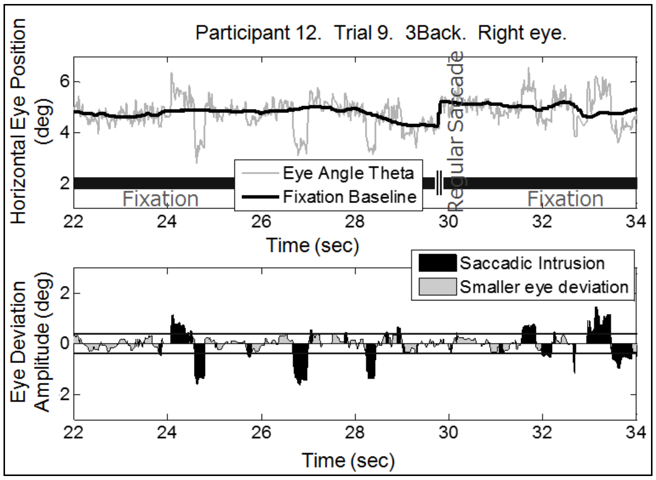

Fig. 10. Sample eye movement data on the high mental workload task. Saccadic intrusions are seen frequently. Large ones are seen at the of 24, 26, 28, 32, and 33 second marks.

D. SI Results of Each Participant

Fig. 11 shows bar graphs of SI values on the three MWL levels in each of the 14 participants. Each bar represents the average SI value of four trials. All the participants had larger SI values for the high MWL than low MWL. Moreover, 11 out of 14 participants had three SI values in the order of low, medium, and high MWL, indicating that a higher MWL task induced more SI eye movements in a systematic fashion. The other three participants who did not precisely follow this pattern were Participants 6, 11, and 14.

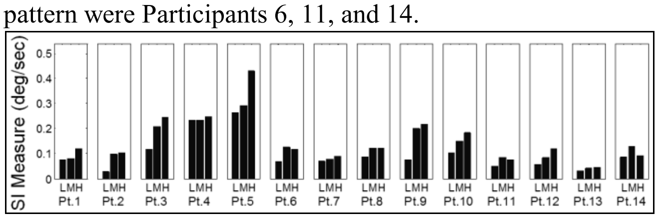

Fig. 11. Saccadic intrusion behavior was quantified into the SI measure shown in the bar graph. All of the 14 participants show more SI measure in the high mental workload condition than the low mental workload condition.

E. SI Results of All Participants Collapsed

In order to do a statistical analysis, all participants' scores were collapsed together. Since the eye data have large individual differences, the SI values were first standardized within each participant, using 12 SI-values for each person, depicted in Fig. 12.

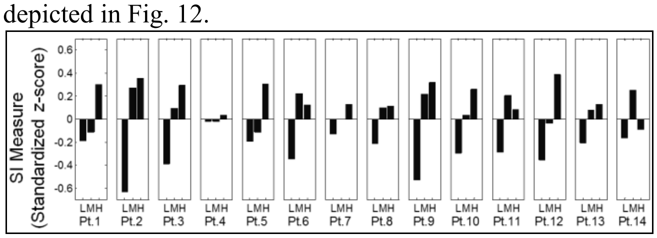

Fig. 12. The standardized z-score of the SI measure shown in Fig. 11. This standardizing process can eliminate the individual differences, so that it is easy to compare between participants.

After taking the standardized SI scores for each participant, all the scores were collapsed together in Fig. 13. This figure shows that the SI value was higher as MWL increased. A one-way ANOVA used to statistically test the differences in the bar graph showed significant differences, $F(2, 39) = 41.8$, $p < 0.05$. The follow-up t-tests also showed significant differences for low vs. medium MWL, $t(26) = 6.60$, $p < 0.05$, and for medium vs. high MWL, $t(26) = 2.15$, $p < 0.05$. This is our main finding in this study; saccadic intrusions were more frequently observed when mental workload was higher. In our previous studies, we found the same results using a dot fixation task, confining the eye movements. In this current study, we replicated the result using a free-viewing task without the confinement of the eye movements. Saccadic intrusions were detected with high accuracy even though the eye freely moved.

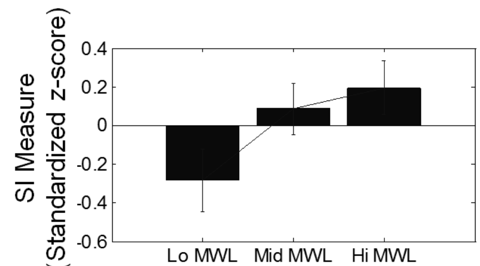

Fig. 13. The average SI measure of the 14 participants shows saccadic intrusions were statistically more observed in higher mental workload conditions.

F. Pupil Diameter Results of Each Participant

In addition to our new finding on the correlation between SI and MWL in Fig. 13, we also examined pupil diameter, which is known to be an indicator of MWL [8]. Pupil diameter reflects MWL with the best accuracy out of the physiological measures that can be observable from outside the human body, if environment brightness is controlled well [1]. The pupil diameter data is shown in Fig. 14. Our results show that the pupil diameter is also related to the MWL level.

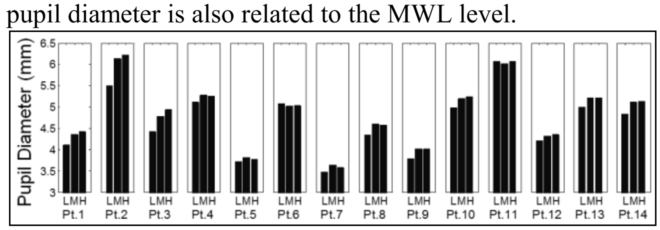

Fig. 14. Pupil diameter in millimeter is shown by the three mental workload conditions. This seems that the pupil diameter measure is not as accurately reflecting mental workload as saccadic intrusions did.

G. Pupil Diameter Results of All Participants Collapsed

Fig. 15 shows the collapsed pupil diameter results of all the 14 participants. A one-way ANOVA test showed significant differences, $F(2,39) = 23.07$, $p < 0.05$. The follow-up t-tests showed significant difference between the low and the medium MWL, $t(26) = 6.65$, $p < 0.05$. However, the other t-test could not significantly differentiate the medium MWL and high MWL, $t(26) = 0.81$, $p = 0.21$. In our result, the SI value seems to be a better indicator of MWL than the pupil diameter.

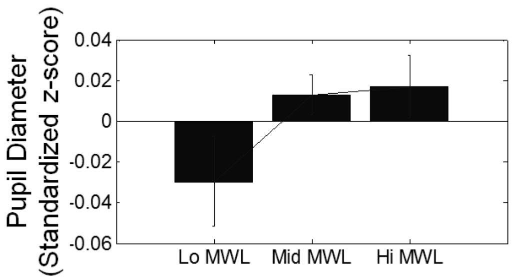

Fig. 15. Collapsed results of the pupil diameter of 14 participants. The medium and high mental workload conditions were not statistically different while saccadic intrusions (Fig. 13) could differentiate them.

VI. Neurology

The neurological basis of SI is not well understood yet, and we do not know exactly why SI were more observed when MWL was high in our previous studies [6], [7] and in this current study. One possible explanation for this relationship is that the fixation neurons in the superior colliculus of the midbrain are responsible for maintaining fixational eye gaze. With distraction, fixation is not stable [11]. The same thing might be happening in our studies; the MWL task might have engaged fixation resources and may have caused SI to occur during fixational eye movement periods.

VII. Conclusion

This present study demonstrated that mental workload (MWL) induced a specific type of eye deviations called saccadic intrusions (SI). The algorithm made by the author reliably detected SI eye movements in the eye data where both regular saccades and fixational eye movements were intermingled. The eye movements were recorded using a video-based eye tracker. Many of the settings used in this study were applicable to a real driving situation. Using this method, it may be possible to estimate a driver's MWL in real-time, and therefore possible to predict a dangerous state of the driver when he/she is not concentrating on driving.

There are several advantages of this method over other MWL estimation methods. First, SI are strongly correlated with MWL. SI seems to be a better indicator of MWL than the currently most accurate measure of MWL (i.e., pupil diameter measure). Second, SI are eye movements large enough to observe using a relatively inexpensive eye tracker or using eye data that include noise. Third, unlike pupil diameter, the SI measure may be more robust in a driving environment. SI is not affected by environment brightness, and was detected accurately even when participants freely moved their eye gaze in this study.

The present study used a stationary picture of highway driving scenes. This might have produced a non-natural eye movement set. In order to increase the reliability of this new method to estimate MWL, a new study is planned using a more realistic driving situation.

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