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Using Saccadic Intrusions To Quantify Mental Workload

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This study proposes a new method to quantify mental workload (MWL) automatically, without interfering with the operator's primary task performance. An unobtrusive Tobii eye tracker recorded eye movements while participants were engaged in a cognitively demanding N-back task. Original algorithms automatically analyzed the eye data, detected specific eye deviation movements called saccadic intrusions (SIs), and automatically quantified the eye deviation accounted for SIs. This SI measure was strongly correlated with the task difficulty levels in the N-back tasks and with pupil diameter. This indicates that the SI measure appeared to reflect MWL and may be used as a measure of MWL.

INTRODUCTION

Mental workload (MWL) has been an important concept in Human Factors. In a human-machine system, MWL can at times explain operator errors. For example, a driver may not appropriately control a vehicle while in conversations on a cell phone or with passengers (Sayer, Devonshire, & Flannagan, 2006). Quantifying mental workload would be useful in detecting potential lapses in attention of human operators so that the operator can be alerted or automated routines like auto braking can be executed thereby reducing the risk of potentially severe accidents.

This study used eye movements to estimate MWL because eye movement measures have the potential to satisfy all the characteristics required for the ideal MWL measure. An ideal MWL measure should be able to estimate the operator's performance (1) accurately, (2) automatically, (3) in real-time, (4) without interfering with the operator's primary task, such as driving. This study tries to achieve all of these with the future goal of implementing the method in a driving condition with non-intrusive eye cameras like the Tobii eye tracker.

Studies have shown that eye behavior changes when MWL is heavy. For example, pupil diameter increases (Just, Carpenter, & Miyake, 2003) and the vestibulo-ocular reflex (VOR) becomes more unpredictable as a function of head movement (Obinata, Tokuda, & Shibata, 2008). This study proposes a new MWL measure using a different kind of eye movement, called saccadic intrusions.

Three types of fixational eye movements

Eye gaze is never perfectly stable even when one is trying to steadily fixate. Small eye movements during gaze are called fixational eye movements. These movements serve to help desensitize people to visual stimuli since perfectly stabilized images on the retina will be habituated and not visible after several seconds (Martinez-Conde, 2006; Engbert, 2006). There are at least three types of fixational eye movements: tremors, drifts, and microsaccades.

Tremors are prevalent and have the highest frequency (up to 150 Hz) among the three types of fixational eye movements (Abadi & Gowen, 2004; Leigh & Zee, 2006). Tremors have very low amplitude around 0.004 degrees and have a duration of a few milliseconds. Figure 1 shows a set of horizontal eye

movements. The angular rotation of the eye on the horizontal plane (Figure 1, right) was plotted for a period of 15 seconds in Figure 1 (Left). The hundreds of high frequency movements prevalent during the period are considered tremors, although the Tobii eye tracker used to record this data is not accurate enough to measure very fine movements of 0.004 deg.

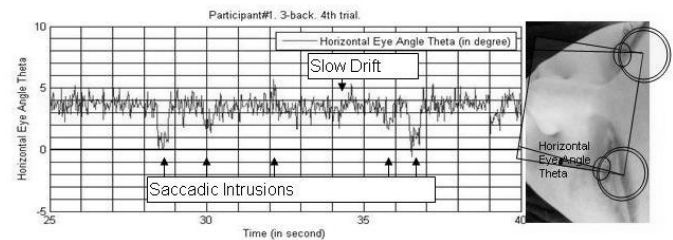


Figure 1 (left). Examples of fixational eye movements, including tremors, slow drifts, and saccadic intrusions.

Figure 1 (right). Horizontal eye angle theta.

Drifts or slow drifts, small angular rotation changes, occur simultaneously with tremors. Each slow drift has a duration of up to a few seconds. In Figure 1, among the many smaller drifts, a large slow-drift is easily noticed between the 34th and the 35th seconds (labeled "slow drift").

The third and fourth types of fixational eye movements are microsaccades and saccadic intrusions (SIs). Both are spike-like and have the largest amplitudes among fixational eye movements. Both are saccadic eye movements that intrude upon gaze or fixation against the intentional effort to maintain steady fixation (Gowen, Abadi, & Poliakoff, 2005). Both occur 0.1 to 3 times a second with a duration of 30 ms for a one-way trip. There are small differences between these two kinds of eye movements. While microsaccades have amplitudes of up to 0.2 deg, SIs have larger amplitudes, ranging from 0.1 to 4.1 deg or larger (Abadi & Gowen, 2004). Also unlike microsaccades, SIs usually have a round-trip eye deviation; eye gaze deviates from the previous gaze position, dwells at the deviated location for a short period of time, and then returns to the original gaze position. In Abadi & Gowen (2004), dwelling duration ranged from 40 ms to 800 ms for the period between a round-trip. Microsaccades and SIs might be qualitatively the same eye behavior with quantitative differences in the amplitudes. This study limits the focus of saccadic intrusions to include only larger eye movements with amplitudes of more than 0.4 deg.

SIs share many characteristics with saccades (regular saccades), such as being fast, short, jerky, ballistic, and usually conjugated. However, there are other characteristics that distinguish SIs from regular saccades. While regular saccades can occur in any direction, SIs typically occur only on the horizontal plane. Therefore, horizontal eye movement analysis is sufficient enough to detect SIs.

Saccadic intrusions and cognitive states

Previous studies have shown that microsaccades reliably increased their frequency approximately 350ms after visual presentation of the attention cue (Engbert & Kliegl, 2003; Laubrock et al., 2007). Also auditory stimuli can invoke the same microsaccade changes (Rolf, Engbert, & Kliegl, 2005). Since SIs and microsaccades behave similarly (Gowen et al., 2007), results based on microsaccades may be applicable to SIs as well. These studies indicate that increases of attention can be correlated with increases of SIs. This is consistent with our hypothesis of a correlation between MWL and SIs.

Our study used the auditory N-back task, which is cognitively demanding in terms of attention, working memory (WM), and mental workload (MWL). This study does not examine what aspects of the N-back task (attention, WM, MWL, or something else) contributes most to the physiological change (i.e. SIs). However, we use the word MWL for this hypothetical cognitive activity that is linked to SIs for the following reason. The N-back tasks impose sustained information processing effort that can vary within a person. The word “attention” represents perceptual effort rather than higher cognitive processing effort. Also MWL implies that cognitive loads are varied within a person whereas WM implies that memory abilities are varied across individuals. The authors are interested in physiological changes that occur to any person when his/her cognitive load is high.

METHOD

Participants

The study recruited ten students from the university (7 females and 3 males, 9 right-handed and 1 left-handed) ranging in age from 24 to 45 ($M = 30.2$, $SD = 7.2$). All subjects were healthy in their vision and hearing. All of them voluntarily participated in the study and signed consent forms. Out of ten, two participants were excluded from the analysis. One participant became moderately dizzy after engaging in the visual task and the other did not satisfactorily perform the visual fixation task.

Materials

The Tobii 1750 was used to collect eye activity data. Tobii is an infrared, non-intrusive eye-tracker, so that participants did not have to wear any devices (See Figure 2). The temporal resolution of recording was 20 ms (50Hz). The spatial resolution is 0.25 deg.

A Windows PC controlled both the Tobii and the experimental stimuli, programmed in C++ language by the

author. The experimental stimuli were both visual and auditory. The visual stimuli were presented on the Tobii monitor, which is a color LCD monitor 25 cm high and 34 cm wide. The auditory stimuli were presented from the computer speakers located next to the Tobii monitor. The participant sat approximately 50 cm away from the monitor. The eye height level of each participant was roughly equalized to the center of the Tobii monitor, so that every participant used similar experimental settings.



Figure 2. Pilot experiment scene.

Tasks and Procedures

A dual-task method was used to examine if saccadic intrusion (SI) patterns would change while the participants experienced various levels of MWL. The visual task was used to measure eye movements such as SIs. The auditory tasks were used to systematically vary MWL.

The visual stimulus was a red dot on a black background. The participants were instructed to stare at the red dot and maintain steady fixation. The red dot was 2 mm in size, or 0.2 deg of visual angle. The position of the red dot was fixed in the center of the computer screen except during the first seven seconds and the last seven seconds in each block. During these periods, the red dot was located at one of the four diagonal corners about 10 deg away from the screen center. These two eye recalibration periods served to later confirm that the eye data were appropriately collected.

Between these two eye recalibration periods was a 36 second experimental period during which the participants performed a dual task. While engaged in the visual task above, a random number between 1 and 4 was presented every 2.4 seconds. The numbers, pre-recorded by a native English speaker, were played from the computer speakers. The auditory stimuli were set to about 70 dB. Each of the 2.4 second periods consisted of 0.5 seconds of voice and 1.9 seconds of silence. The first number was played at the 8.6th second (1.6 seconds after the eye calibration) and the last number (14th number) was played at the 39.8th second.

Using the auditory stimuli, the participants were instructed to perform one of the three auditory N-back tasks at a time, which consisted of a 0-back task (or also called Simple Reaction Task, SRT), a 1-back task, and a 3-back task. The SRT, 1-back, and 3-back tasks served as light, medium, and heavy MWL tasks, respectively. See Obinata et al. (2008) for the details of the auditory N-back tasks. The N-back tasks were chosen for the study because they can monotonically vary MWL within each participant.

The dependent variables were pupil diameter and the saccadic intrusion (SI) measure, which was calculated from the collected eye movement data. The SI analysis algorithm, developed by the first author, took the eye movement data as

input and then automatically isolated and quantified SIs. The three MWL tasks were run in separate trials.

Each experimental trial lasted about 50s, followed by a 20s break. After practicing each of the three conditions at least once (SRT, 1, and 3-back tasks), each participant could choose either to practice more or to start the experiment. Times to practice the most difficult task (3-back task) varied from once to five times among the participants. All the participants engaged in the study for no more than 40 minutes to minimize eye strain. This length was determined from pilot experiments. Depending on the experimental progress and the practice length during the 40 minute session, each participant completed between two and four trials on each of the three levels of MWL blocks, producing the data set between six trials and 12 trials for each participant. The order of the trials was pseudo-random.

Analysis of Saccadic Intrusions

The analyses of the eye data had several goals: (1) to develop an automatic algorithm to replace missing data, (2) to define saccadic intrusions, (3) to develop an automatic algorithm to quantify SIs so that the algorithm can reflect the SI definition, and (4) to examine the relationship between the independent variables (the MWL levels such as SRT, 1 and 3-back tasks) and the dependent variables (the SI measure). The first three stages are explained in this section. The fourth stage is explained in the Results section.

1. Automatic algorithm to replace missing data. The 10 participants completed a total of 90 fifty-second trials (30 blocks each for the 3 levels of MWL tasks). Out of 90, 78 blocks were analyzed for the eight participants. During these 4500 seconds, eye events were recorded every 20 ms, producing a total of 225,000 events. Each event consisted of 16 kinds of eye behavior data, including horizontal eye gaze, pupil diameter, and screen distance of the two eyes. Out of the 225,000 events of the data, 218,620 were validly recorded by Tobii, and 6,380 were invalid (2.8%). The size 2.8% was small enough to replace with valid data. Most of these missing data were probably due to blinks or eye lash interferences.

The invalid data events were automatically replaced with a copy of the previous data if the missing event was a single event. For consecutive series of missing data, the average of the previous 10 events (200ms) were substituted, so that a missing series right after an extreme eye movement did not keep replicating the extreme scores.

2. Definition of Saccadic Intrusions. This present study defined a saccadic intrusion (SI) as a saccadic eye movement that satisfies both of the following two criteria. First, it is an intruding eye movement in an otherwise stable eye movement period with an intrusion amplitude of more than 0.4 deg of visual angle on the horizontal plane between the otherwise stable eye position and the actual intrusion position. The number 0.4 deg was derived from Abadi & Gowen (2004), who show that SIs under 0.4 deg are prevalent and can be considered noise. Second, the eye movement dwells on the deviated location more than 60 ms and less than 800 ms. This criteria is also adapted from Abadi & Gowen (2004).

3. Automatic algorithm to quantify saccadic intrusions.

The two criteria above were implemented in Matlab. First, eye angle theta (Fig. 3a) was calculated using the Tobii data, such as the distance between the screen and each of the eyes, eye gaze on the screen, and the eye location relative to the Tobii. The two 7 second periods of eye calibration are observed in the beginning and at the end. While eye angle theta was calculated for the whole 50s, the SI measure (Fig. 3d) was quantified only between 18.2 and 42.2s, in which MWL was imposed in all three conditions.

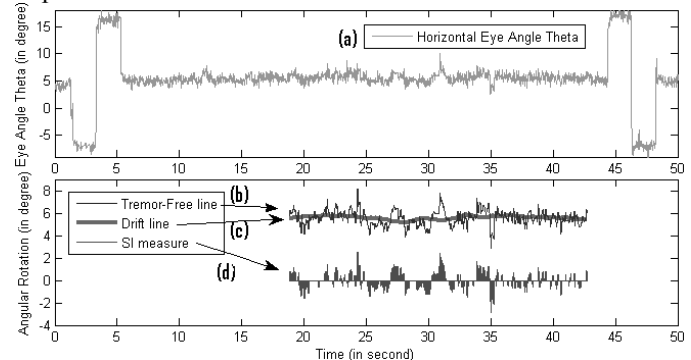


Figure 3. The algorithm calculates the difference (the SI measure) between the tremor-free eye position and the drift eye position. Line (a) is the raw eye angle data, (b) tremor-free line, (c) drift line, and (d) the SI measure.

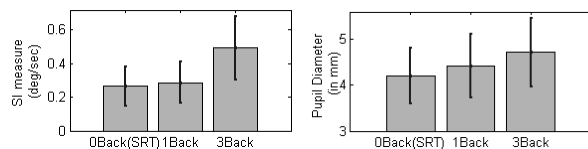
The proposed SI quantification method is based on the characteristics of the four types of fixational eye movements. Given that a participant is intentionally fixating upon a stable point and making no regular saccades, then eye gaze can deviate from the intentional gaze point as a result of (1) tremors, (2) drifts, (3) microsaccades, and (4) SIs. In this analysis, SIs were extracted by removing the other three forms of eye deviation.

First, Tremors were removed by smoothing the data with a moving average procedure based on median eye position during a 100 ms period (5 samples). The moving median, rather than the moving average, was used so that extreme values would not have a large effect on small values. The tremor-free line (Fig. 3b) represents the eye movements after removing tremors. Another line (3c) representing only drifts is drawn. Drifts (3c) were calculated in a similar manner, using a moving median over a period of 2,000 ms. The calculated drifts (3c) were removed from the tremor-free line (3b), leaving microsaccades and SIs alone.

The smaller microsaccades were filtered by a SI threshold line at the amplitude of ± 0.4 deg based on the study by Abadi & Gowen (2004). The product after filtering is the SI measure at the moment (Fig. 3d). The absolute values of the SI measures were accumulated over the evaluation period, which was between 18.2 and 42.2s, then the cumulated SI measure was divided by the time period, 24 seconds. For example, a SI measure of 0.26 deg/s in 24s means that there was an average eye deviation of 0.26 degrees per second during the period. This is the final SI measure for a block. This final SI measure was used as the dependent variable for the block.

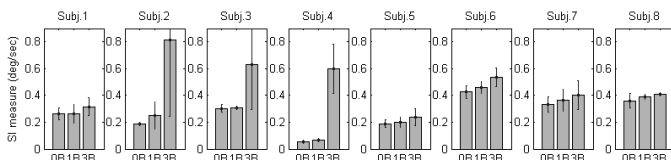
RESULTS

Congruent with the hypothesis, saccadic intrusions (SIs) increased as mental workload (MWL) increased. Figure 4 shows that the average quantified eye gaze deviation in the saccadic intrusion form was 0.26 deg/s for the light MWL task (SRT), 0.29 for the medium MWL task (the 1-back task), and 0.49 for the heavy MWL task (the 3-back task). This SI measure result is consistent with the pupil diameter data, having the largest scores on the 3-back condition (Fig. 5).

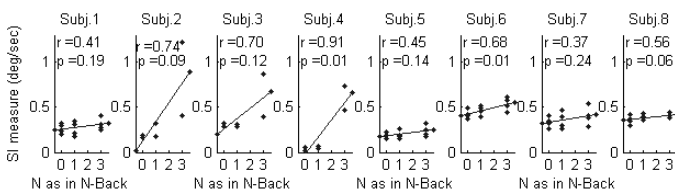


Figures 4 and 5. Grand mean scores of the collapsed 8 participant results with a total of 78 trials. The y-axes are the saccadic intrusion measures (Fig.4) and pupil diameter (Fig.5). The x-axes are the mental workload levels; light, medium and heavy. The error bars show one standard deviations.

Likewise, each of the participants also showed the same pattern, having the largest scores on the most difficult task (the 3-back task), and smaller scores on the Simple Reaction Task (Fig. 6a). The 24 data points in Fig. 6a differ significantly as a function of the N-back tasks, $F(2, 7) = 8.02$, $p < 0.01$. The results are elaborated in Fig.6(b), showing the correlations between the SI measure and the N-back tasks. Each circle represents one experimental trial. All the participants have strongly positive relationships with the correlation coefficient r , ranging from 0.37 to 0.91.



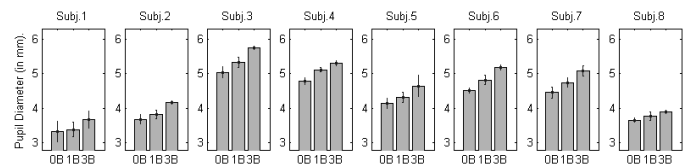
Figures 6(a). Sub-summaries of the saccadic intrusion measure on the three MWL levels (0-Back=Simple Reaction Task, 1-Back, 3-Back tasks).



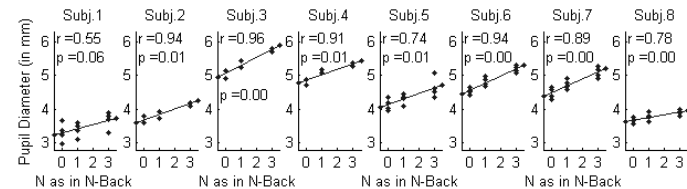
Figures 6(b). Correlation between the saccadic intrusion measures and the N-back tasks on each participant. Subjects 2, 3, and 4 performed two blocks (6 data points). The other subjects performed four blocks (12 data points).

The main finding of this study is the strong relationship between the SI measure and MWL. To validate the main finding, the other measure such as the pupil diameter was examined. Before showing the direct correlations between pupil diameter and the SI measure, Figures 7a and 7b confirm the previous research (i.e. Just et al., 2003) that pupil diameter

was strongly correlated with MWL. Fig.7b shows the correlations ranging from 0.55 to 0.96. All of the correlations have a positive direction.

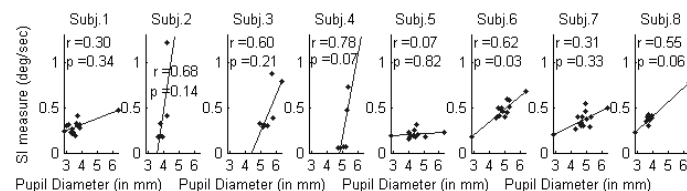


Figures 7(a). Pupil diameter in 8 participants with the 3 mental workload levels.



Figures 7(b). Correlation between the pupil diameters and mental workloads of each participant.

A correlation analysis was conducted between the SI measure and pupil diameter. Consistent with the results in Figures 6 and 7, larger SI eye movements were observed (Fig. 8) when the pupils dilated. Since pupil diameter is known to reflect MWL, this result validates that the SI measure can reliably reflect MWL. All the participants have a positive relationship. Except for participant 5, all the correlations are larger than 0.3, which are strong correlations.

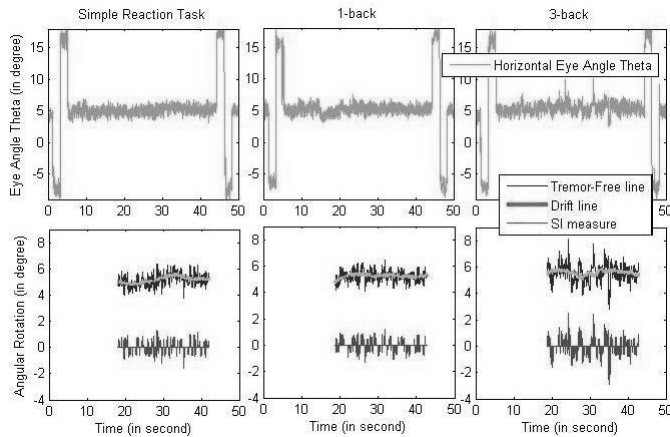


Figures 8. Correlation between the saccadic intrusion measure and pupil diameter.

Sample data are shown in Fig. 9. The x-axis is the time from 0 to 50s in each trial. The y-axes represent horizontal eye angle theta. The negative and positive numbers on the y-axis indicate that the eye was directed on the left and right sides, respectively. These graphs are from the three mental workload conditions, from the left side; easy, medium, and difficult tasks. Accordingly, as the difficulty level increases, more saccadic intrusions (the lines at the bottom of the lower graphs) are observed.

DISCUSSION

The results show that the saccadic intrusion (SI) measure appeared to be effective in detecting mental workload (MWL) in several ways. First, the three levels of mental workload were reflected in the collapsed scores (Fig. 4). Second, and perhaps more convincingly, each participant showed consistent patterns (Fig. 6a and 6b). Third, the SI measure is positively correlated with pupil diameter (Fig. 8). All of these



Figures 9. Sample data for each of the 3 levels of mental workload tasks (SRT, 1-back, and 3-back). The difficult task (the 3-back) has more saccadic intrusions of larger amplitudes.

findings suggest that the SI measure was reliably correlated with MWL.

In addition to these results, it should be noted that the SI measure might be more effective at quantifying heavier than lighter MWL. This is indicated by several observations. First, Figures 4 and 6 seem to show an exponential curve, rather than a linear line. This means SIs did not occur much until MWL reached a critical level. Second, Participant 5 commented that the 3-back task was not very difficult and, consistent with his report, Figures 6 and 7 show that this participant had very small SIs even for the 3-back task, compared to the other participants. Participant 5 might have shown more SIs if he experienced even more difficult tasks. These observations imply that the SI measure may be more sensitive at detecting heavier MWL than light MWL. While another reliable MWL measure, pupil diameter, can easily become victim to a ceiling effect because the pupil can dilate only so much, the proposed MWL measure (the SI measure) may have greater range and thus a higher ceiling. This possibility warrants further investigation.

CONCLUSION

The most important finding from this study was the monotonic (or one-directional or ordinal) relationship between mental workload (MWL) and saccadic intrusions (SIs). SIs were measured with a novel algorithm, which seems to efficiently and effectively quantify eye movements. This study also showed that the SI-and-MWL relationship was prevalent in all the participants in a consistent pattern, suggesting that this MWL measure may be generalized to the population. The algorithms automatically processed the eye data to quantify MWL without any tailoring by the experimenter. This is promising for a future automatic system that would be able to automatically quantify MWL using the SI measure. The eye data was recorded by the Tobii eye tracker, which offers moderate temporal/spatial resolution. Although Tobii is not primarily designed for physiological experiments like those reported in this study, SIs seem to be large enough for the Tobii to record. The data were sufficient to measure SIs and

therefore MWL. This indicates that this method may be applicable in industry with an inexpensive eye-tracking device.

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