Development of Fatigue-Associated Measuresment to Determine Fitness for Duty and Monitor Driving Performance

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Abstract. Long distance driving has been a major factor leading to road accidents [1-2]. With the lack of reliable validation on driver fatigue technology systems [3], the aim of this study is to correlate the measurements of two cognitive tests: Psychomotor Vigilance Task Tester-PVT [4] and PenScreen-PS [5] to establish the threshold levels of fatigued driving performance that will form the basis to prevent fatigued drivers from handling vehicles. PVT is recommended to be the first line of defense against putting fatigued drivers on duty. Drowsiness can be detected by SmartEye Anti-Sleep-AS, acting as a monitoring tool. Eye closure analysis on AS's eyelid opening data showed that AS is a feasible system for real-time monitoring of fatigue while driving. The results also suggested a simpler and more economical way of monitoring fatigue using AS system. PS could be used in conjunction with PVT to detect for any malingering intent.

Keywords: Fatigue, Fitness for Duty, Driving Performance.

1 Introduction

Long haul driving is an example of a prolonged operation or task that demands sustained vigilance in which human performance eventually breaks down as a result of mental fatigue. This can cause safety to be compromised. Operator fatigue has been one of the most prevalent reasons behind accidents, even in military settings, leading to the development of Fatigue Management Technologies (FMT) [6]. Generally, the fatigue problem is tackled by these FMTs in two ways.

One of the ways to mitigate driver fatigue is to monitor fatigue real-time and indicate its onset through a warning system. Such monitoring systems have the added advantage of measuring driver's alertness while he drives, without requiring him to perform additional and possibly, distracting tasks. However, current technology is limited to detecting the onset of fatigue instead of predicting it, and hence does not allow for early intervention. Additionally, current behavioral attributes monitored are largely controllable by conscious means. In other words, unmotivated operators can

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mimic fatigue-like behaviors to trick the fatigue-warning system, so as to be excused from mandatory duties. One such system is the PERCLOS system that measures the percentage of eyelid closure to infer sleeping behavior.

Therefore, there is a need to develop a robust early predictor by monitoring attributes that cannot be voluntarily controlled by the observed driver. Monitoring involuntary attributes like saccadic eye velocity (quick eye movement speed) and pupil reflexes seems to be a better approach and these actions have been found to be highly correlated to fatigue levels [7-12]. Heart rate variability has been found to be a useful covariate of fatigue [13-17] as well as electrodermal activity (EDA), which detects the changes in skin activities [18, 19]. This study aims to validate eye reflexes, heart rate and EDA measures as effective early predictors for unacceptable fatigue levels.

This study would potentially lead to improvements in operation safety of extended operations and sustained demand for vigilance by preventing human errors due to fatigue. Furthermore, the detection concepts developed here have the advantage of not requiring the driver to perform additional tasks which can be a hassle to the driver and potentially detract him from his primary task.

2 Method

Forty healthy Singaporean male participants (aged 20 - 45) licensed to drive a motor vehicle weighing no more than 3000 kg with no bad driving records for the past one year were recruited. All interested and eligible participants attended a recruitment brief at least three days ahead of their trial. During the brief, details on the conduct of the trial, trial safety aspects, and subject reimbursement were presented. Participants willing to take part in the trial signed an informed consent in the presence of a witness (minimum 21 years of age). Each of them was issued an ActiWatch, a wrist-device to log their sleep duration for 3 days before his trial. This study required participants to have minimum 6 hours of sleep every night, for 3 nights, prior to their trials.

Informed consent, indemnities and recruitment work processes was administered to those interested on the same day, less those who are below 21 years of age and require parent's consents.

The fatigue driving trial required participants to perform prolonged monotonous driving (30km/hr, up to a maximum of 4 hours) within a closed-circuit road (refer to Table 1). Three cognitive systems deployed to determine the participants' pre–post fatigue driving differences. A monitoring system tracked the participants during the entire driving duration.

Each participant was required to complete both Trial A and B on separate weekends at least 6 days apart to prevent fatigue interaction between trials. The sequence of trials was counterbalanced between two groups of participants. Trial A was designed to apply cognitive test hourly during the 4 hours driving, while in Trial B, cognitive tests were administered pre and post driving.

Table 1. Work flow for Trial A & B

Time Start	**Activities**	**Equipment (Trial A)**	**Equipment (Trial B)**
0730 hrs	Reporting and Safety Briefing	All equipment ready. ActiWatch data to be downloaded. Health Declaration signing.	
0750 hrs	Equipment Familiarization	PVT, PS – Demo	
0830 hrs	Driving Familiarization	On-the-road Driving 5 Rounds	
0840 hrs	Breakfast	Food	
0915 hrs	Measurement #0 – Trial Baseline	PVT, PS, VAS	
0930 hrs	Driving Game	PS3 Game console	
1130 hrs	Measurement #1 – Before Driving	PVT, PS, VAS	
1205 hrs	Light lunch	Food	
1215 hrs	Baseline Driving	ET(AS),	
1230 hrs	Driving 30km/hr for 4 hours*	Continuous data collection – ET(AS), Hourly stoppage for PVT, PS, VAS	Continuous data collection – ET(AS),
1630 hrs	Measurement #2 – After Driving	PVT, PS, VAS	
1700 hrs	Monotonous Driving Game#	Continuous data collection - ET(AS), PS3 Game console	Continuous data collection - T(AS), PS3 Game console
1900 hrs	Measurement #4 – After Game	PVT, PS, VAS	
1815 hrs	End of Trial-Run	Pack all equipment	

PVT – Psychomotor Vigilance Task Tester

PS – PenScreen

VA – Visual Analogue Scale (Fatigue Survey)

EDA – Electro-Dermal Activity

ET(AS) – Eye tracker (Smart Eye Anti-Sleep)

Note: *Participant will proceed to the next item if he dozes off less than 4 hours into driving.
#Participant will proceed to end the trial if he dozes off less than 2 hours into the monotonous driving game.

3 Results and Discussion

Actiwatch II – Participants, on average, rested 441.22 minutes per night for 6 nights prior to taking part in the driving trials. The Actiwatch II registered 91.2% of these times as sleep times. On the night before the trial, participants rested, on average, 384.11 minutes. No significant correlations between rest/sleep duration and driving duration or cognitive task performance.

3.1 Visual Analogue Scale [VAS]

On average, participants in Trial A drove for 151 minutes while participants in Trial B drove for 149 minutes. The analysis on VAS showed that the participants' perception of fatigue increased significantly after the driving task. This supports the claim that the driving task successfully induced fatigue. The duration of driving in Trial B did not correlated with the increase in VAS score, meaning with a longer period of driving did not corresponded to a proportionate increase in the participants' rating in fatigue and that the two measures were independent of each other.

3.2 Grouping of Participants (Refer to Table 2)

From the results derived from Psychomotor Vigilance Test (PVT) and PenScreen (PS), serving as potential screening tool, the performance of these participants were classified into three groups. One group of participants (n = 11, were labeled as Elites), all the participants drove for more than 220 minutes for both Trial A and B. They were able to successfully complete the full driving task without lane deviation. Another group of participants (n = 14) could only drive less than 90 minutes for both trials were known as the Vulnerable drivers, as they could not complete the full 4-hour driving task and had to be stopped for causing danger to other road users. Seventy-five percent of this group of participants for managed to drive for more than 40 minutes. The longest driving duration in the group was 160 minutes and the shortest driving duration in the group was 18 minutes. The last group of participants (n = 15), better known as the Malingerers, managed to drive for more than 140 minutes for both trials on average before lane deviating. They have the tendency to drive almost 90 minutes longer during the first trial and most of the time participants in this group did not lane deviate in the first trial, but lane deviated in the second trial.

In summary, it was believed that the participants in this group purposefully drove less on their second trial than on their first to try to end the trial earlier, regardless of the different task demands required for each trial. We call this group the Malingerers, as they seemed to have feigned fatigue to get off the driving trial when we suspect they have not reached their maximum fatigue level. 13 out of the 15 Malingerers, who drove for more than 180 minutes, did it only for their first trial but not for the second trial. The longest driving duration for the group was 242 minutes while the shortest driving duration was 16 minutes.

Table 2. Grouping criteria for elite, vulnerable and unmotivated drivers

<table>
<tr><td></td><td>Elites</td><td>Vulnerable</td><td>Unmotivated</td></tr>
<tr><td>First Trial</td><td rowspan="2">Can last approximately 4 hours of driving without deviating from lane.</td><td rowspan="2">Can only last approximately 1 hour of driving without deviating from lane.</td><td>Can last approximately 4 hours of driving without deviating from lane.</td></tr>
<tr><td>Second Trial</td><td>Can only last approximately 1 hour of driving without deviating from lane.</td></tr>
</table>

Sleep records obtained from the Actiwatch found no significant differences between these 3 groups of participants in terms of rest and sleep duration ($F(1,36) = 0.18$, $p = 0.836$). Thus, all significant differences that are found from analyses that follow cannot be due to the effects of rest and sleep.

3.3 Cognitive Test –Psychomotor Vigilance Test (PVT)

The results from the Vulnerable group revealed that PVT can reliably screen for fatigue individuals who are unfit for road duties. The following tables described the significant differences between and within group comparison for PVT mean reaction time and its standard deviation.

Table 3. PVT mean RT (ms) with lapses

<table>
<tr><td>Trial</td><td>Time</td><td>Elite</td><td>Vulnerable</td><td>Malinger</td><td>Comparison by Group</td><td>Comparison by Time</td></tr>
<tr><td rowspan="2">A</td><td>Start</td><td>249.83 (28.51)</td><td>280.66 (55.05)</td><td>265.70 (39.44)</td><td rowspan="2">F(2,37) = 5.17
p <0.05
(Elite vs.</td><td rowspan="2">F(1,37) = 27.57
p<0.01</td></tr>
<tr><td>End</td><td>279.20 (60.36)</td><td>560.77 (282.72)</td><td>450.15(215.12)</td></tr>
<tr><td colspan="2">Comparison within groups</td><td>F(1,10)= 4.29
p = 0.065</td><td>F(1,13)=15.72
p < 0.01</td><td>F(1,14)= 14.32
p < 0.01</td><td colspan="2">Time*Group Interaction
F(2,37)=5.04, p < 0.05</td></tr>
<tr><td rowspan="2">B</td><td>Start</td><td>264.75 (32.51)</td><td>264.60 (31.90)</td><td>289.58 (68.23)</td><td rowspan="2">F(2,37) = 0.74
p = 0.483</td><td rowspan="2">F(1,37) = 5.13
p<0.05</td></tr>
<tr><td>End</td><td>295.54 (52.58)</td><td>505.90 (337.94)</td><td>499.01 (704.58)</td></tr>
<tr><td colspan="2">Comparison within groups</td><td>F(1,10)=8.63
p < 0.05</td><td>F(1,13)= 7.28
p <0.05</td><td>F(1,14)= 1.66
p = 0.218</td><td colspan="2">Time*Group Interaction
F(2,37)=0.77, p = 0.471</td></tr>
</table>

Note: values in brackets are Standard Deviation of its respective mean.

Table 4. Standard deviation (SD) of RT with lapses

Trial	Time	Elite	Vulnerable	Malinger	Comparison by Group	Comparison by Time
A	Start	61.49 (30.04)	137.37 (186.86)	73.88 (46.84)	***F*(2,37) = 6.05 p < 0.01 (Elite vs**	***F*(1,37) = 13.58 p < 0.01**
	End	76.12 (41.99)	612.75 (614.77)	344.68(338.81)		
Comparison within groups		F(1,10) = 3.41 p = 0.095	***F*(1,13) = 7.53 p < 0.05**	***F*(1,14) = 10.86 p < 0.01**	Time*Group Interaction ***F*(2,37) = 3.51, p < 0.05**	
B	Start	77.47 (42.13)	79.73 (40.04)	100.68 (89.64)	F(2,37) = 0.77 p = 0.469	***F*(1,37) = 5.03 p < 0.05**
	End	114.50 (82.35)	412.02 (577.51)	319.10 (756.67)		
Comparison within groups		F(1,10) = 4.28 p = 0.065	F(1,13) = 4.50 p = 0.054	F(1,14) = 1.52 p = 0.238	Time*Group Interaction F(2,37) = 0.90, p = 0.416	

3.4 Cognitive Test –PenScreen (PS)

PS tasks of non-matching pairs with active distracters (NAC) and matching pairs with neutral distracters (MNC) tasks was found to be a promising screening tool for drivers who have malingering intent. The following tables described the significant differences between and within group comparison for NAC and MNC tasks.

Table 5. NAC mean RT: non-matching pair – active distracters

Trial	Time	Elite	Vulnerable	Malinger	Comparison by Group	Comparison by Time
A	Start	852.34 (273.70)	815.16 (145.65)	779.58 (95.19)	F(2,37) = 2.67 p = 0.083	***F*(1,37) = 7.53 p < 0.01**
	End	810.85 (204.10)	1160.71 439.69)	863.53 (248.06)		
Comparison within groups		F(1,10) = 0.90 p = 0.365	***F*(1,13) = 9.62 p < 0.01**	F(1,14) = 1.95 p = 0.185	**Time*Group *F*(2,37) = 5.73, p < 0.01**	
B	Start	790.43 (164.80)	827.28 (171.39)	744.82 (103.58)	F(2,37) = 1.38 p = 0.265	F(1,37) = 3.59 p = 0.066
	End	802.07 (176.05)	894.31 (204.76)	791.65 (158.41)		
Comparison within groups		F(1,10) = 0.52 p = 0.490	F(1,13) = 2.00 p = 0.181	F(1,14) = 1.68 p = 0.218	Time*Group F(2,37) = 0.51, p = 0.606	

Table 6. NAC SD: non-matching pair – active distracters

Trial	Time	Elite	Vulnerable	Malinger	Comparison by Group	Comparison by Time
A	Start	186.61 (125.86)	173.75 (86.46)	160.05 (53.03)	***F*(2,37) = 5.30 p < 0.01 (Elite & Malinger vs Vulnerable)**	***F*(1,37) = 20.51 p < 0.01**
	End	200.88 (131.28)	622.11 (440.57)	316.17 (212.09)		
Comparison within groups		*F*(1,10) = 0.16 p = 0.702	***F*(1,13) = 15.64 p < 0.01**	***F*(1,14) = 9.64 p < 0.01**	**Time*Group *F*(2,37) = 7.71,**	
B	Start	156.28 (106.62)	241.20 (275.08)	141.36 (64.60)	*F*(2,37) = 1.918 p = 0.162	*F*(1,37) = 2.55 p = 0.119
	End	179.57(85.85)	295.11 (139.59)	244.68(252.57)		
Comparison within groups		*F*(1,10) = 0.81 p = 0.390	*F*(1,13) = 0.55 p = 0.472	*F*(1,14) = 2.09 p = 0.172	Time*Group *F*(2,37) = 0.38, p = 0.688	

Table 7. MNC mean RT: non-matching pair – neutral distracters

Trial	Time	Elite	Vulnerable	Malinger	Comparison by Group	Comparison by Time
A	Start	720.85 (146.08)	697.14 (80.12)	693.74 (80.26)	*F*(2,37) = 1.15	***F*(1,37) = 5.66 p < 0.05**
	End	717.07 (146.88)	888.54 (314.99)	750.57 (184.96)		
Comparison within groups		*F*(1,10) = 0.041 p = 0.843	***F*(1,13) = 5.00 p < 0.05**	*F*(1,14) = 2.03 p = 0.176	Time*Group *F*(2,37) = 2.79,	
B	Start	705.00 (113.55)	736.38 (243.98)	688.93 (102.48)	*F*(2,37) = 0.69 p = 0.510	*F*(1,37) = 0.015 p = 0.902
	End	683.30 (106.69)	751.19 (138.15)	704.30 (90.06)		
Comparison within groups		*F*(1,10) = 2.48 p = 0.146	*F*(1,13) = 0.058 p = 0.813	*F*(1,14) = 0.88 p = 0.365	Time*Group *F*(2,37) = 0.26, p = 0.771	

Table 8. MNC SD: non-matching pair – neutral distracters

Trial	Time	Elite	Vulnerable	Malinger	Comparison by Group	Comparison by Time
A	Start	129.14 (59.11)	147.84 (63.08)	146.53 (110.15)	*F*(2,37) = 2.92 p = 0.067	***F*(1,37) = 19.36 p < 0.01**
	End	193.25 (128.98)	397.31 (270.73)	256.68 (169.27)		
Comparison within groups		*F*(1,10) = 3.95 p = 0.075	***F*(1,13) = 11.80 p < 0.01**	***F*(1,14) = 6.01 p < 0.05**	Time*Group *F*(2,37) = 3.00,	
B	Start	137.49 (53.77)	228.32 (402.05)	128.46 (58.52)	*F*(2,37) = 2.08 p = 0.140	*F*(1,37) = 1.08 p = 0.305
	End	141.26 (55.14)	288.02 (212.75)	177.65 (108.77)		
Comparison within groups		*F*(1,10) = 0.07 p = 0.803	*F*(1,13) = 0.38 p = 0.549	*F*(1,14) = 3.15 p = 0.098	Time*Group *F*(2,37) = 0.206, p = 0.815	

3.5 Monitoring System (Smart Eye Anti-Sleep, AS)

This is an off-the-shelf eye tracker (Smart Eye AB, Sweden) that can be mounted onto any vehicle to collect eyelid opening data at 60 times a second (60 Hz). It operates over a wide range of ambient lightings from dark to bright daylight with the capabilities to cancel spectacle reflections which may interfere with the tracking. The unit of measure is percentage PERCLOS, which stands for the proportion of time in a minute that the eyes are at least 80 percent closed (Wierwille et al., 1994)[20]. It reflects slow eyelid closures rather than blinks. This parameter is simple yet sensitive to driver fatigue making it a hot topic for research in driver fatigue for the past half a decade. With advance in technologies, PERCLOS can be derived real-time using eye tracking systems like AS. Even this, the AS system like others need to be validated with an Asian population where people generally have smaller eyes. The version of AS used in this study is tuned towards research where data can be logged and post analyzed for PERCLOS, allowing the researcher to fully understand the behaviour of data over time.

Thirty-three participant's data was analysed. Percentage of Eyelid Closure over a minute (PERCLOS) was statistically significant between 5 minutes at the start of driving (BP) and the point of 1-sec microsleep (P1) as shown in Fig.1. Traditional P-80 criteria where eyelid closure was defined as 80% eye closed yields 3.69% and 8.30% PERCLOS at BP and P1 respectively, and this difference was statistically significant ($F(1.49,44.65) = 7.8$, $p < 0.01$). The simpler but novel EO-7 criteria defined eyelid closure as 7 mm system eye opening reading (approximately 3mm actual eyelid opening corresponded to 2/3 eye closure). This EO-7 criteria yields 10.66% and 20.16% PERCLOS at BP and P1 respectively, and this difference was also statistically significant ($F(1.77, 53.05) = 12.58$, $p < 0.01$). EO-7 generated wider differences between alert and fatigued state and fewer tendencies for Type 1 error without the need for algorithms to determine baseline eyelid opening and to remove blink data.

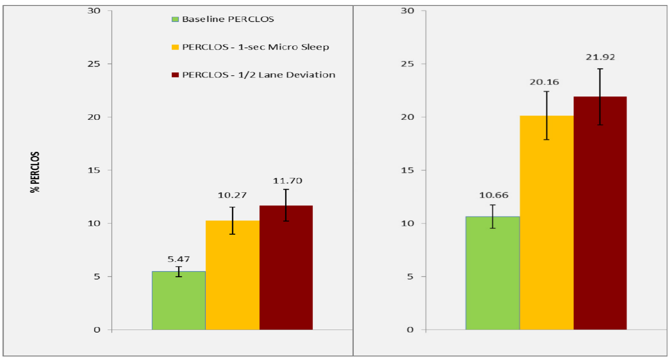

Fig. 1. Multiple comparisons between different data sets

The results and recommendation in this study will provide evidence for the customization of embedded AS suitable for Singapore population context. The analysis of data is steered towards how to make AS's PERCLOS measurement as hassle-free as possible for implementation in typical driving context.

4 Conclusions

The study had successfully derived screening, monitoring criteria and a prediction method for driver fatigue as part of risk management. It was proposed that PVT and PenScreen could be deployed as screening tools while Smart Eye Anti-Sleep PERCLOS was the recommended monitoring tool and using eye pupil tracking for fatigue prediction to reduce driving risk.

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