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Editorial

Letter from the Editors - Fourth international symposium on naturalistic driving research

The *Journal of Safety Research* is pleased to present this collection of papers that were originally presented at the *Fourth International Symposium on Naturalistic Driving Research*. The symposium, hosted by the National Surface Transportation Safety Center for Excellence (NSTSCE) at Virginia Tech, was held in August 2014. From over 40 papers and posters exploring a wide range of naturalistic driving topics, these studies have been selected through our peer-reviewed process to be presented in this special issue.

Although all of the studies included in this special issue use naturalistic driving research methods, the topics explored and analysis methods used vary widely. Studies in this collection can be roughly categorized into three broad groups:

Novice driving:

- Naturalistic teenage driving study — Findings and lessons learn
- Using naturalistic driving data to examine drivers' seatbelt use behavior, comparison between teens and adults
- Personality and crash risk
- Conducting in-depth naturalistic riding study: examples from beginner motorcyclists

Distracted driving:

- Creation of the NEST distracted driving dataset
- Are cellular phone blocking applications effective for novice teen drivers?
- Drivers' visual behavior when using handheld and hands-free cell phones
- Examination of drivers' cell phone use behavior at intersections by using naturalistic driving data

Methodological papers exploring innovative techniques in data extraction and analysis:

- Population distributions of time to collision at brake application during car following from naturalistic driving data
- Evaluation of a video-based measurement of driver heart rate
- Drunk driving detection based on classification of multivariate time series
- Naturalistic drive cycle synthesis for pickup trucks
- Older driver fitness-to-drive evaluation using naturalistic driving data

We hope you find this collection of naturalistic driving research valuable. Through programs like SHRP 2 (see accompanying letter and articles in this issue) naturalistic driving research will become more prevalent in the years to come with the potential of revolutionizing our understanding of motor vehicle safety. However, all research methodologies have limitations, and no single methodology can fully explain the complex causal nature of crashes. The Journal invites all researchers conducting rigorous evidence-based investigations, regardless of the methods used or conclusions made, to consider submitting their studies. These studies add to the understanding of us all. Only through the publishing of findings in peer-reviewed journals and through the subsequent debate on the merits of the research can the field of motor vehicle safety research advance. In this light, the Journal invites thoughtful commentary on this collection of studies.

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Editorial

The 4th International Symposium on Naturalistic Driving Research

The Virginia Tech Transportation Institute is proud to have hosted the 4th International Symposium on Naturalistic Driving Research in August of 2014. The papers presented in this special issue are expanded versions of the papers and posters presented at that symposium, and they represent the first dedicated collection of papers in this new area of research. In the past 20 years, we have seen the field of naturalistic driving research expand in incredible fashion. Advances have occurred in all aspects: from vehicles with car trunks and truck cabs filled with analog recording equipment to state-of-the-art miniaturized data collection systems, from a few participants to thousands of participants per study, from manual coding of data using video tape players and spreadsheets to sophisticated data coding and extraction software, and from simple parametric statistical analysis to advanced statistical modeling techniques. Most importantly, naturalistic driving has progressed to the point that the methods, equipment, and data are now available to a wide variety of researchers.

This is what made the 4th Symposium so special: for the first time there were enough researchers doing work in the field that we were able to have a call for papers. By contrast, the three previous symposia were introductory in nature — introducing the methods, equipment, and analysis techniques to a new generation of researchers, with invited papers from those known to be working in the field.

We hope that you find the papers presented in this issue to be useful in your own research, and that you will consider adding the naturalistic driving techniques and data to your research portfolio. Most importantly, we hope that the research highlighted in this issue will provide the impetus to help save lives and improve transportation efficiency worldwide.

Jon Hankey
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Evaluation of a video-based measure of driver heart rate

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ABSTRACT

Introduction: Internal driver events such as emotional arousal do not consistently elicit observable behaviors. However, heart rate (HR) offers promise as a surrogate measure for predicting these states in drivers. Imaging photoplethysmography (IPPG) can measure HR from face video recorded in static, indoor settings, but has yet to be examined in an in-vehicle driving environment. *Methods:* Participants ($N = 10$) completed an on-road driving task whilst wearing a commercial, chest-strap style heart rate monitor ("baseline"). IPPG was applied to driver face video to estimate HR and the two measures of HR were compared. *Results:* For 4 of 10 participants, IPPG produced a valid HR signal (± 5 BPM of baseline) between 48 and 75% of trip duration. For the remaining participants, IPPG accuracy was poor (<20%). *Conclusions:* In-vehicle IPPG is achievable, but significant challenges remain. *Practical applications:* The relationship between IPPG accuracy and various confounding factors was quantified for future refinement.

1. Introduction

There is substantial evidence that drivers frequently divert their attention away from tasks necessary for safe driving toward competing secondary behaviors (Johnson et al., 2011; Klauer et al., 2006; Koppel et al., 2011). These secondary behaviors may include activities such as speaking with passengers, using a cell phone, or adjusting the radio. Tasks that involve making single glances away from the forward roadway that last more than 2 s have been shown to double the risk of a crash or near-crash event (Klauer et al., 2006) and, in Australia, a cross sectional survey of drivers cited distraction as contributing to 21% of crashes (McEvoy et al., 2006). Distractions associated with overt physical behaviors such as playing with child passengers, eating, or otherwise looking away from the forward roadway are relatively easy to observe and quantify through video analysis. In contrast, cognitive distractions, such as emotional rumination and daydreaming, may not result in any observable behavior.

Experimentally, the inaccessibility of some driver states to objective measurement has been demonstrated in studies such as that conducted by White and Caird (2010) where confederates engaged participant drivers in flirtatious conversation while drivers completed a simulated driving task. No differences in eye-glance behavior were reported between the control and conversation conditions. However, drivers who self-reported feeling greater anxiety, which was significantly associated with attraction to the conversation partner, were significantly more likely to look but fail to react appropriately to road hazards, highlighting the challenges associated with detecting and quantifying cognitive distractions and emotional states using video analysis. Similarly, using driving performance metrics as a measure of cognitive distraction remains ambiguous. In experiments involving aural/memory tasks of increasing difficulty, cognitive distraction and emotional arousal have been associated with significantly increased brake reaction time and a greater number of driving errors (e.g., failing to indicate, exceeding speed limits; Briggs, Hole, & Land, 2011; Chen & Chiuhsiang, 2011). These same factors, perhaps counter-intuitively, have also been shown to be associated with decreased lane position variance (although the implications for safer driving remain unclear; Engström, Johansson, & Östlund, 2005; Lansdown & Stephens, 2013).

In contrast to the difficulties in identifying a behavioral marker for cognitive distraction and emotional states, findings relating to the effects of these phenomena on heart rate are more robust, with positive correlations being observed between heart rate and cognitive load, anxiety, and emotional valence (Briggs et al., 2011; Brookhuis & de Waard, 2010; Johnson et al., 2011; Lang et al., 1993; Veltman & Gaillard, 1998). Recent evidence suggests that under increased cognitive workload, effects on heart rate may even precede changes in driving performance (Johnson et al., 2011; Mehler et al., 2012). A significant limitation of heart rate measurement in road safety research is the reliance on intrusive technologies such as the electrocardiogram (ECG) or photoplethysmography (PPG), necessitating the routing of wires in the vehicle and sustained physical contact with drivers, rendering these systems impractical for naturalistic driving studies.

In recent years, the emergence of imaging PPG technology (IPPG) has allowed researchers to unobtrusively measure heart rate using

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consumer-grade video equipment. Conventional PPG utilizes a dedicated infrared light source and infrared camera mounted to participants' fingers via a spring-loaded clip, detecting changes in skin reflectance as a function of local blood flow (Allen, 2007). In contrast, IPPG measures these changes across wider areas of skin, using ambient light and visible-spectrum cameras without requiring any physical contact with participants (Verkruysse et al., 2008). Previous laboratory-based physiological studies of IPPG have demonstrated its suitability as a surrogate measure of heart rate (Aarts et al., 2013; Sun et al., 2011). However, a number of challenges exist for applications in real-world settings, particularly where there is movement of the participant (e.g., when undertaking physical exercise or driving a vehicle) or where there is variability of ambient lighting, both of which could introduce artifacts to the heart rate signal. To account for these artifacts in naturalistic applications, several techniques have been explored including image stabilization, face tracking, and a variety of signal processing algorithms (Poh et al., 2010; Sun et al., 2011), achieving accuracy rates within 3 to 5 beats per minute of conventional PPG. The current investigation seeks to apply these techniques within a dynamic, in-vehicle environment in order to assess their effectiveness in real-world applications for measuring driver heart rate.

Using the current best practice of ECG as a benchmark, the aim of this study was to develop and test an IPPG solution in an on-road in-vehicle environment. The successful implementation of in-vehicle IPPG would assist researchers in assessing internal driver events such as emotional arousal, cognitive workload, and cognitive distraction that have not typically been observable under standard naturalistic procedures.

2. Methods

2.1. Participants

The participant sample comprised five older (mean age: 74.6 years (2.97), 4 male) and five younger (mean age: 30.0 years (3.08), 3 male) drivers, recruited through a Monash University Accident Research Centre database for a separate on-road pilot study of cognitive load (Koppel et al., 2014). All participants were of European descent and had no discernible facial hair or any other personal factors (e.g., clothing, long hair) that would obscure the view of their face from the camera. To be eligible to participate, participants were required to hold a current Victorian driver's license, own a vehicle model that was newer than 2004 (for hardware compatibility with in-car data acquisition devices), and meet the medical standards outlined by the Austroads (association of Australasian road transport and traffic agencies) Fitness to Drive Guidelines (Austroads., 2013) required for safe driving.

2.2. Apparatus

For the duration of the driving task, two video cameras (ATC9K HD Action Camera, http://uk.oregonscientific.com) were fixed to the inside of the windscreen of the participant's own vehicle, providing a view of the driver's profile and the forward roadway in color at 29 frames per second and 1920 × 1080 pixel resolution.

Participants were fitted with a Zephyr Bioharness 3 (http://www.zephyranywhere.com/), a chest-strap style physiological heart rate monitor. The Bioharness is designed for use as a performance monitoring tool in military and athletic settings, and comprises a 45 mm × 10 mm circular electronic device fitted to participants via a neoprene chest and shoulder strap. ECG signals detected through conductive pads on the chest strap are used to derive a heart rate measurement between 0 and 240 beats per minute (BPM), which is recorded on the Bioharness and downloaded post-hoc when the device is removed. The Bioharness has been shown to be a valid measure of ECG under standard exercise protocols, demonstrating strong correlation and low bias (r = 0.99, bias = 1.3 BPM) when compared to a 3-lead ECG device (Zephyr Technology, 2008), and capable of providing a physiologically-consistent heart rate signal 97–99% of the time under strenuous physical activity (Zephyr Technology, 2009).

2.3. Procedure

Participants were instructed to drive along a pre-determined, standardized urban route in their own vehicle around the suburbs surrounding Monash University. The driving task took approximately 15 min to complete and comprised a variety of maneuvers including cross-traffic gap selection, roundabouts, freeway driving, and high-density pedestrian crossings within the university campus. The drive was conducted at various times of day under varying weather/ambient lighting conditions, as detailed in Table 1. Brightness was calculated by converting the upper half of each video frame to the Hue–Saturation–Value color space and calculating the mean “Value” (corresponding to perceived luminance). The upper half of each video frame was cropped in order to minimize systematic bias from fixed structures (e.g., vehicle registration stickers, A-pillars), which were typically visible in the lower half of the video frame.

During the driving task, one researcher provided the participant with directions from the front passenger seat while a second researcher, seated in the rear, observed and scored the participants' driving performance as part of the cognitive load study (Koppel et al., 2014).

2.4. Analysis

An overview of the signal processing protocol is presented in Fig. 1 below. Initially, a 100 × 100 pixel region of interest from the driver's face was cropped using a face-tracking algorithm. A feature-based tracker could not be reliably implemented due to frequent occlusion of key facial features from the camera view. Instead, a color-based tracker was used, with the largest continuous region of skin color selected to represent the driver's face. From this general region, the left cheek was selected for analysis on the basis of its affordance of the most continually unobstructed area of skin. Since the objective of the study was to explore the feasibility of IPPG in an on-road driving environment, no restrictions were imposed on participants' choice of eyewear, make-up, or movement.

Participant videos were recorded in RGB, a color model in which the color of each pixel is represented by a combination of varying intensities of red, green, and blue. Spatially-averaged green values were extracted from the cropped region of interest based on previous IPPG research identifying the green signal as most closely representing local blood flow due to the light-absorbing properties of red blood cells (Verkruysse et al., 2008).

To determine the optimal window size for the short time Fourier transform, root mean square error was calculated for window sizes

Table 1
Overview of driving sessions by participant number, time of drive, weather condition, and mean and standard deviation (SD) of forward roadway brightness.

Participant number	Time of drive	Weather condition	Brightness	
			Mean	SD
1	0930	Clear	97.42	4.02
2	1200	Clear	94.8	0.92
3	1430	Cloudy	82.69	5.69
4	1430	Overcast	84.06	16.73
5	0930	Cloudy to overcast	80.2	4.86
6	1200	Cloudy to clear	94.6	9.37
7	1430	Overcast to light rain	82.29	6.78
8	0930	Clear to overcast	69.02	1.54
9	1200	Cloudy to clear	88.07	2.46
10	1430	Cloudy	73.2	1.46

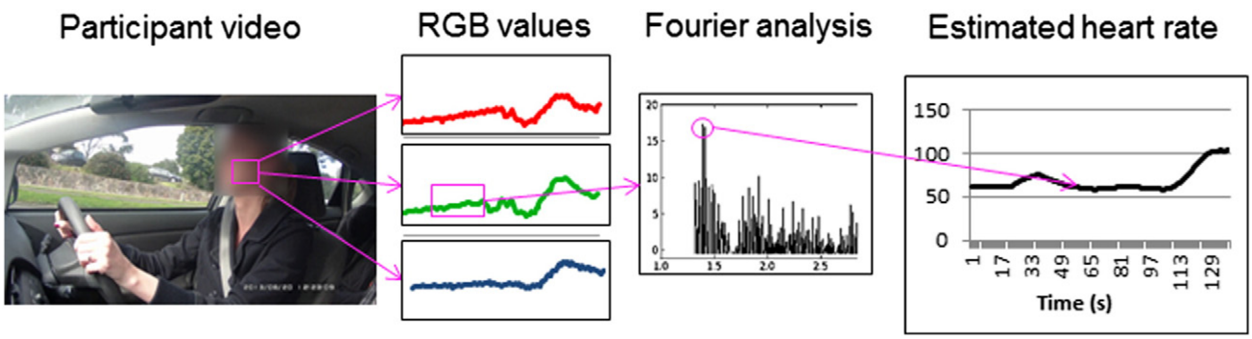

Fig. 1. Overview of imaging photoplethysmography (IPPG). Data plots for reference only and do not reflect actual calculations.

ranging from 1 to 160 s. A window size of 18.48 s with a 1 s step corresponded to the lowest root mean square error was selected. The short time Fourier transform was performed on the windowed green values, with the maximum frequency value between 0.84 and 2.67 Hz (corresponding to a range of between 50 and 160 BPM), extracted and converted to BPM. This range was selected to adequately encompass the heart rate measurements likely to be encountered in a driving task. In previous research on the effects of cognitive load while driving, participant heart rates have not been observed to exceed 100 BPM (Brookhuis & de Waard, 2010; Johnson et al., 2011; Reimer & Mehler, 2011).To obtain the final second-by-second BPM measure, a moving 15 s triangular window was applied and acute drops in output (i.e. gradient < -0.5) were smoothed.

To compare IPPG and BioHarness output across time and frequency domains, an accuracy variable was calculated, comprising the percentage of time per trip that Bioharness and IPPG outputs differed by less than 5 BPM. This criterion has been shown in previous research to represent the mean heart rate change related to medium to high cognitive workload (Mehler et al., 2012; Reimer & Mehler, 2011).

3. Results

Table 2 shows the mean difference scores between BioHarness and IPPG outputs, standard deviations, and accuracy scores per participant. A large discrepancy in IPPG performance was observed between participants. For 6 out of 10 participants, IPPG performance was poor, ranging from 4% to 20% accuracy. For the remaining participants, IPPG accuracy ranged from 48% to 75%.

Standard deviation of the algorithm-tracked region-of-interest (i.e., left cheek) was calculated for the x and y axis per participant across driving task duration to determine the effect of lateral and vertical head movement on IPPG performance (Fig. 2). No significant differences between the low and moderate accuracy groups were observed. In contrast, a significant power relationship was observed between standard deviation of brightness and IPPG performance, $r = -0.644$, $p = 0.045$, indicating large decreases in IPPG accuracy with increasing brightness variability (Fig. 3).

Table 2
Mean, standard deviation (SD), and mean differences (D) for heart rate estimates from Bioharness and IPPG per participant. All values in BPM.

Participant		Bioharness		IPPG		Bioharness–IPPG		Accuracy
Age group	Number	Mean	SD	Mean	SD	D	SD	
Older	1	75.23	6.45	75.14	11.98	0.09	13.26	16.48
Older	2	66.27	10.02	68.91	4.88	−3.43	9.77	49.97
Older	3	100.20	2.38	86.10	8.93	14.10	8.86	8.10
Older	7	83.51	3.06	77.30	4.34	6.20	4.24	47.76
Older	9	81.26	4.05	78.28	5.64	2.98	7.12	57.01
Younger	4	95.88	31.55	60.54	2.18	35.34	35.76	5.67
Younger	5	77.90	4.25	88.88	5.75	−10.97	7.23	11.66
Younger	6	70.49	3.26	96.26	9.60	−25.77	9.71	4.08
Younger	8	90.61	4.22	90.61	2.56	0.005	4.43	73.59
Younger	10	95.37	9.59	83.81	8.14	11.56	13.17	19.97

4. Discussion

Using high definition video and face-tracking technologies, a novel method for measuring driver heart rate was tested in an on-road, in-vehicle environment. Moderate consistency with a conventional ECG measure was observed for 4 of 10 participants, achieving accuracy rates of within 5 BPM for 48% to 74% of trip duration. For the remaining participants, IPPG performance was poor, with large variability of forward roadway brightness correlating inversely with low accuracy. The use of heart rate as a surrogate measure of cognitive workload and emotional arousal has been explored extensively in the literature, with results supporting its use as an early predictor of driving performance impairment (Briggs et al., 2011; Johnson et al., 2011; Mehler et al., 2012). While other heart rate measurement methods exist, the non-contact nature of IPPG supports its use as a real-time driver state monitoring method (as part of an advanced driver assistance system) and for the post-hoc analysis of driver heart rate in naturalistic driving video. The results of the present study show that, for brief durations of time, it is possible to calculate driver heart rate from video footage. However, significant advances will be required before a consistent and reliable measure can be obtained from IPPG alone.

Large changes in forward roadway brightness were observed to correlate significantly with poor IPPG accuracy. Given that IPPG is dependent on minute color changes in a subject's skin tone, it is likely the case that fluctuating ambient light is masking the underlying heart rate signal. With a more precise measure of the change in ambient lighting on a driver's face (i.e., through the use of in-vehicle sensors, in

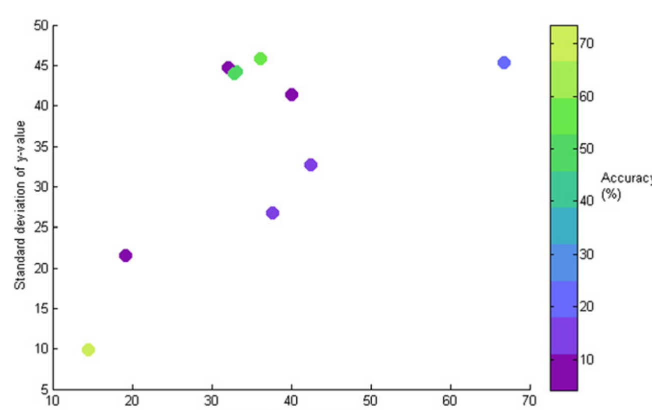

Fig. 2. Plot of IPPG accuracy as a function of region-of-interest position standard deviation.

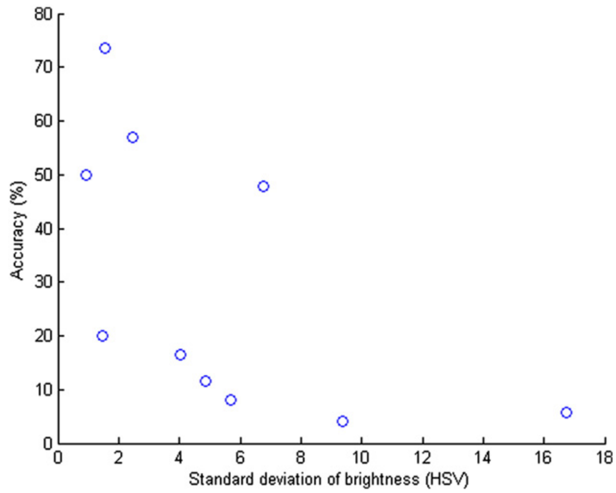

Fig. 3. Plot of IPPG accuracy and standard deviation of forward roadway brightness.

contrast to the broad measure of forward roadway brightness used in the present study), it may be possible to quantify and account for these artifacts in the heart rate signal. However, if it is the case that ambient light is of such intensity that the driver's skin tone is completely obscured, then no underlying heart rate signal may be present in the video sequence at all. This is a significant challenge to be resolved if IPPG is to be adapted for use in an in-vehicle environment. Additionally, driver head movement was hypothesized to be another potential confounding factor. In the current analysis, no significant effect was observed for standard deviation of head position and IPPG accuracy, which is contrary to previous research. Given the small sample size, this result is to be interpreted with caution and it is entirely plausible that with further observations, a clearer pattern may emerge.

More general limitations of IPPG include the dependence on visible areas of skin — different areas of the face may need to be sampled in a way that accommodates personal factors such as drivers' choice of clothing, hair style, or facial hair. While a number of regions of interest on which IPPG may be applied have been explored in the literature (Sun et al., 2013; Verkruysse et al., 2008), widespread application to naturalistic driving data would dictate the selection of an area that afforded the most continually unobstructed area of skin: in the present study, the driver's left cheek fulfilled this criteria, with the 100×100 pixel region-of-interest residing well within the boundaries of observable skin area when tracking was reliable. Further investigations could explore the relationship between varying region sizes and the corresponding IPPG signal-to-noise ratio. While the current implementation of IPPG also depended on visible spectrum light, the use of an infra-red illuminator and infra-red-band pass camera could potentially extend the technique for night drives or other low-light conditions. Increased signal noise can also be expected in applications of IPPG to datasets using lower resolution or greyscale video. While IPPG has been successfully applied to greyscale video in previous research (recorded indoors with stationary participants), further refinements of the technique for active environments are likely to be initially realized through the use of higher resolution video prior to any post-hoc applications to existing datasets. Notwithstanding these shortcomings, the underlying concept of IPPG has received strong support in physiological studies (Sun et al., 2013). The findings of the present study show that while it is possible to implement IPPG within an in-vehicle environment, significant challenges remain.

5. Practical implications

IPPG requires significant development and refinement prior to any real-world applications. In the current pilot study, a valid heart rate signal was briefly observed using the IPPG technique in an in-vehicle environment, and potential confounding factors were quantified. Standard deviation of forward roadway brightness was observed to be correlated inversely with IPPG accuracy. In the context of naturalistic driving studies, IPPG could be used as a surrogate measure of driver cognitive load and emotional states. Similar factors could also be measured in the context of a driver-state monitoring module as part of an intelligent transportation system, incorporating driver factors when calculating appropriate moments to display warnings or otherwise take over control of the vehicle.

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