2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Relationship between pre-driving heart rate and driving performance in formula car racing: a case study

Naoki Saijo, Ryota Nishizono, and Makio Kashino, *Member, IEEE*

***Abstract*— Formula car racing is highly competitive and induces significant physical stress. Previous studies have shown that intense physical stresses, such as g-force, accelerate the driver's heart rate (HR). In contrast, it remains unclear whether psychological stress affects the physiological states of racers and racing performance. To investigate this phenomenon, we developed a wearable monitor that can track the driver's HR during a race. The HR and driving performance of two professional drivers were monitored in real racing situations. Changes in HR were then evaluated based on changes in the racing situation and car behavior. The results suggest that HR acceleration is strongly correlated with race situations such as free practice or qualifying sessions, and that such changes are related to subsequent driving performance.**

I. INTRODUCTION

Racing drivers exhibit distinctive skills in car races. In formula racing, car speeds exceed 300 km/h, and a strong gravitational force (g-force) is induced by quick braking and steering actions. Under such high physical stress, racing drivers compete for placements that are often separated by split-second differences in lap time.

Previous studies have investigated the physical abilities of racing drivers, such as endurance against the g-force, muscle fatigue, and cardiovascular regulation, in a real racing environment [1]–[3]. For example, professional racing drivers exhibit HR values of over 150 bpm in race-speed test driving, and such values increase as lap time decreases [3]. Given that faster car speeds are associated with a greater g-force and increases in the weight of the steering wheel, these results highlight the intensity of physical stress on the driver.

In contrast, drivers devote much effort to shortening their lap times by even a few milliseconds. Although a millisecond difference in lap time would induce only a slight difference in physical stress, its effects on psychological stress are more pronounced. In such a competitive situation, athletes exhibit changes in both their psychophysiological states and performance [4], [5]. To win the race, drivers would have to control the car very precisely under such high psychological stress.

Although several studies have mentioned that psychological factors can influence the physiological responses of drivers [1], [2], it remains unclear how these factors affect the physiological state of the racer and racing performance. One issue involves measuring the slight changes in the driver's emotional state under experimental conditions, such as those in which drivers are asked to increase the car speed to the racing speed [2]. Even if there are effects of psychological stress on physiological states in such simulated situations, the huge effect of physical stress may mask the effects of psychological stress. In contrast, drivers are motivated to win in real racing situations, which will undoubtedly affect psychophysiological states. Therefore, observing the racer's physiological states and performance in real racing situations is necessary to examine the effect of psychological stress on the driver. In addition, to assess the relationship between physiological states and driving performance, the driver's physiological states must be measured in synchronization with car performance data in a real racing environment.

The main purpose of this study was to investigate whether psychological stress affects the HR of racing drivers and driving performance. We developed a new wearable HR monitor that can measure the formula car driver's HR in a real racing environment, which can be synchronized with the timeline of the car performance data. By using this system and collaborating with the top Japanese racing team, we conducted a preliminarily investigation of HR in professional drivers during a real race and analyzed the relationship between changes in HR and driving performance.

II. MATERIALS AND METHODS

A. Participants

Two professional drivers (32 and 23 years of age) participated in this study. Both drivers belonged to the top Japanese formula car racing team (Super Formula).

The participants were given an information sheet that outlined the general purpose of the study and gave written informed consent to participate in the study. All methods employed in this study were approved by the Ethics and Safety Committees of NTT Communication Science Laboratories and were conducted in accordance with the Declaration of Helsinki. The protocol number of the Ethics and Safety Committees of NTT Communication Science Laboratories is H30–002.

B. Apparatus

Figure 1A shows the driver undergear developed for this experiment. To acquire electrocardiograms (ECGs) during driving, two electrodes and a data transmitter mount were attached to the gear. hitoe®, which is an electrically conducting fabric with hydrophilic properties and good adhesion to skin [6], was selected as the electrode for acquiring the ECG. The electrode was placed slightly below the chest to avoid noise caused by the seat belt. To ensure contact between the electrode and the skin, the chest circumference of the garment was slightly tightened by squeezing the side. The ECG signals were measured and processed by a hitoe® transmitter [7] that was placed on the

N. Saijo, R. Nishizono and M. Kashino are with NTT Communication Science Laboratories, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa Pref., 243-0198, Japan. e-mail: naoki.saijo@hco.ntt.co.jp).

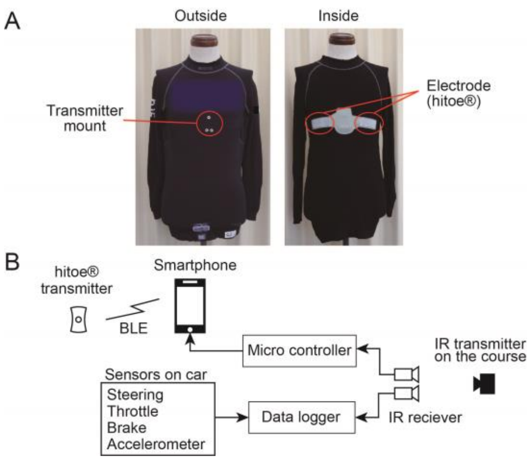

Figure 1. A: Driver's undergear. B: Measurement system

mount, and HRs calculated by the transmitter were sent to a smartphone. The transmitter updated the HR approximately every second.

Figure 1B shows the data collection system. Two infrared (IR) receivers (C16S IR Timing Beacon Receiver, Cosworth Ltd.) were installed on the car. One was for the car data logging system (Cosworth Ltd.), while the other was for the HR monitor. The IR transmitter was used to trigger the timing when the car passed through a control line. This timing information was sent to both the car data logging system and the smartphone for the HR monitor. The smartphone received a serial command generated by a microcomputer (PIC16F1705, Microchip Technology Inc.) at the completion of each lap. This time stamp was recorded on the timeline of the HR recording, which was based on the Network Time Protocol (NTP) time in the smartphone. The accuracy of the time synchronization between the HR monitor and the car data logger was estimated using the lap times, which were defined based on the duration between two lap timings. The average difference in the lap times between the systems was 3.4 ± 11 ms. We assumed that this difference was small enough to analyze the relationship between changes in HR and changes in car behavior. In addition, the time when the car was removed from and returned to the pit was manually recorded using Global Positioning System (GPS) watch time.

Various parameters of car behavior, including lateral and longitudinal acceleration, speed, steering angle, and brake application, were recorded using the car data logging system. The recorded data were fetched at 50 Hz after the race sessions.

C. Procedures

Measurements were obtained during the official free practice (FP) and qualifying (QF) sessions of the 2020 season of the Japan Super Formula Championship series (Round 5) at the Suzuka circuit. Both drivers raced on these courses. The FP session was held 1 day before the QF session. The weather was good, and the outdoor temperature was 8°C on both days.

In both the FP and QF sessions, one stint consisted of three laps, and four or five stints were completed in one session. Typically, in one stint, the drivers left from the pit and completed one warm-up lap, following which they completed an attack lap in which they drove the car as fast as possible. After the attack lap, the car was run relatively slower for one more lap and then returned to the pit. Both drivers completed four or five stints in the FP session and four stints in the QF session. The intervals between the stints, which were defined based on the duration between the pit-in and pit-out points, ranged from approximately 90 s to over 30 min. On average, the stint interval was relatively longer in the QF session than in the FP session (driver A: FP: 387 ± 161 s, QF: 682 ± 943 s; driver B: FP: 367 ±198 s, QF: 379 ±336 s).

D. Data analysis

The recorded HR was resampled at 50 Hz and aligned with the car performance data using the time stamp of the lap trigger. The steering angle and accelerometer data were smoothed using a second-order Savitzky-Golay filter.

The HR before pit-out was defined as the average HR from 90 s before pit-out. The average HR and car acceleration data during the attack lap and 120 s before the attack lap were obtained. To test the statistical significance of changes in HR among the sessions and phases, a two-way repeated measures analysis of variance (ANOVA) was conducted with the factors of SESSION (FP/QF) and PHASE (before pit-out/pre-attack/attack). The significance level was set to 5%.

III. RESULTS

Figure 2 shows the HR and car performance data during the pre-attack and attack phases for two drivers. In the pre-attack phase, car behavior varied among laps, indicating that driving was not stable. There are various reasons for this unstable driving. One reason was to warm up the tires to increase grip force. The driver exhibited left-right swinging of the steering wheel as well as some instances of brake pumping. Then, the driver entered the attack laps, during which car performance became consistent among laps. The difference in car behavior between the FP and QF sessions was smaller in the attack laps than in the pre-attack phase. Given that racers compete to achieve millisecond differences in lap times, this small difference critically influences the race results.

HR gradually increased as driving time increased. As previously reported [1], strong g-forces were observed (two bottom panels in Fig. 2). The maximum g-force in the lateral direction was approximately 3.4 *g*, while that in the longitudinal direction was 3.1 *g*. This indicated that the driver had to endure a strong g-force to maintain their body posture in the cockpit and required precise control of the car. This endurance force exertion contributes to the increase in HR during driving.

Differences in HR between the FP and QF sessions were observed from the pre-attack phase to the end of the attack lap in both drivers (top panel in Fig. 2). Moreover, these differences were observed even before the pit-out phase. Figure 3 shows the average HRs in the before-pit-out, pre-attack, and attack phases in both sessions. A two-way repeated-measures ANOVA with the factors of SESSION and PHASE revealed no significant interaction effects [$F(2, 18) = 1.12$, $p > 0.3$ for driver A; $F(2, 21) = 0.54$, $p > 0.5$, for driver B] but significant main effects of SESSION [$F(2, 18) =$

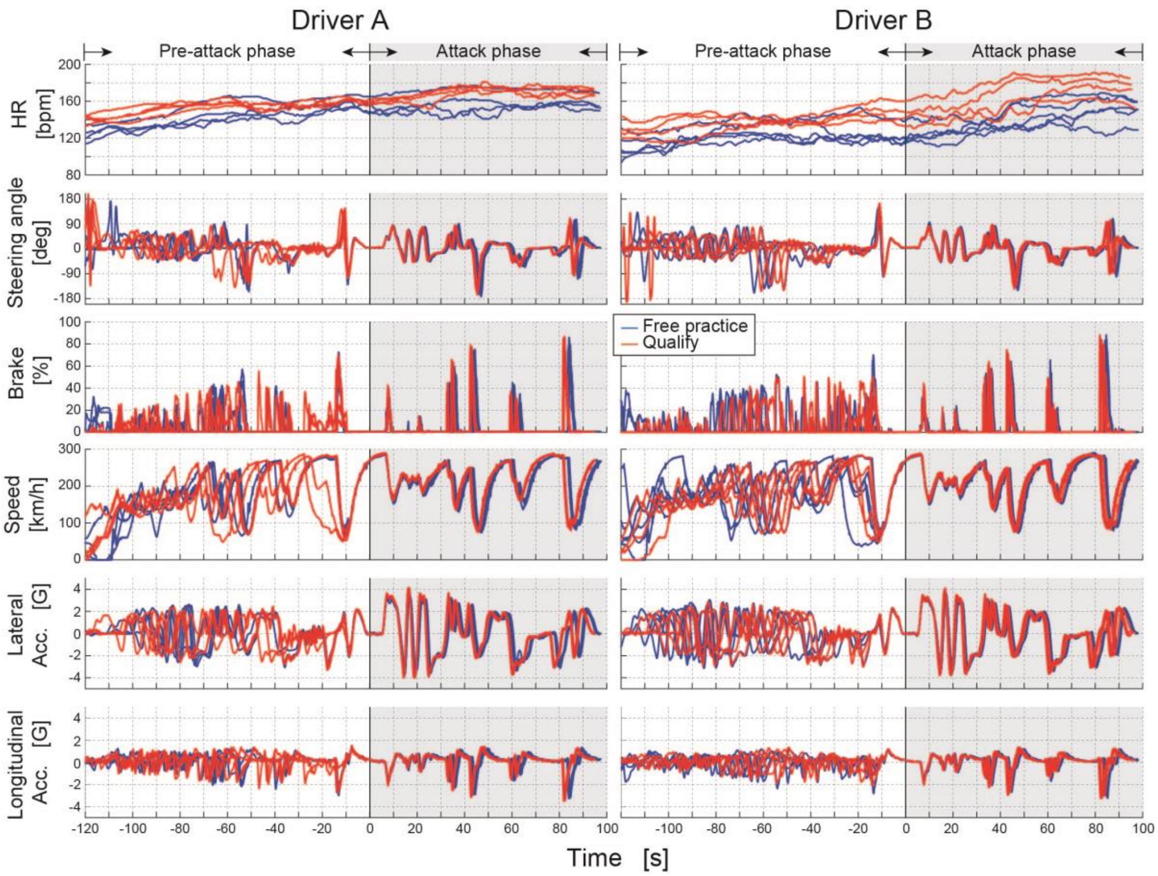

Figure 2. Temporal patterns of HR and car behavior during pre-attack and attack phases.

58.4, $p < 10^{-7}$ for driver A, $F(2, 21) = 26.74$, $p < 10^{-5}$ for driver B] and PHASE [$F(1,18) = 22{,}1$ $p < 10^{-3}$ for driver A; $F(1,21) = 24.91$, $p < 10^{-4}$ for driver B]. A post hoc test revealed a significant difference in HR in the before-pit-out phase in both drivers (Tukey's honest significant difference (HSD) test, $p < 0.05$). This indicates that HR was higher in the QF session than in the FP session, and that this difference was not directly related to driving the car.

To examine the relationship between the g-force and HR, we obtained the average g-force on the horizontal plane in the pre-attack and attack phases and compared it with the average HR. Figure 4 shows the relationship between the average g-forces and HRs in the pre-attack and attack phases. In the pre-attack phase, there were no clear correlations between the two. In contrast, in the attack phase, there was a significant correlation between g-force and HR in one driver ($R = 0.90$, $p < 0.001$) and a marginal correlation in the other driver ($R = 0.67$, $p = 0.07$). The g-force in the attack phase was approximately twice as large as that in the pre-attack phase. A comparison of the pre-attack (top panels in Fig. 4) and attack phases (bottom panels in Fig. 4) revealed that HR increased as a function of g-force. However, the correlation was only observed in the attack phase when a larger g-force was induced. This indicates that a large g-force affects the driver's endurance force required to maintain posture in the cockpit, and that sustained force exertion results in an increase in HR, whereas a small g-force does not.

As mentioned above, the higher HR in the QF session than in the FP session was not directly related to driving actions, indicating that it may have been related to psychological factors. In the next step, we investigated the

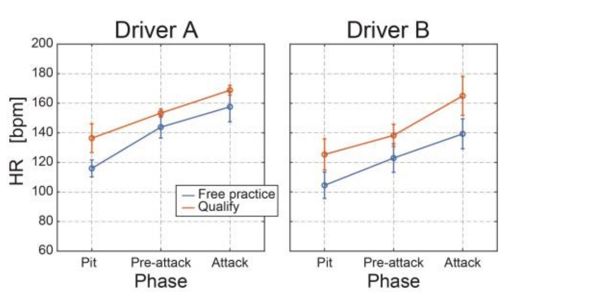

Figure 3. Average HR in before-pit-out, pre-attack, and attack phases.

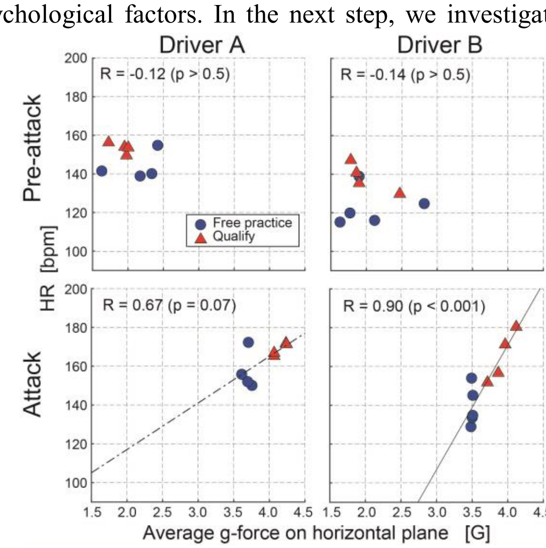

Figure 4. Relationship between g-force and HR.

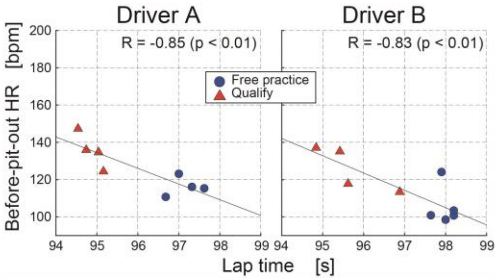

Figure 5. Relationship between average HRs before pit-out and driving performance (lap time) in the attack phase.

relationship between HR before the attack phase and performance in the attack phase. Performance was defined based on lap times, which were calculated from the interval between the times received by the IR beacon. Figure 5 shows the correlation between the average HR in each phase and lap time in the following attack phase. Lap time was significantly correlated with average HR in the before-pit-out and pre-attack phases (R = -0.85 [$p < 0.01$] for driver A and R = -0.85 [$p < 0.01$] for driver B). This result indicates that the increase in HR in the QF session was associated with better performance in future attacks.

IV. Discussion

In this study, we investigated the relationship between changes in HR and the performance of formula car drivers in a real racing situation. The results suggest that there are psychological factors that modulate HR even before physical changes in racing performance, and that these factors are related to subsequent performance.

Formula driving induces strong physical stress. Previous studies have investigated the relationship between physical stresses (e.g., g-force) and physiological responses [1]. Real racing situations induce strong psychological stress on the driver. As shown in Fig. 3, the HRs in the QF session were significantly higher than those in the FP session for both drivers. Notably, HR in the before-pit-out phase was higher in the QF session than in the FP session. This may be because drivers waited to leave the pit during this period without significant body movement, indicating that HRs in the before-pit-out phase were measured in the quasi-resting state. Therefore, this result suggests that the HR difference in the before-pit-out phase was caused by the difference in the psychological state between the sessions.

The HR accelerated in the attack phase compared to the pre-attack and before-pit-out phases (Fig. 3). One strong factor influencing HR is the g-force induced by driving, as previous studies have suggested [1]–[3]. A comparison of HR and g-force between the pre-attack and attack phases revealed that average HR increased as a function of g-force. However, a between-session (FP and QF) comparison revealed that HR was correlated with the average g-force only in the attack phase (bottom panels in Fig. 4). Because the range of the g-force in the attack phase was approximately twice as high as that in the pre-attack phase, this result suggests that the driver's exertion of endurance force in high g-force situations leads to an increase in HR. In contrast, the effort required to maintain body posture and/or control the steering wheel is not as great in low g-force situations.

Interestingly, lap time—which is a clear indicator of driving performance—was correlated with HR in the before-pit-out phase (Fig. 5). This indicates that the physiological state in the before-pit-out phase may be related to driving performance in the attack phase. Previous studies on sports performance have suggested that HR increases when the game situation becomes more competitive, such as when approaching competitive attempts or progressing game situations from practice to finals [8], [9]. Such findings suggest a relationship between HR and cognitive pressure. Research has also indicated that high cognitive pressure or emotional stress degrades subsequent performance (so called "choking" [5]). However, the opposite effect was observed in the present study: Increases in HR in the competitive situation (QF session) were associated with better performance (faster lap times), suggesting that the increase in HR may not be simply caused by cognitive pressure but may reflect a state of heightened arousal related to driving performance.

We recognize that the statistical reliability of our data is not sufficient to conclude the effect of psychological stress on race driving, as we only examined HR changes in two drivers. Despite this limitation, we were able to assess the relationship between HR and performance during a real racing situation. Indeed, real-world situations are quite different from the laboratory environment in that the level of cognitive pressure may be far higher. Our preliminary results suggest the importance of observing "in-the-wild" situations to examine the effect of psychological stress on physiological states and athletic performance.

References

[1] M. B. Reid and J. T. Lightfoot, "The Physiology of Auto Racing," *Med. Sci. Sports Exerc.*, vol. 51, no. 12, pp. 2548–2562, 2019, doi: 10.1249/MSS.0000000000002070.

[2] P. L. Jacobs, S. E. Olvey, B. M. Johnson, and K. A. Cohn, "Physiological responses to high-speed, open-wheel racecar driving," *Med. Sci. Sports Exerc.*, vol. 34, no. 12, pp. 2085–2090, 2002, doi: 10.1097/00005768-200212000-00033.

[3] P. L. Jacobs and S. E. Olvey, "Metabolic and Heart Rate Responses to Open-Wheel Automobile Road Racing: A Single-Subject Study," *J. Strength Cond. Res.*, vol. 14, no. 2, pp. 157–161, 2000, doi: 10.1519/00124278-200005000-00007.

[4] M. R. Wilson, "Anxiety: Attention, the brain, the body, and performance.," *Oxford Handb. Sport Perform. Psychol.*, pp. 173–190, 2012, doi: 10.1093/oxfordhb/9780199731763.013.0009.

[5] C. Mesagno and J. Beckmann, "Choking under pressure: theoretical models and interventions," *Current Opinion in Psychology*. 2017, doi: 10.1016/j.copsyc.2017.05.015.

[6] "http://www.hitoe-toray.com/." .

[7] "https://www.nttdocomo.co.jp/info/news_release/2014/09/30_02.html #p03." .

[8] A. E. Carrillo, V. X. Christodoulou, Y. Koutedakis, and A. D. Flouris, "Autonomic nervous system modulation during an archery competition in novice and experienced adolescent archers," *J. Sports Sci.*, vol. 29, no. 9, pp. 913–917, 2011, doi: 10.1080/02640414.2011.568514.

[9] L. Rodríguez-Zamora, X. Iglesias, A. Barrero, D. Chaverri, P. Erola, and F. A. Rodríguez, "Physiological Responses in Relation to Performance during Competition in Elite Synchronized Swimmers," *PLoS One*, vol. 7, no. 11, pp. 1–10, 2012, doi: 10.1371/journal.pone.0049098.