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MESTRADO INTEGRADO EM MEDICINA

2022/2023

Alícia Sandra de Olim Noia de Freitas

Monitoring fatigue and drowsiness in motor vehicle occupants using electrocardiogram and heart rate – A systematic review

Julho, 2023

FMUP

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Monitoring fatigue and drowsiness in motor vehicle occupants using electrocardiogram and heart rate – A systematic review

Mestrado Integrado em Medicina

Área: Ciências médicas e da saúde

Tipologia: Dissertação

Trabalho efetuado sob a Orientação de:

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E sob a Coorientação de:

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Trabalho organizado de acordo com as normas da revista:
Safety Science

Julho, 2023

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UC Dissertação/Projeto (6º Ano) - DECLARAÇÃO DE INTEGRIDADE

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Ciências médicas e da saúde

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Monitoring Fatigue and Drowsiness in motor vehicle occupants using electrocardiogram and heart rate - A systematic review

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Faculdade de Medicina da Universidade do Porto, 01/07/2023

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Monitoring Fatigue and Drowsiness in motor vehicle occupants using electrocardiogram and heart rate - A systematic review

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Abstract

Background: Fatigue is a complex state that can result in decreased alertness, often accompanied by drowsiness. Driving fatigue has become a significant contributor to traffic accidents globally, highlighting the need for effective monitoring techniques. Various technologies exist to enhance driver safety and minimize accident risks, such as fatigue detection systems that alert drivers as drowsiness sets in. In particular, measuring heart rate (HR) patterns may offer valuable insights into the occupant's physiological condition and level of alertness and may allow them to understand their fatigue levels. This review aims to establish the current state of the art of monitoring strategies for vehicle occupants, specifically focusing on fatigue assessed by HR and heart rate variability (HRV).

Methods: We performed a systematic literature search in the databases of Web of Science, SCOPUS and PubMed, using the terms vehicle, driver, physiologic monitoring, fatigue, sleep, electrocardiogram, heart rate and heart rate variability. We examine articles published between the 1st of January 2018 and the 31st of January 2023.

Results: A total of 294 papers were identified from which 71 articles were included in this study. Among the included papers, 57 utilized electrocardiogram (ECG) as the acquired signal for HR measures, with most ECG readings obtained through contact sensors (n=41), followed by non-intrusive wearable sensors (n=11). The majority of the works rely on subjective self-reported fatigue ratings (n=27) and video-based observer ratings (n=11). Regarding validation, 16 papers do not report validation of any kind. From the included papers, only 13 comprise a fatigue and drowsiness estimation system, 9 with reported validation. Some report acceptable performances, but reduced sample size limits the reach of any conclusions.

Conclusions: This review highlights the potential of HR analysis and non-intrusive instrumentation for continuous monitoring of driver's status and detecting sleepiness. One major issue is the lack of sufficient validation and estimation methods for fatigue, contributing to insufficient methods in providing proactive alarm systems. This area shows great promise but is still far from being reliably implemented.

Keywords: Simulated driving; Biomedical; Physiologic; Occupant; Heart rate; Electrocardiogram

1. Introduction

Sleep insufficiency is a prevalent issue that significantly impacts both health and daily functioning. The impact of inadequate sleep can have wide-ranging consequences, affecting various aspects of an individual's life. Reduced cognitive abilities resulting from sleep deprivation, whether resulting from inadequate sleep, a medical condition, or medication, can place individuals at risk. One area where this risk is particularly evident is in driving, as it demands high levels of alertness. Therefore, the importance of monitoring drivers becomes apparent.

It also applies to other domains, such as the detection of sudden illnesses. Effective monitoring techniques that promote safe and alert driving primarily serve as a preventive measure against accidents and resulting injuries.

The US National Highway Traffic Safety Administration has estimated that worldwide every year, about 100 000 road accidents are caused by drowsiness, accounting for > 1500 deaths and > 70,000 injuries (Saleem, 2022). Incidents related to driving fatigue are increasing as transportation networks quickly grow, becoming one of the major causes of traffic accidents in the world (Wang T, 2018).

A study conducted by the European Sleep Research Society estimated the average prevalence of falling asleep at the wheel in recent years as 17%. Among subjects who fell asleep at the wheel, the median prevalence of sleep-related accidents was

7.0%. For Portugal, the odds ratio of falling asleep at the wheel was 1.34 (95% CI: 1.13; 1.58), reflecting a high probability of falling asleep, though with a relatively smaller effect size compared to the mean value (Goncalves et al., 2015).

Fatigue is a complex state that can result in decreased mental and physical performance and reduced alertness, often accompanied by drowsiness (K.L. Lal & Craig, 2001) which is feeling the need to sleep. Some factors can lead to the suboptimal psychophysiological state of driving fatigue, including exertion and sleep-related issues, i.e., sleepiness or drowsiness (Dement & Carskadon, 1982). In addition to sleep-related causes, certain driving characteristics, such as task demand and driving environment, can lead to task-related fatigue. This type of fatigue can be further subdivided into active task-related fatigue, such as caused by driving in high-traffic conditions, and passive task-related fatigue, resulting from driving in a monotonous environment (May & Baldwin, 2009).

Fatigue can cause a driver's attention to decrease, leading to distraction and potentially dangerous driving behaviors, such as speeding, running a red light, and getting out of track (Utomo et al., 2019). Therefore, it is crucial to investigate fatigue detection methods to prevent accidents and promote safe driving practices. This could be particularly important for workers with irregular shift schedules (such as health workers and professional drivers) or anyone who drives on monotonous routes, and for long periods, which may even lead to drowsiness (Harma et al., 2002).

Numerous technologies are available to enhance driver safety and minimize the risk of accidents, including fatigue detection systems that can alert drivers when they are becoming drowsy. Investing in these monitoring systems is of great significance for public safety and the development of the social economy. It aims to reduce the number of driving-related emergencies and ensures that emergency response teams can provide essential aid (Wan et al., 2019).

The estimation of driver fatigue and drowsiness is typically done through subjective and/or objective evaluations of the driver. Subjective evaluations are based on post-evaluations of drivers; this often involves the use of questionnaires that ask drivers to provide their perception of their own fatigue/sleepiness levels while driving (Ahsberg et al., 2000). Some common subjective sleepiness scales used by researchers include the Karolinska Sleepiness Scale (KSS), the Chalder Fatigue Scale (CFS), the Stanford Sleepiness Scale (SSS), and the Swedish Occupational Fatigue Inventory (SOFI) (Stasi et al., 2011). These scales are often used as ground truth for drowsiness detection systems.

In terms of objective estimation of in-vehicle fatigue and drowsiness detection methods, there are three broad categories: (a) driver's behavioral-based methods, (b) vehicle operational performance-based methods, and (c) driver's physiological-based methods (Jiao et al., 2022). Driver's facial characteristics involve video monitoring to capture various parameters of the driver's facial expressions, such as eye movement activity (e.g., blinking, eye closures, saccade frequency, percentage of eye closure) and body posture (e.g., head and body movements) (Ji et al., 2004) (Fan et al., 2008). Vehicle dynamics-based methods use of data from the vehicle's performance, such as deviation from the lane position, steering angle, standard deviation of lateral position (SDLP) and speed, to estimate driver fatigue and drowsiness (Takei & Furukawa, 2005). Physiological signals involve the use of sensors to monitor a driver's physical state and are considered the best measurements for driving fatigue detection (Chowdhury et al., 2018). These physiological indicators, such as electroencephalography (EEG), electrooculography (EOG), electrocardiography (ECG), electromyography (EMG), respiration, galvanic skin resistance, and body temperature, have been used for drowsiness detection and have shown high accuracy (Balandong et al., 2018) (Murugan et al., 2020). Each method has its own unique advantages and limitations. The most accurate outcomes can be achieved by combining psychological parameters, such as self-reports and physiological measurements (Lal & Craig, 2001). Physiological signals offer consistent, reliable, and robust information about a driver's internal state (Murugan et al., 2020). However, the intrusive nature of signal acquisition methods has limited their use. Despite efforts to develop non-intrusive measurement techniques for EEG, EMG, and EOG signals, acquiring these signals still requires direct contact and permanent placement on the driver's body, causing discomfort. EEG signals are acquired through a 10-20 electrode cap system that can be inconvenient and intrusive for drivers. Additionally, these signals are prone to artifacts caused by eye blinks, heart activity, and other movements, increasing the computational complexity and algorithm performance. EOG signals are picked up from the electrodes placed near the eyes disturbing the driver while driving (Jiao et al., 2020).

Nevertheless, ECG signals have been utilized in various applications related to driver state estimation, including mental workload (Heine et al., 2017), emotion (Wang et al., 2020), stress (Keshan et al., 2015), and drowsiness (Chui et al., 2016). Furthermore, cardiovascular conditions are particularly dangerous, as patients may lose consciousness while operating a vehicle (D'Allegro, 2017). Incidents like these created the awareness of the necessity of systems that can detect abnormal heart rates and promptly alert emergency teams (Hanna, 2010).

ECG signals are the most stable for real-time measurements (Hu et al., 2009). With the advances in sensor technology, heart rate (HR) data acquisition via wearable devices has become increasingly convenient in real working conditions. Researchers have developed non-intrusive methods of acquiring ECG signals, such as using Bluetooth devices with ECG or HR sensors attached to the steering wheel (Jung et al., 2014) or chest electrodes attached to clothing (Begum, 2013). However, such methods are prone to movement artifacts and errors caused by improper electrode contact, resulting in less accuracy (Sahayadhas et al., 2015). Developing a non-intrusive wireless wearable device capable of providing a good flow of information without data loss is a significant challenge, and effective filtering techniques are required to remove artifacts.

The HR, is the number of heartbeats in a minute, and the heart rate variability (HRV), consists on the sequence of the time difference between consecutive heartbeats (R to R Intervals, RRI), physiologically regulated by the sympathetic nervous system (ANS) and the parasympathetic nervous system (PNS) from the autonomic nervous system (ANS) (Jiao et al., 2022) (Garcia-Perez et al., 2023). The HRV features are commonly used for drowsiness and fatigue detection as ANS balance changes during stress, extreme fatigue, and drowsiness episodes (Vicente et al., 2016). HRV series are commonly studied in 3 domains: time-domain, frequency-domain, and non-linear (Shaffer & Ginsberg, 2017) . By analyzing the time domain indices, we can measure its variability changes through time. In the frequency domain, HRV is analyzed by decomposing the signal into different frequency bands: Ultra Low Frequency (ULF)**,** Very Low Frequency (VLF)**,** Low Frequency (LF)**,** and High Frequency (HF). Two main bands are high frequency (HF) and low frequency (LF). Both PNS and SNS activity contribute to LF power, and PNS activity primarily contributes to HF power. (Shaffer & Ginsberg, 2017) proposed that a high LF/HF ratio indicates sympathetic dominance and a low LF/HF ratio reflects parasympathetic dominance, which may be related to a state of fatigue. Non-linear measurements of HRV capture the unpredictability of the time series and the complexity of the mechanisms regulating HRV. An important parameter to analyze in HRV is the LF/HF power ratio, which provides insights into the sympathovagal balance and offers a comprehensive assessment of driving fatigue (Patel et al., 2011). Measuring HR from drivers is essential in understanding their fatigue levels. Previous studies have demonstrated the usefulness of HR in detecting driver drowsiness, confirming that SNS and PNS activity are associated with varying fatigue levels (Persson et al., 2021).

This paper aims to establish the current state of the art of monitoring strategies for vehicle occupants, specifically focusing on fatigue and drowsiness. The primary focus is on the identification of fatigue and drowsiness among motor vehicle occupants, utilizing ECG and/or HR measurements. The inclusion of cardiac information is essential due to its close relationship with the state of consciousness. Therefore, by examining HR patterns, valuable insights can be gained regarding the occupant's physiological condition and level of alertness.

This review targets motor vehicle occupants (P-population) on a journey, or simulated journey, in a vehicle or simulator while collecting ECG and or HR (I – Intervention or exposure), aiming fatigue monitoring (O – Outcome). Comparisons, namely as validation facing a fatigue reference values, are desirable, but not mandatory, as no golden standard exists. All study designs are admitted.

Moreover, the review addresses the following questions:

RQ1: How can ECG and HR be used to monitor fatigue and drowsiness in motor vehicle occupants?

RQ2: What are the potential benefits of using ECG and HR to monitor fatigue and drowsiness in motor vehicle occupants?

RQ3: How reliable are ECG and HR readings in assessing fatigue and drowsiness in motor vehicle occupants?

2. Material and methods

This study took into account the preferred items for systematic reviews and meta-analyses (PRISMA) statements (Moher et al., 2009).

2.1. *Search Strategy*

We performed a literature search in the databases of Web of Science, SCOPUS, and PubMed until 03rd of February. We examine articles published between the 1st of January 2018 and the 31st of January 2023 to investigate the state of the art of vehicle occupants monitoring strategies regarding fatigue (or equivalently drowsiness or sleepiness), using ECG, HR and HRV readings.

To improve query relevance, the search queries were formulated considering the terms in titles, abstracts, keywords, author-keywords, and keywords plus. Queries fundamentally included terms to identify the intended system, referencing vehicle, driver, and physiologic monitoring, among other relevant reference words to find articles of interest and adding terms to specify the search, fatigue, sleep, electrocardiogram, heart rate and heart rate variability.

After refining the query and performing sensitivity analysis, the final queries are reported in Table 1. The queries needed to be adjusted based on the specific database being used. For instance, PubMed is the only database that provides the option of using MeSH terms.

2.2. *Eligibility Criteria*

Only studies written in English were considered. Considering both screening and full-text analysis phases, documents were included if they (1) monitor physiological signals during a journey or simulated journey in a vehicle or simulator; (2) monitor fatigue (or equivalently drowsiness or sleepiness) using ECG, HR, HRV or derived indexes; (3) and published between 2018-2023. Exclusion criteria include non-English publications, articles with no abstract available, letters, editorials, comments, abstract only publications, and reviews. An additional exclusion criterion was considered in the full-text analysis: no full text available and studies without implementation (idea only).

2.3. *Analysis*

Screening analysis phase, which involved reviewing titles and abstracts, was performed by two independent reviewers, with the help of a software system, Rayyan, for recording decisions. The two reviewers screened records independently with Blind On. Disagreements were resolved through consensus between the two reviewers.

Full-text analysis phase was performed by four independent reviewers, forming all six possible combinations of pairs, following the strategy:

- the list of retrieved publications was divided into six batches with an equivalent number of publications;
- each batch was assessed by two different reviewers, that performed the data extraction;
- final data were reviewed in a consensus meeting.

2.4. *Data Extraction and Quality Assessment*

Data extraction was part of the full-text analysis phase. The two researchers' extraction occurred independently, followed by the consensus meeting. The information structure extracted from publications is reported in Table 2.

This review focuses on a health-related problem that requires software engineering development and studies. Usual quality instruments and assessment checklists for medical studies are inadequate. Alternative quality assessment instruments specific to software engineering studies have been proposed. The most frequently adopted for systematic reviews, according to (L. Yang et al., 2021), is the 11 criteria checklist by Dybå and Dingsøyr's (Dybå & Dingsøyr, 2008). Each criteria is evaluated as 1- "yes" or 0 - "no"). These criteria are presented in Table 3. To better adapt to the current review, the criteria 6, was enlarged also to consider comparison with reference, as listed in PRISMA. Those were considered in this review as part of eligibility criteria, information extraction or specific quality analysis by two reviewers. Attending for subjectivity, for each included study, the mean of the two independent scores normalized by the maximum of the scale is considered as a quality assessment.

Table 1. Final queries, per database consulted.

Database	**Query**
SCOPUS	(TITLE-ABS-KEY (vehicle OR car OR motorbike OR bus OR rail* OR plane OR road OR "simulated driving" OR "simulator drive" OR "simulator driving" OR traffic*) AND TITLE-ABS-KEY (biomedical* OR physiologic* OR biometric*) AND TITLE-ABS-KEY (driver* OR occupant* OR passenger*) AND TITLE-ABS-KEY (ecg OR "heart rate" OR "electrocardiogram" OR "hr" OR "hrv") AND TITLE-ABS-KEY (fatigue OR sleep*) AND (PUBYEAR > 2017))
PubMed	("vehicle"[Title/Abstract] OR "car"[Title/Abstract] OR "motorbike"[Title/Abstract] OR "bus"[Title/Abstract] OR "rail*"[Title/Abstract] OR "plane"[Title/Abstract] OR "road"[Title/Abstract] OR "simulated driving*"[Title/Abstract] OR "simulator drive*"[Title/Abstract] OR "simulator driving*"[Title/Abstract] OR "traffic"[Title/Abstract]) AND ("biomedical*"[Title/Abstract] OR "physiological*"[Title/Abstract] OR "biometric*"[Title/Abstract]) AND ("driver*"[Title/Abstract] OR "occupant*"[Title/Abstract] OR "passenger*"[Title/Abstract])) OR ("Fatigue"[MeSH Terms] AND "automobile driving*"[MeSH Terms]) OR ("automobile driving*"[MeSH Terms] AND "monitoring, physiologic*"[MeSH Terms]) OR ("accidents, traffic/prevention and control"[MeSH Terms] AND "monitoring, physiologic*"[MeSH Terms])) AND 2018/01/01:2023/01/31[Date - Publication] AND 2018/01/01:2023/01/31[pdat] AND ("ECG"[Title/Abstract] OR "heart rate"[Title/Abstract] OR "electrocardiogram"[Title/Abstract] OR "HR"[Title/Abstract] OR "HRV"[Title/Abstract]) AND 2018/01/01:2023/01/31[Date - Publication]) AND

	(2018/1/1:2023/1/31[pdat]) Filters: from 2018/1/1 - 2023/1/31
Web of Science	TI=((vehicle OR car OR motorbike OR bus OR rail* OR plane OR road OR "simulated driving" OR "simulator drive" OR "simulator driving" OR traffic* OR "simulation driving")AND(driver* OR occupant* OR passenger*)AND(ECG OR "heart rate" OR "electrocardiogram" OR ”HR” OR ”HRV”) AND(Fatigue OR sleep*)) OR AB=((vehicle OR car OR motorbike OR bus OR rail* OR plane OR road OR "simulated driving" OR "simulator drive" OR "simulator driving" OR traffic* OR "simulation driving")AND(driver* OR occupant* OR passenger*)AND(ECG OR "heart rate" OR "electrocardiogram" OR ”HR” OR ”HRV”) AND(Fatigue OR sleep*)) OR AK=((vehicle OR car OR motorbike OR bus OR rail* OR plane OR road OR "simulated driving" OR "simulator drive" OR "simulator driving" OR traffic* OR "simulation driving")AND(driver* OR occupant* OR passenger*)AND(ECG OR "heart rate" OR "electrocardiogram" OR ”HR” OR ”HRV”) AND(Fatigue OR sleep*)) OR KP=((vehicle OR car OR motorbike OR bus OR rail* OR plane OR road OR "simulated driving" OR "simulator drive" OR "simulator driving" OR traffic* OR "simulation driving")AND(driver* OR occupant* OR passenger*)AND(ECG OR "heart rate" OR "electrocardiogram" OR ”HR” OR ”HRV”) AND(Fatigue OR sleep*))

Table 2. List of variables considered for data extraction.

Variables
Domains considered other than fatigue
Sensors and devices for ECG and HR/HRV
Additional physiological parameters
Additional activities monitored
Health status and lifestyle habits
Special physiological framework
Experiment environment
Source of data
Extension and type of validation
Sample size
Participants age and gender
Data processing and Golden Standard
Performance for fatigue detection
TLR of the technology
Main contributions and Limitations

(ECG- electrocardiogram; HR- heart rate; HRV- heart rate variability; TLR- technology readiness level).

Table 3. Quality assessment criteria, Changes with respect to **Dybå and Dingsøyr marked as Italic.**

Criteria as proposed by (Dybå & Dingsøyr’s, 2018)
1. The study reported empirical research or whether it was merely a ‘‘lessons learned” report based on expert opinion.
2. The aims and objectives were clearly reported (including a rationale for why the study was undertaken).
3. There was an adequate description of the context in which the research was carried out
4. The research design was appropriate to address the aims of the research
5. There was an adequate description of the sample used and the methods for identifying and recruiting the sample.
6. Any control groups, *or comparisons with standard*, were used to compare treatments.
7. Appropriate data collection methods were used and described
8. There was an adequate description of the methods used to analyze data and whether appropriate methods for ensuring the data

analysis were grounded in the data.

9. The relationship between the researcher and participants was considered to an adequate degree.

10. The study provided clearly stated findings with credible results and justified conclusions.

11. They provided value for research or practice.

3. Results

3.1. *Study Selection Process*

The PRISMA flow diagram model demonstrates the detailed study selection process, as shown in Figure 1. After applying the final query to the three databases, a total of 371 documents were retrieved, which was reduced to 294 publications after eliminating the duplicates found (n=77 duplicates). In the title and abstract screening phase, a total of 194 studies did not meet our inclusion criteria and were excluded. A total of 71 articles were finally included and analyzed.

All of the publications focused on fatigue monitorization (n=71), followed by drowsiness/sleep (n=42) and cognitive workload (n=6) detection systems. Original research articles published in international journals comprise most of the included publications (n=53), as only fifteen documents were conference papers, and three were book sections. Additionally, the period encompassed in the included publications ranged between 2018 and 2023, with most publications occurring in 2022 (n=19) (Figure 2).

In Sections 3.2–3.4, the body of the literature was further summarized according to data collection methods, challenges and limitations to be addressed, and quality assessment of the included publications, respectively.

3.2. *Data Collection Methods*

3.2.1. Additional Domains

Regarding the domains, in addition to fatigue, 42 out of the 71 studies refer explicitly to Drowsiness/Sleep, while 15 included one or more additional domains, as represented in Figure 3.

3.2.2. Sensors and devices for ECG and HR/HRV

Data collection methods of biomedical parameters measured across the included publications typically occurred from different signal acquisition. Regarding the assessment of the primary physiological parameter, HR/HRV, four different signal acquired measurements were reported. Most of the publications (n=57) utilized ECG as the acquired signal, followed by photoplethysmography (PPG) (n=20). Some publications (n=7) used both ECG and PPG to obtain HR. Another way to assess HR was through radar-based signal acquisition (n=1), a non-contacting detection of heartbeat signals. Similarly to the auscultation method, one paper used an acoustic pulse signal (n=1) to obtain HR.

Regarding the sensors utilized to capture the signals from HR, there were essentially two categories of sensors: vehicle sensors, which are integrated or installed on the vehicle, and subject sensors, which can either be wearable or instrumentalized. Figure 4 summarizes the type of sensor used per signal acquired measurements for HR/HRV access across the included publications.

For ECG readings, most studies utilized instrumentalized sensors with electrodes positioned in the body (n=41). Some of the studies utilized non-intrusive methods of acquiring ECG signals, such as wearable sensors (n=11) and vehicle sensors (n=6). Among the wearable ECG sensors, the chest belt type sensors were the most utilized across multiple studies (Lu et al., 2022), (Rome, 2019), (Zhang et al., 2018), (Watling et al., 2022), (Magana et al., 2020), (Gielen & Aerts, 2019), (Garcia-Perez et al., 2023). Additionally, one study (Yuda et al., 2021) employed a Biometric Smart Shirt with embedded electrodes in the shirt, while other study (Huang et al., 2019) used an ECG vest. Amid vehicle ECG sensors, 4 studies (Afghari et al., 2022), (Abbas, 2020a), (Abbas, 2020b), and (Esteves et al., 2021) employed ECG sensors attached to the steering wheel, while 2 studies (Bhardwaj & Balasubramanian, 2019) and (Balasubramanian & Bhardwaj, 2018) utilized ECG sensors installed on the car seat.

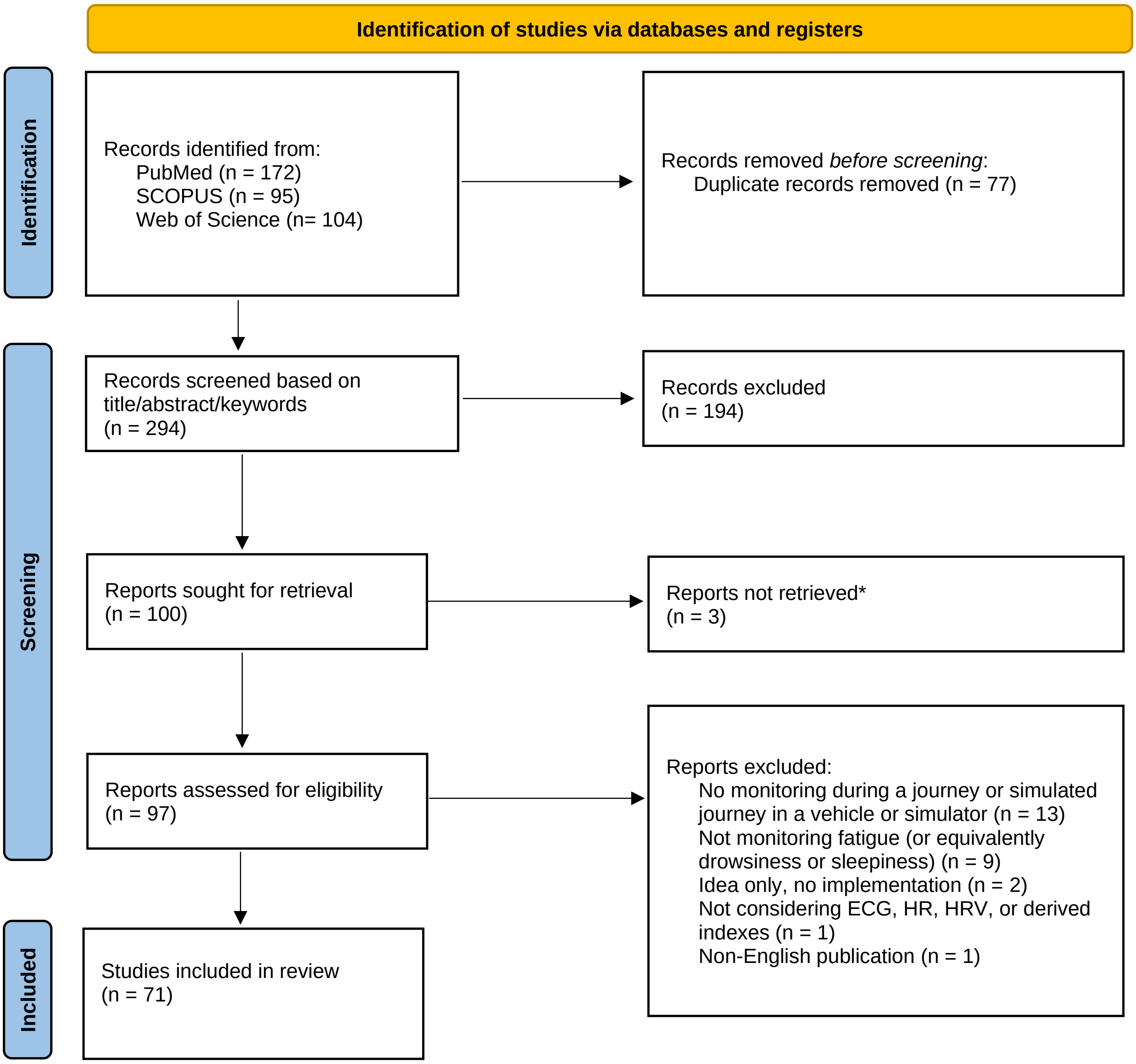

Figure 1. PRISMA flow diagram model. *No full-text available.

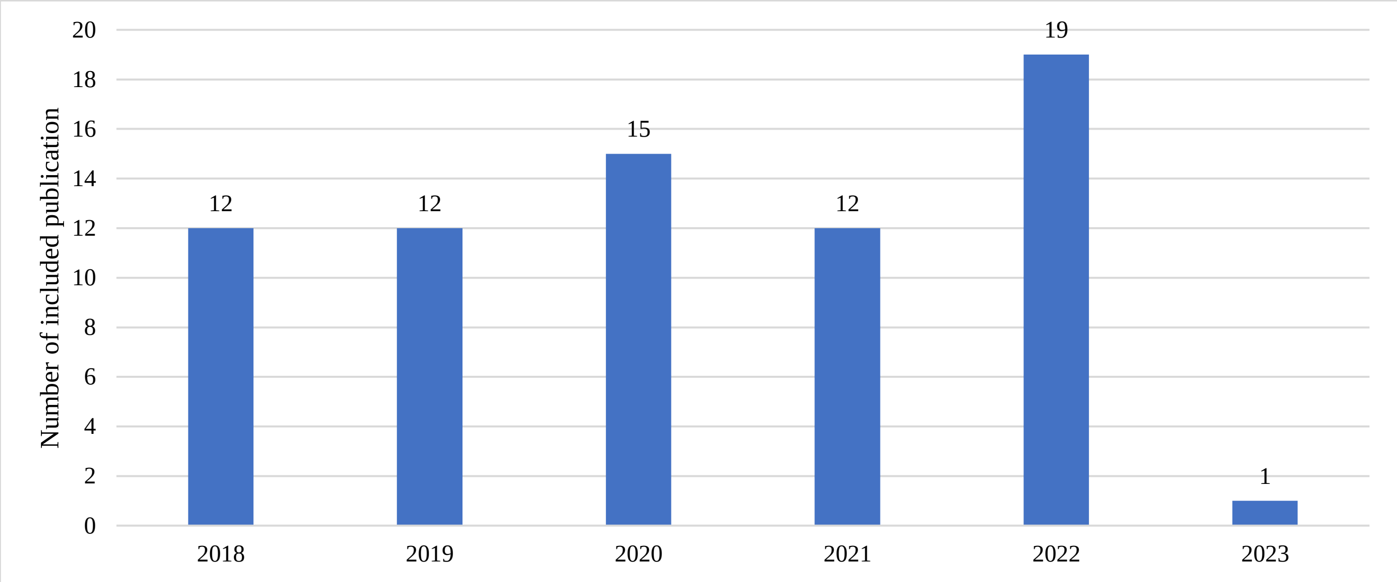

Figure 2. Number of included publications over time.

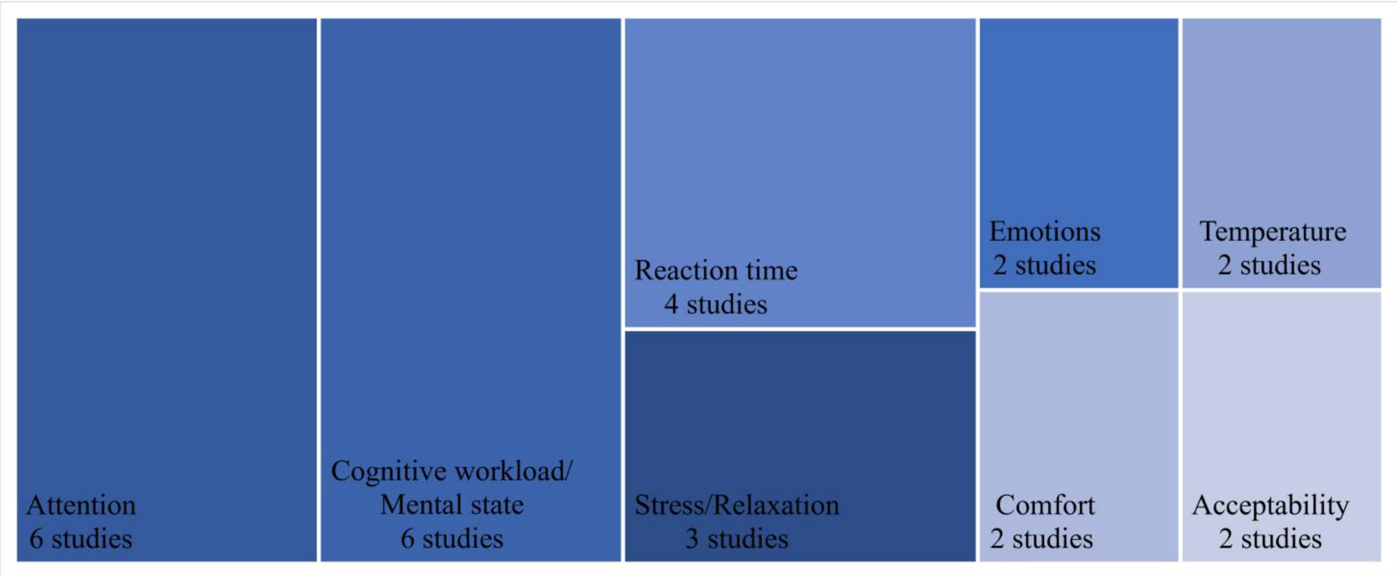

Figure 3. Additional domains reported by included studies, in addition to fatigue (some studies include more than one additional domain).

The wearable type of sensor is predominantly utilized for PPG readings (n=17). Among these, 14 studies utilized wristwatch-type sensors, specifically Empatia E4 (Polar) (Kim et al., 2018), (Tsai et al., 2022), (Kundinger et al., 2021), (Kundinger & Riener, 2020), (T. Kundinger et al., 2020), (Kundinger et al., 2020), (Mizusako et al., 2019), (Jing et al., 2020), (Esteves et al., 2021), (Jiao et al., 2022), (Dong et al., 2021), (Wolkow et al., 2020), (Antunes et al., 2022), (Aghajarian et al., 2019). For acoustic pulse signal acquisition, 1 study (Salvati et al., 2021) employed a microsensor inserted into the seat vehicle, and for radar-based signal acquisition, 1 study (Dong et al., 2021) utilized a millimeter wave radar embedded in the vehicle.

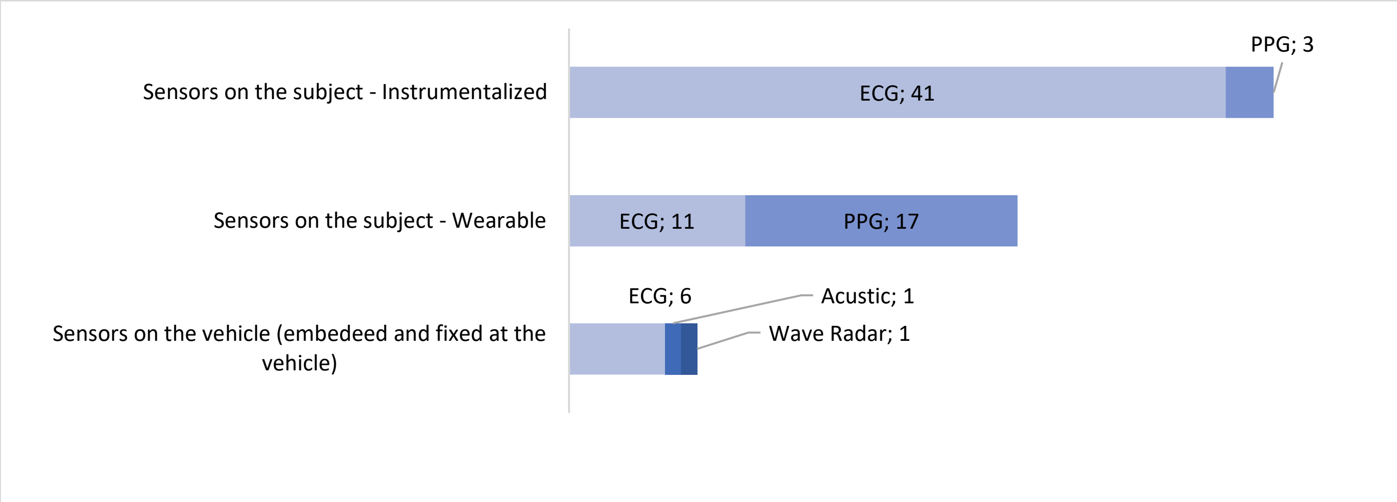

Figure 4. Type of sensor used, per signal acquired measurements for HR/HRV.

3.2.3. *Additional Physiological Parameters*

Additional physiological parameters were collected by 23 studies, namely brain activity, respiratory rate, Peripheral Capillary Oxygen Saturation (SpO2) and Skin Conductivity. Table 4 summarizes the acquired signals by the different studies for each targeted biomedical parameter.

Table 4. Additional biomedical parameters measured across the included publications and the type of acquired signal.

Biomedical parameter	Signal acquired
Brain Activity	• Electroencephalogram (EEG) (Lees et al., 2021) (Pugliese et al., 2022) (Gwak et al., 2020) (Wörle et al., 2019) (Fujiwara et al., 2019) (Zeng et al., 2020) (Balasubramanian & Bhardwaj, 2018) (Riquelme et al., 2022) (Sheibani et al., 2022) (Arefnezhad et al., 2022) (Murugan et al., 2020) (Gwak et al., 2018) (Chen et al., 2022) (Y. Yang et al., 2021)
Respiratory Rate	• Respiratory Excursion (Wörle et al., 2019) (Yuda et al., 2021) (Naurois et al., 2019) • Thermal Imaging (Ebrahimian et al., 2022) • Respiratory Temperature Monitoring (Darzi et al., 2018) (Aghajarian et al., 2019) • Oronasal Airflow (Arefnezhad et al., 2022) • Radar-based signal (Dong et al., 2021)
Peripheral Capillary Oxygen Saturation (SpO2)	• Oxygen Saturation/Pulse oximeter (Jing et al., 2020) (Murugan et al., 2020)
Skin Conductivity	• Skin's Electrical Impedance (Wörle et al., 2019) (Naurois et al., 2019) (Arefnezhad et al., 2022) (Varadam & Ganesh, 2021) (Magana et al., 2020) (Y. Yang et al., 2021) (Darzi et al., 2018) (Aghajarian et al., 2019)

3.2.4. <u>Additional Activities</u>

Additional data monitored were collected by 44 studies, namely driver's behavioral-based data and vehicle operational performance-based data, as shown in figure 5.

Regarding driver's behavioral-based data, studies have focused on facial expressions parameters and body posture. Within facial expression parameters, eye movement patterns such as eye blinking, eye gaze, eye saccade, eye aspect ratio, pupil area, PERCLOS and eyelid distance were evaluated. Additionally, other facial expression parameters included yawn detection, mouth openness, and mouth aspect ratio. In terms of data extracted from body posture, the most common features include nodding, head-tilted ratio, head posture and movement, head aspect ratio, and body position. For recording these data several sensors were used, specifically a camera with a video recording of driver's face, eye tracker technology, electrooculography (EOG), electromyography (EMG) and body position sensor. Table 5 summarizes the sensor variant employed for capturing behavioral-based data.

Regarding vehicle operational performance-based parameters, Table 6 represents the different variables extracted from the papers that describe the motion and behavior of a vehicle.

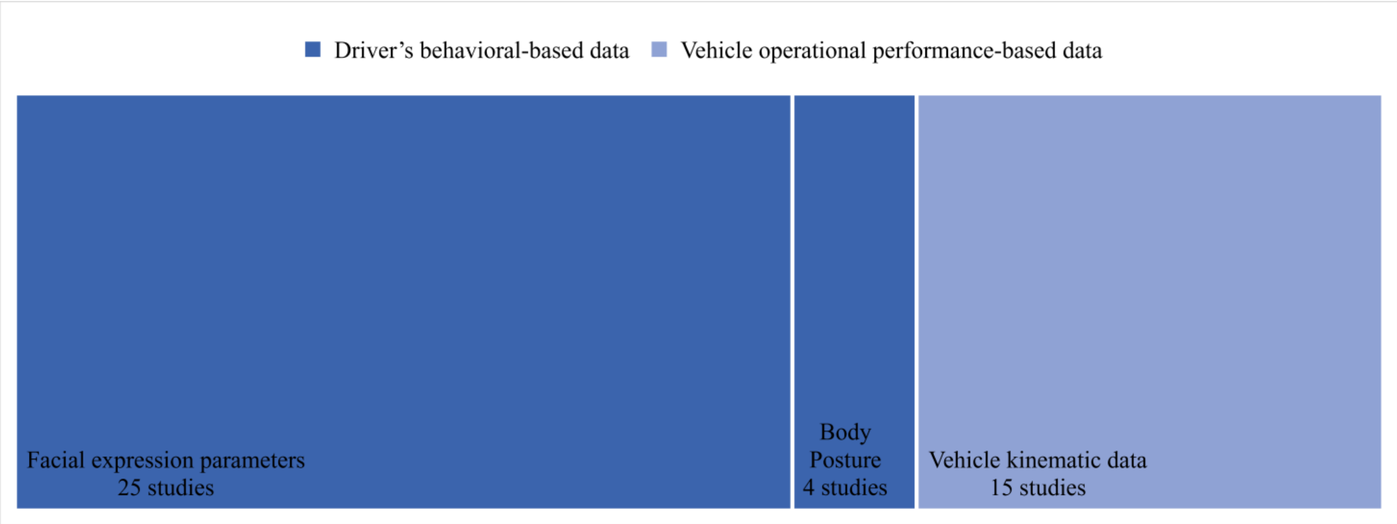

Figure 5. Additional activities monitored across the included studies.

Table 5. Sensor variant employed for capturing behavioral-based data.

Behavioral based data	Sensors		
	Sensors on the vehicle (Embedded and fixed at the vehicle)	Sensors on the subject	
		Wearable	Instrumentalized
Facial expression parameters	• Camera with video recording of driver's face (Salvati et al., 2021) (Utomo et al., 2019) (F. Wang et al., 2019) (T. Kundinger et al., 2020) (Rahman et al., 2022) (Abbas, 2020a) (Abbas, 2020b) (Pugliese et al., 2022) (Zeng et al., 2020) (Riquelme et al., 2022) (Cheng, 2021) (Esteves et al., 2021) (Murugan et al., 2020) (Antunes et al., 2022)	• Eye Tracker glasses (F. Wang et al., 2019) (Ma et al., 2020)	• EOG (Riquelme et al., 2022) (Oliveira et al., 2018) (Pugliese et al., 2022) (Murugan et al., 2020)

	• Optical Eye Tracker (Oliveira et al., 2018) (Gwak et al., 2020) (Watling et al., 2022) (Naurois et al., 2019) (Arefnezhad et al., 2022) (Varadam & Ganesh, 2021) (Arefnezhad et al., 2020) (Gwak et al., 2018) (Lee et al., 2018)	• EMG ocular eye blink sensor (Caceres et al., 2021)	
Body posture	• Camera (Oliveira et al., 2018) (Riquelme et al., 2022) (Varadam & Ganesh, 2021) (Antunes et al., 2022)		• Body position sensor (Murugan et al., 2020)

(EMG- electromyography; EOG- electrooculography).

Table 6. Variables extracted from studies that describe vehicle performance metrics and its features.

Vehicle performance metrics	**Features**
Vehicle velocity	Speed limit, mean, and standard deviation.
Steering Wheel	Steering angle, steering wheel acceleration.
Acceleration	Harsh, longitudinal, and lateral acceleration; Accelerator pedal angle and depth.
Braking	Harsh braking, break reaction time, brake pedal depth.
Headway	Time and distance headway.
Offset from lane center	Standard deviation of lateral position (SDLP)
Lane crossing	Time and number of lane crossing

3.2.5. Health Status and Lifestyle factors

Regarding health status and lifestyle factors, some studies offer insights into the inclusion criteria established for participant selection. These criteria are related to the participant's health status and personal habits. The health status of individuals was assessed based on the presence or absence of disease. Most studies (n=40) reported that eligible participants were required to have good overall health, without any diseases, and maintain high sleep quality. Concerning subject's lifestyle factors, multiple studies implemented a range of criteria, such as have a valid driver's license (n=37), refrain from sedative or stimulant substances (n=36), maintain a regular sleep schedule (n=17), and not take chronic medication (n=6). Figure 6 summarizes the health status and lifestyle conditions across the included papers.

3.2.6. Special Physiological Framework / Experiment Environment

Several studies included in the review utilized a specialized physiological framework to manipulate physiological responses and establish controlled environments. Within these frameworks, 23 studies focused on inducing driving fatigue, 19 studies incorporated sleep-deprived conditions, 6 studies examined the effects of shift work and 1 study induced distraction. These specialized physiological frameworks are closely related to the experimental environment. Table 7 summarizes the controlled environment in which the studies with special physiologic frameworks were conducted.
Regarding the sleep-deprived framework, aside from the 13 studies that induced drowsiness using low light conditions, an additional 6 studies induced drowsiness by implementing short-term sleep restrictions.

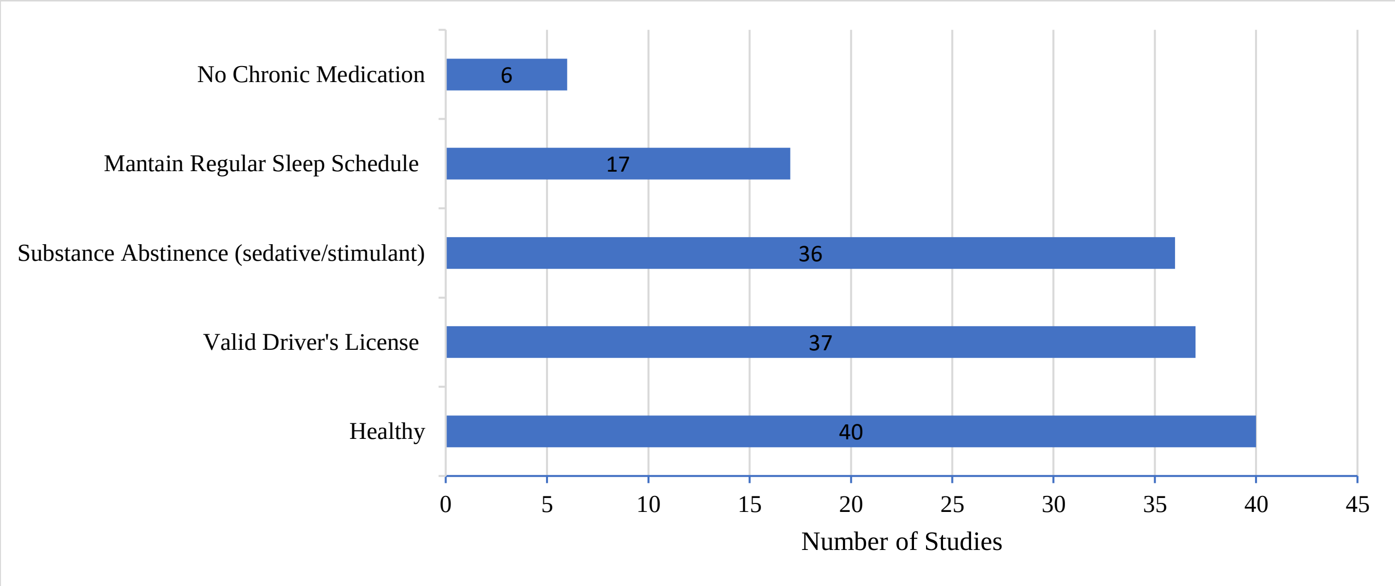

Figure 6. Summary of health status and lifestyle factors across included studies.

Table 7. Summary of Controlled Environments in Studies with Special Physiological Frameworks.

Special Physiological Framework	**Controlled Environment**
Driving Fatigue Induction	Monotonous driving task and Scenario (tedious route, low traffic volume, warm vehicle temperature, low/constant driving speed) (Akiduki et al., 2022) (Ebrahimian et al., 2022) (Lees et al., 2021) (Halomoan et al., 2020) (Wang et al., 2019) (Kundinger et al., 2021) (Kundinger & Riener, 2020) (T. Kundinger et al., 2020) (Zhang et al., 2018) (Kundinger et al., 2020) (Gwak et al., 2020) (Wörle et al., 2019) (Fujiwara et al., 2019) (Zeng et al., 2020) (Balasubramanian & Bhardwaj, 2018) (Bhardwaj et al., 2018) (Naurois et al., 2019) (Sheibani et al., 2022) (Murugan et al., 2020) (Arefnezhad et al., 2020) (Gwak et al., 2018) (Lee et al., 2018) (Antunes et al., 2022)
Sleep Deprivation	Low Luminosity Conditions (early morning, nighttime, simulated night period) (Lecca et al., 2022) (Abtahi et al., 2018) (Lu et al., 2022) (Buendia et al., 2019) (Persson et al., 2021) (Oliveira et al., 2018) (Zhang et al., 2018) (Fujiwara et al., 2019) (Mizusako et al., 2019) (Murugan et al., 2020) (Darzi et al., 2018)
Shift Working	Real World Driving (heavy vehicle, train and metro drivers working shifts) (Lecca et al., 2022) (Kim et al., 2018) (Afghari et al., 2022) (Y. Jiao et al., 2022) (Wolkow et al., 2020) (Huang et al., 2019)
Driving Distraction Induction	Interaction with Mobile Phone (send messages and take calls) (Murugan et al., 2020)

3.2.7. Source of Data

The data source of the included papers is presented in Figure 7. Most studies (n=63) collect new datasets through real or simulated environments. Some studies utilized data from an existing dataset experiment on real or simulated environments (n=4), public databases on real or simulated environments (n=3), and other databases not from real or simulated environments (n=3). There were 3 studies that did not provide clear information about the data source.

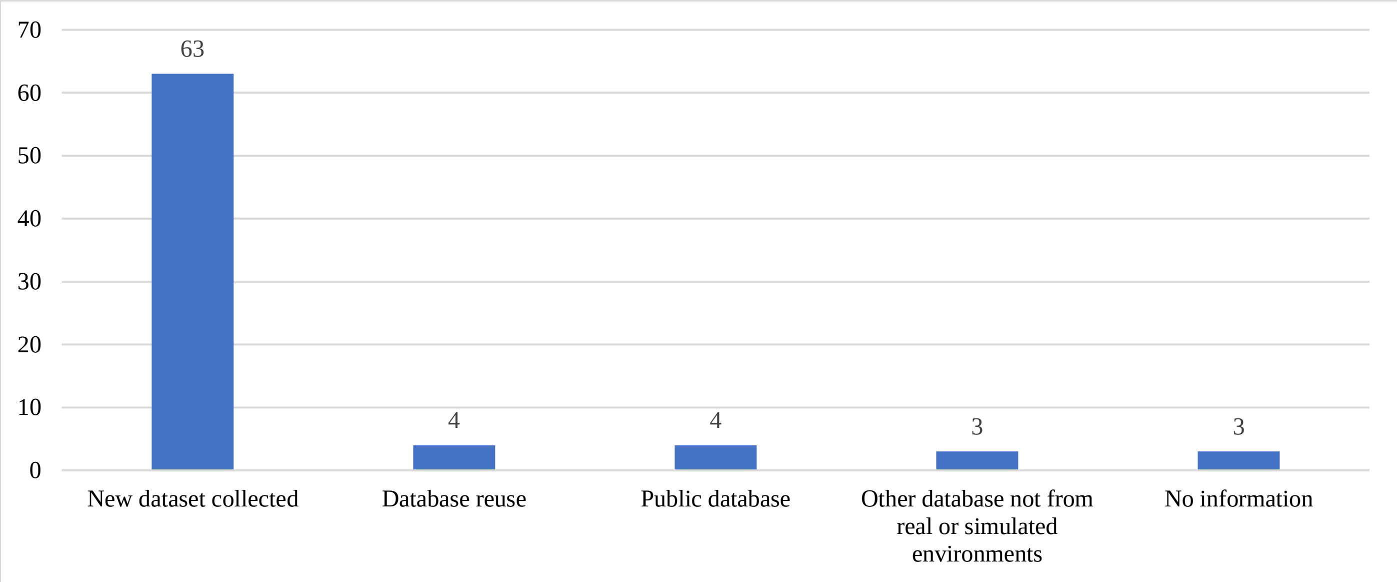

Figure 7. Data sources across included studies.

3.2.8. <u>Extension and Type of Validation; Sample Size; Participants Age and Gender</u>

The extension setup across the included papers is presented in Figure 8. Most studies (56%) employed a simulation environment, either in a realistic driving simulator (19%) or in a driving simulator room (28%). Real-world/naturalist environment was employed by 38% of the studies, and 6% had a setup experiment unclear.

Validation is missing, referred but not reported or only illustrative (sample size below 10 subjects) for 16 (23%) of the included studies. A sample of more than 30 subjects was considered by 20 studies (28%), and only one study included more than 100 subjects (Y. Jiao et al., 2022). Across all studies data from 1075 males and 351 females was reported, with 15 studies not reporting gender. The ages of subjects are mainly reported using range (33 studies) or mean (20 studies), with 12 not reporting the age of the subjects. The maximum mean value reported is 45 years old, while reported age only included subjects over 50 years old in 17 studies. Differences between age groups are analyzed in 5 studies, all with small samples.

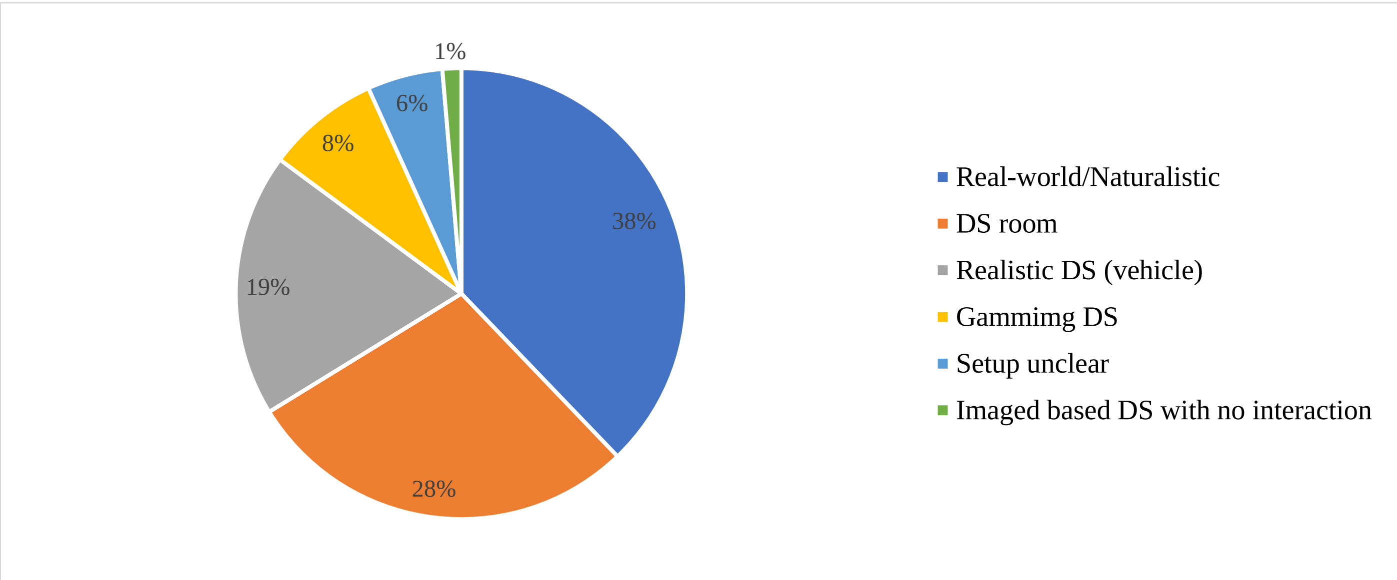

Figure 8. Extension setup across included papers. DS- driving simulator.

3.2.9. Data Processin, Golden Standard; Performance for fatigue detection; TLR of the Technology

The summary of the data processing methods is presented in Figure 9. The majority of the studies (51%) explored one or more machine learning methods, namely Linear and Probabilistic Models, Generative Adversarial Networks Clustering, Ensemble Learning, Instance-Based, Tree-Based and Neural Network-Based Algorithms. Nevertheless, more than 39% only employed descriptive statistics and thresholding approaches.

Monitoring fatigue was an eligibility criteria, thus found in all included papers. Nevertheless, only 13 presented an estimation and/or alert system for fatigue and drowsiness, as described in Table 8.

For 29 studies, no fatigue scale reference to validate the methods was reported. The ground truth for fatigue is summarized in Figure 10 and it was mainly obtained from subjective self-ratings (27 studies) or video-based trained observer ratings (11 studies).

Only 52 (73%) of the studies reported any kind of performance of the proposal, with 13 (18%) comparing two or more methods/models/approaches. Regarding the 13 studies that proposed fatigue and/or drowsiness estimation, only 10 reported validation (Table 8).

Regarding technology readiness levels (TRL), 61 studies were considered to describe effective research and development, with ongoing or to be done laboratory validation, corresponding to TLR levels of 3 - Experimental proof of concept (Project Plan) - or TLR 4 - Technology validated in a lab (development). For 7 studies, there was no proof of concept, following in TLR level 2- Technology concept formulated, while 2 studies evidence validation in a relevant environment - TLR level 5.

3.3. Research Challenges and Limitations

Several limitations were found in the studies included in the review.

Most experiments occur in a simulation environment rather than in realistic or naturalistic settings. Driving simulators can differ from real-world driving conditions in terms of factors like vibration, changes in gravity, and sound. Drowsiness may occur later in simulators, and the vibrations from real-world driving could affect the quality of HR data, leading to different outputs regarding fatigue quantification.

One major issue is the lack of sufficient validation. Very few articles have proper validation, and some do not report validation. The limited sample size of many studies compromises the results' reproducibility and generalization. It also restricts the potential benefits of personalization in fatigue detection systems. Additionally, most study participants were young males, neglecting older age groups and females. This leads to biased participant samples and limits the generalization of the results. In some articles, gender and age are not even considered.

Regarding ground truth, the majority rely on subjective self-reported fatigue ratings (e.g., KSS scale) or video-based observer ratings. The main drawbacks of the KSS scale are that the subjective feeling does not always reflect the actual sleepiness level. Due to the lack of ground truth data, it is challenging to quantify the accuracy of fatigue detection methods precisely.

Only a few articles in the review include fatigue estimation systems. Most of the focus is on detection and recognition systems, contributing to the insufficiency of methods in providing proactive alarm systems for fatigue. Furthermore, most articles measure HR using instrumentalized ECG, which requires contact with electrodes and specific positioning. This approach is less acceptable for drivers as it can be more intrusive during driving tasks. Additional limitations found in the studies include limited knowledge of participants’ health status and personal habits; absence of a non-exposed control group; insufficient description of the physiological states classification (e.g., transition states not evaluated); poor statistics description; and unclear data and testing setting.

These limitations highlight the challenges faced by fatigue and drowsiness detection studies and suggest areas for improvement in future research.

3.4. Quality Assessment of the Included Articles

As explained in section 2, from the 11-point quality assessment, a mean score normalized by 11 (maximum possible) was obtained. The minimum- maximum scores were 18,2% and 90,0%, respectively, with mean (standard deviation) of 64,8% (17,6%). Figure 11 presents the distribution of the quality assessment score.

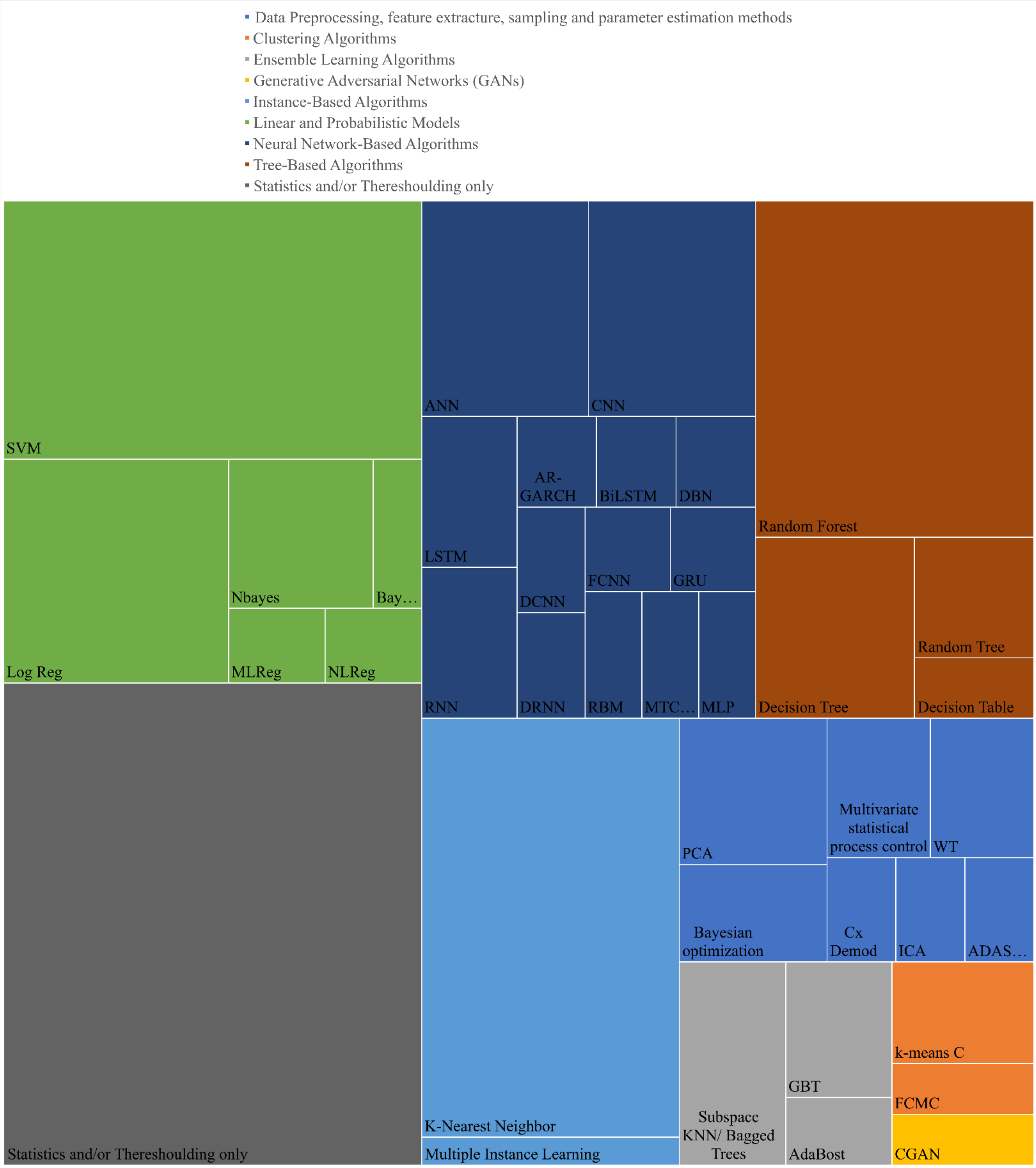

Figure 9. Data processing methods reported. SVM- Support Vetor Machine; LogReg- Logistic Regression; MLReg- Multiple linear Regression; NLReg- Non-linear Regression; Nbayes- Naive Bayes.; BayesN- Bayesian Network; ANN- Artificial Neural Network; CNN- Convolutional Neural Networ; LSTM- Long Short-term Memory; BiLSMT- Bi-directional Long Short-term Memory; DBN- Deep Belief Network; RNN- Recurrent Neural Netwok; DCNN- Deep Convolution Neural Network; FCNN- Fuzzy Convolution Neural Network; GRU- Gated Recurrent Unit; DRNN- Deep Residual Neural Network; RBM- Multi-layer Restricted Boltzmann Machine; MTCNN- Multi-Task Cascade Convolution Neural Network; MLP- Multilayer Perceptron; PCA- Principal Component Analysis; WT- Wavelet Transform; Cx Demond- Complex Demodulation; ICA- Independent Component Analysis; ADASYN- Adaptive Synthetic Sampling Approach; KNN- K-Nearest Neighbors; GBT- Gradient Boosting Tree; AdaBost- Adaptive Boosting; K-meansC- K-means Clustering; FCMC- Fuzzy C-means Clustering; CGAN- Cycle-Generative Adversarial Network.

Table 8. Type of proposals for fatigue and/or drowsiness estimation and reported validation.

Proposal	Reported Validation
Estimation of driving fatigue as continuous value	
(F. Wang et al., 2019)	Fatigue estimation model can describe the driver's fatigue status accurately for all the road segments at the plateau area with altitudes from 3540 to 4767 m.
(Peng et al., 2022)	Not reported.
(Cheng, 2021)	If traffic congestion lasts less than 90s, the drivers' level of fatigue witnesses a linear increase, and the level of fatigue increases as the congestion duration gets longer. A certain fluctuation occurred during 20-40 s followed by a steady increase in the level of fatigue. The results showed that there is a certain relationship between the level of fatigue and the duration of traffic congestion. It can also be seen from the results that the longer the traffic congestion lasts, the higher the driver's level of fatigue is.
Multi-level classification of drowsiness	
(Ebrahimian et al., 2022)	The best performance for both three-level and five-level drowsiness classifications was achieved by the CNN-LSTM model, with 91 and 67% accuracy, respectively.
(Kundinger & Riener, 2020)	High accuracies (>99%) and F-measures (0.99) were achieved in both 2- and 3-level classification. KNN, tree (RF, RT) and rule-based (DT, PART) classifiers were more suitable than Bayesian (BN, NB) or function-based classifiers (SVM) as well as neural networks (MLP).
(Mizusako et al., 2019)	The sleepiness level corresponded 10/12=83,3%, outperforming the conventional estimation (3/12=25%).
(Antunes et al., 2022)	Not reported.
Alerting system for fatigue detection before drowsiness	
(Utomo et al., 2019)	System PERCLOS best using LSTM-based, can achieve a true positive rate of 75% and an accuracy of 88%; HRV best uses BPNN-based, yields a true positive rate and accuracy of 80% and 88% respectively.
(Rahman et al., 2022)	Not reported.
(Abbas, 2020a)	On average, the Fatigue Alert DDF system achieved 93.4% detection accuracy on different real-time driver's online datasets (no HRV). On average, the detection accuracy on a real-time dataset was 93.4%. 130 seconds, 140 seconds and 200 seconds videos recorded during real-time driving conditions on KSA highway roads. Fatigue Alert detection system is outperformed compared to other multi-layer deep-learning methods.
(Caceres et al., 2021)	Effectiveness and accuracy of the device is 80% of 100%; Acceptability test showed that safety has the highest effect on the driver's decision to use the device.
(Varadam & Ganesh, 2021)	Not reported.

(Zhao & Ye, 2018)	Precision rate up to more than 95%.

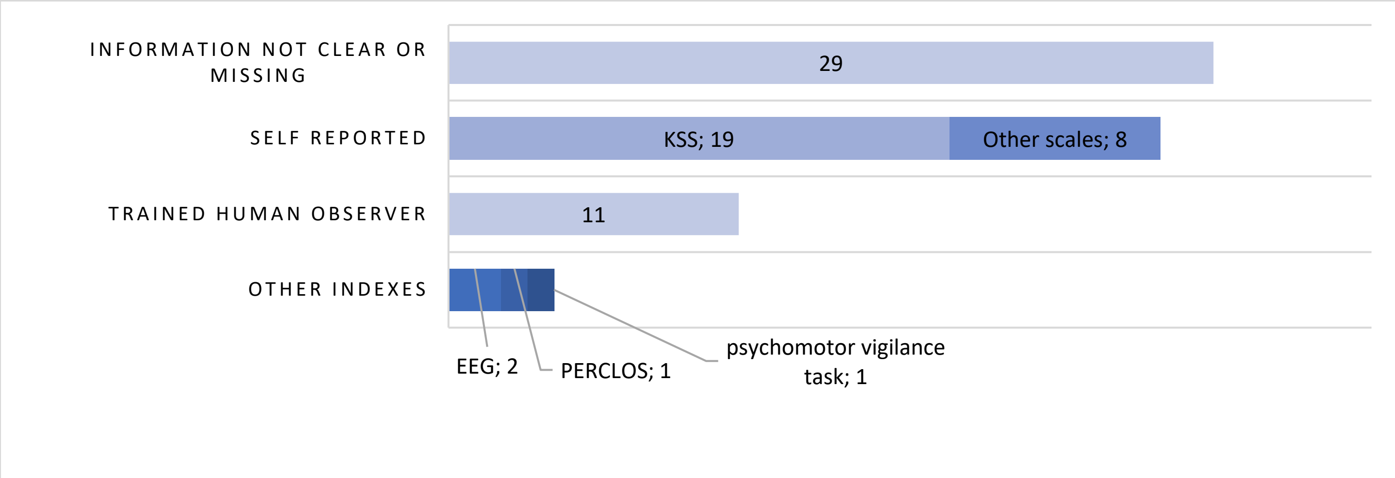

Figure 10. Ground Truth for Fatigue. KSS- Karolinska Sleepiness Scale. EEG- Electroencephalogram. PERCLOS- Percentage of Eye Closure.

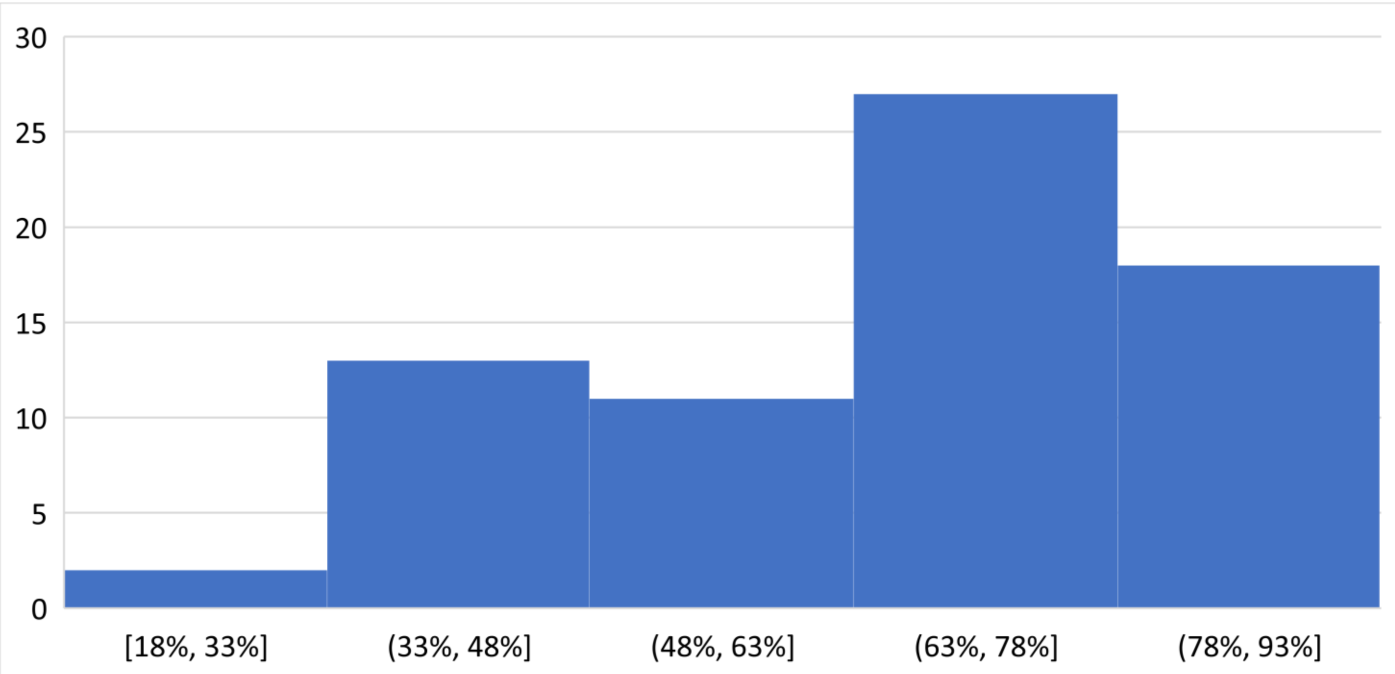

Figure 11. Distribution of the quality assessment score.

4. Discussion

Aside from fatigue, most studies (59%) specifically address drowsiness/sleep monitoring. Fatigue is a complex state that can lead to decreased cognitive and physical performance and reduced alertness, often accompanied by drowsiness (K.L. Lal & Craig, 2001). In this paper, we considered drowsiness as an advanced stage of fatigue that induces a compelling urge to sleep. It is important to acknowledge that discussing drowsiness requires addressing fatigue as a prerequisite. The included studies also considered additional domains such as attention, cognitive workload/mental state, reaction time, stress/relaxation, emotions, comfort, temperature, and acceptability.

The HR and its variability (HRV) features are commonly used for drowsiness and fatigue detection (Vicente et al., 2016). By analyzing the HR and HRV changes, one can assess the autonomic balance of the cardiovascular system, which changes during stress, extreme fatigue, and drowsiness episodes, making it a useful tool in monitoring and assessing drivers' fatigue status.

The most direct method to measure HR is through ECG. ECG signals are widely recognized as the most reliable and stable for real-time HR measurements (Hu et al., 2009). In our study, data collection of HR/HRV across the included publications occurred from 4 different signal measurements. As expected, most of the studies (80%) utilized ECG as the acquired signal. From these, 20% of the studies acquired the ECG signal through wearable technology, mostly chest belt type sensors, biometric Smartshirt, and ECG vest. These data align with findings from (Rachim & Chung, 2016), and (Huang et al., 2018), that also employs HR data acquisition through wearable devices, which has become increasingly convenient in real-world working conditions. Another type of signal collected among the studies reviewed was PPG (n=28%). PPG acquired by wearable wristwatch-type sensors, as considered by 70% of those, use a light source and photodetector as a receiver to measure volumetric changes in blood, which can be used to estimate HR. These devices have been reported to be able to correctly estimate HR (Schuurmans et al., 2020). Nevertheless, accuracy depends on the model and these estimates can be affected by motion artifacts (Friman et al., 2022). On the other hand, camera photoplethysmography has been reported to be affected by skin melanin tone, illumination conditions, subject motion, and compression impacts (Premkumar & Hemanth, 2022).

In addition to HR and HRV features, other physiological parameters can assist in monitoring the driver’s fatigue status. Brain activity is a well-known physiological marker that provides insights into specific patterns and changes of brain’s electrical activity, using EEG readings. Several studies included in this review employed EEG readings to aid in predicting the fatigue state of drivers. According to (Balandong et al., 2018), EEG readings assess brain activity by correlating patterns of brain waves (alpha, beta, theta, and delta waves) with different states of consciousness. (Lees et al., 2021) demonstrate that fatigue often leads to a decrease in higher-frequency waves (such as beta waves) and an increase in lower-frequency waves (such as theta waves), indicating a shift toward a drowsier state.

Besides brain activity, some studies evaluate the breathing patterns and respiratory variability to observe the impact of fatigue on respiratory function. Fatigue often leads to a reduction in respiratory variability, resulting in more regular and consistent breathing patterns. To assess breathing rate, some studies have employed the analysis of chest area expansion and contraction during the breathing process. (Wörle et al., 2019) and (Naurois et al., 2019) utilized a thoracic belt sensor, while (Yuda et al., 2021) employed a smart shirt sensor. In other studies (Ebrahimian et al., 2022), (Darzi et al., 2018) and (Aghajarian et al., 2019), breathing rate was assessed using a thermal camera and a thermistor. These tools measured temperature changes on the body’s surface and airflow during the breathing process.

In the studies (Jing et al., 2020) and (Murugan et al., 2020), oxygen saturation levels (Sp02) were considered as an additional physiological parameter for fatigue detection. By monitoring Sp02 using pulse oximetry, researchers were able to identify fluctuations in oxygen saturation associated with changes in breathing patterns.

In some studies, researchers utilized electrodermal activity (EDA) as a measure to gain insights into changes in sympathetic arousal and infer about the cardiovascular balance (Wörle et al., 2019), (Varadam & Ganesh, 2021), (Magana et al., 2020), (Y. Yang et al., 2021), (Darzi et al., 2018), (Aghajarian et al., 2019).

Additional biomedical monitoring represents extra costs and burdens for the monitoring, with a risk of lower user acceptance. However, it may allow a better fatigue estimation and modelling give rise to a more timed alarm for drowsiness. In this revision, it was not possible to find strong evidence of that, possibly due to the poor validation of most proposals.

Driver’s behavioral-based data and vehicle operational performance-based data were collected by 62% of the studies with most of them (56%) focused on evaluating the driver’s facial expressions through eye movement and yawning episodes detection. To record these data, the studies employed non-intrusive sensors, such as camera sensors with eye tracker technology embedded in the vehicle. Eye trackers require eyes to be visible, open, and unobstructed with glasses, hair or any other object. As other systems based on facial landmarks struggle to differentiate between changes in eye position and head movements relative to the camera (Vijayalaxmi et al., 2020).

Two studies (F. Wang et al., 2019), (Ma et al., 2020) introduced an innovative approach to recording eye movements data using eye tracker glasses, which, according to the authors, revealed to be a practical and acceptable method for measuring this data. Only four studies (Riquelme et al., 2022), (Varadam & Ganesh, 2021), (Antunes et al., 2022), (Murugan et al., 2020) evaluated the body posture of drivers, specifically focusing on nodding behavior and body movements. While this approach could provide insights into the driver's fatigue state, it is important to note that relying solely on these features is insufficient for accurately predicting and estimating fatigue.

Within a subset of studies (n=15), various parameters related to vehicle motion and behavior were collected. These parameters included speed, steering wheel angle, number of lane crossings, harsh braking and acceleration, and the standard deviation of lateral position (SDLP). These metrics were found to be particularly relevant in providing insights into the dynamics of vehicle movements and the driver’s behavior. Nevertheless, they are dependent on previous knowledge about the road, creating practical difficulties. Moreover, these features relate also with driving style, not only with fatigue, which may require further personalization.

Regarding health status and lifestyle factors, most studies (56%n=40) reported healthy participants, without any chronic illnesses that may affect HRV, such as cardiovascular, neurological, respiratory, and sleep disorders; thus the possible advantages in case of consciousness loss related with previous health conditions was not considered. To minimize potential influences on driving behavior, several studies implemented various criteria related to the subjects’ lifestyle. These criteria included refraining from sedative or stimulant substances (50%), such as nicotine, caffeine, alcohol, drugs, or energy drinks, to prevent any impact on psychological indicators and changes in physical condition. Additionally, some studies (24%) required participants to maintain a regular sleep schedule of at least 7 hours per night, to eliminate the effects of sleep restriction on the driving task. As fatigue is very affected by sleep deprivation, its quantification and alarms production will be especially relevant in that context.

A considerable number of studies (32%) focused on inducing driving fatigue by selecting monotonous routes and landscapes with low traffic volume, maintaining a constant and low driving speed, and incorporating warmer temperatures, ensuring that subjects engaged in a monotonous driving task and scenario. Additionally, 27% of the studies incorporated sleep-deprived conditions by controlling the luminosity of the environment and implementing short-term sleep restriction (sleep maximum 4-6h previous night). The potential impact of shift work on alertness and performance was investigated in 6 studies. (Huang et al., 2019) find a significant regression relationship with a mutual incentive effect between workload and fatigue in three shifts of working scenarios. These findings have practical implications and can contribute to the risk for drowsiness alarms in drivers that suffer (or suspect to suffer) from obstructive sleep apnea or other pathology affecting sleep quality and to promote the development of reasonable schedules to ensure operational safety in shift work.

Regarding ground truth, it was observed that 41% of the studies did not report the use of a fatigue scale reference for validating their methods. The ground truth for fatigue was predominantly obtained through subjective self-ratings (66% of those reporting a reference fatigue scale), where participants provided their own assessments of their fatigue levels with the use of KSS and other scales. The main drawbacks of the KSS scale are that the subjective feeling does not always reflect the actual sleepiness level. Ratings from trained observers who assessed fatigue levels based on video recordings were considered by 27% (out of the 41%). Due to the lack of ground truth data, it is challenging to precisely quantify the accuracy of fatigue detection methods.

Understanding the data sources is crucial in evaluating the reliability and generalizability of the findings presented in the studies. Most studies (89%) collect new dataset through real or simulated environments. This approach allows for a more accurate assessment of human behavior, performance, and physiological responses in a controlled yet realistic setting. The data collected in such environments provide valuable insights into the specific context being studied, enhancing the validity and applicability of the findings to real-world situations.

The distribution of extension setups gives insights on the varied approaches adopted by researchers and enables a comprehensive evaluation of the study findings. Most studies (56%) reviewed favored a simulation environment, with 19% specifically employing a realistic driving simulator. Alternatively, 38% of the studies opted for naturalistic environments, reflecting a closer approximation of real-world conditions. This approach ensures that the findings are more applicable and generalizable to real-life situations. Nevertheless, regarding sample size, validation is clearly insufficient for most of the included studies, with 23%, 28%, and 1% having sample sizes below 10 subjects, more than 30 subjects, and more than 100 subjects, respectively. The majority of the studies lack experiments involving females and older age groups, predominantly relying on young male participants. This can contribute to a biased participant sample and limit the generalizability of the results. (Zeng et al., 2020) emphasizes the significance of considering sex differences when examining the influence of fatigue on autonomic nervous system activity in drivers.

Most of the studies (51%) in this review explore the application of various machine learning methods, highlighting the increasing interest in employing such approaches for the analysis and interpretation of driver-related physiological data. However, it is important to acknowledge that a substantial portion (more than 39%) of the studies relied solely on descriptive statistics and thresholding approaches, which may limit the depth of analysis and potential insights that could be derived from the data.

Although monitoring fatigue was a requirement in all the included papers, only 13 (18%) of them presented an estimation and/or alert system for fatigue and drowsiness. (Ebrahimian et al., 2022) introduced a 3-level and 5-level classification of drowsiness, achieving an accuracy rate of 91% and 67%, respectively, over 30 male subjects. Similarly, in (Kundinger & Riener, 2020) a 2 or 3 level classification of drowsiness was proposed, achieving high accuracies (>99%) and an F-measure of 0.99 for both classifications, over 30 subjects, considering 2 age groups. The study found that classifiers such as KNN, random forest (RF), decision tree (DT), and rule-based (PART) performed better compared to Bayesian (BN, NB) or function-based classifiers. Furthermore, an alerting system for fatigue detection was introduced in (Caceres et al., 2021), (Abbas, 2020a) and revealed an overall device effectiveness and accuracy of 80% and 93.4%, respectively, but data sets were two small (10 and 4 subjects) to allow strong conclusions. These results show the potential for high-accuracy applicability of this type of system detection, but still to be demonstrated in more complete validation protocols.

The quality assessment resulted in only 25% of the included papers scoring above 75%. This expresses mainly the lack of clear description of methods, data and validation and the insufficiency of the latter.

The main limitations identified in the included studies can be summarized in seven points:

- Simulation environments used instead of real-world settings, affecting the accuracy of fatigue quantification.
- Lack of proper validation and limited sample sizes compromising reproducibility and generalizability of the results.
- Bias towards young male participants, neglecting older age groups and females.
- Reliance on subjective self-reporting and video-based observer ratings as ground truth, which makes it challenging to precisely quantify the accuracy of fatigue detection methods.
- Insufficiency of fatigue estimation systems and focus on detection rather than proactive alarm systems.
- Use of intrusive instrumentalized electrocardiography (ECG) for measuring heart rate rather than non-intrusive measurements.
- Unclear classification testing settings, data analysis and statistical description.

These limitations also reflect the low technology readiness levels (TRL) predominant with only 2 studies evidencing validation in relevant environments - TLR level 5 - and none above.

Regarding main contributions, most studies highlight the potential of continuously monitoring the driver's physiological status, specifically by analyzing HRV to assess the balance of ANS. This could be promising for detecting driver fatigue and preventing accidents. One main contribution is the introduction to advantageous hybrid approaches to monitor the driver's physiological signals and detect fatigue. These approaches integrate visual features, non-intrusive ECG signal acquisition, and vehicle-based data. Multiple studies investigate the feasibility and applicability of wrist-worn wearable devices as a convenient and effective tool for monitoring and detecting driver fatigue.

Finally, certain studies demonstrate the possibility of developing a fatigue driving pre-warning system that effectively distinguishes fatigue and provides timely alerts to the driver. Such systems could play a crucial role in driver safety and mitigating the risk of accidents.

5. Conclusion

ECG is an effective tool for assessing driver’s HR and HRV, enabling the evaluation of the autonomic balance in the cardiovascular system. By analyzing the LF/HF power ratio in HRV, we can gain insights into the driver's state of arousal and determine their fatigue and drowsiness status. ECG can be acquired non-intrusively, using wearable and in vehicle sensors, to accurately assess the HR of the drivers. This innovative technology represents a significant advancement, as it becomes more user-friendly, enhances its acceptability and practicality for users, and facilitates its implementation in motor vehicle industries. Moreover, other technologies such as PPG were also used for HR estimation. Both HR from ECG and from other sources seem to be reliable. Nevertheless, HR by itself may not be enough to allow precise fatigue estimation and can generate false alarms. Further research, in particular fully validation protocols are needed to determine the full value of HR for fatigue quantification and drowsiness detection, by itself or combined with additional information.

Fundings: This work was supported by the Project BBAI- Brain Behavior analysis using the most advanced Artificial Intelligence and Computer Vision (ref: NORTE-01-0247-FEDER-069809), Agência Nacional de Inovação S.A., P2020 | COMPETE - Projetos em Copromoção

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Appendices

Appendix 1 – Reporting guidelines (PRISMA statement- Preferred reporting items for systematic reviews and meta-analysis)

Section/topic	#	Checklist item	Reported on page and paragraph/ table #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both. **- MANDATÓRIO**	Page 5
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number. **– SEGUIR RECOMENDAÇÕES DA REVISTA**	Page 5, (paragraph 1)
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. **– MANDATÓRIO** ***O rationale corresponde à justificação da importância da revisão sistemática***	Page 6 (paragraph 1-2) Page 7 (paragraph 1)
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS). **- MANDATÓRIO**	Page 7 (paragraph 3)
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number. **– FACULTATIVO**	
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale. **– MANDATÓRIO** ***É altamente recomendado, de acordo com as boas práticas da Cochrane, que não sejam aplicados critérios de exclusão baseados na língua e/ou data de publicação dos estudos.***	Page 8 (paragraph 2)

Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched. **– MANDATÓRIO** ***Em consonância com as boas práticas da Cochrane, é mandatório que se verifique pesquisa em pelo menos duas bases de pesquisa bibliográfica (idealmente, deverão ser pesquisadas duas bases generalistas e uma específica da área). No caso de revisões sistemáticas de estudos experimentais/ensaios clínicos aleatorizados, é altamente recomendado que uma das bases pesquisadas corresponda à CENTRAL ou a bases de ensaios clínicos como a ClinicalTrials.gov.*** ***Estudos de revisão da literatura em que a pesquisa decorra numa única base de dados não serão classificados como revisões sistemáticas.***	Page 7 (paragraph 9)
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated. **– MANDATÓRIO** ***A query de pesquisa deve ser obrigatoriamente disponibilizada. A utilização de filtros de pesquisa da InterTASC é altamente recomendada (https://sites.google.com/a/york.ac.uk/issg-search-filters-resource/home)***	Page 7 (paragraph 10) Page 8 (paragraph 1)
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis). **– MANDATÓRIO** ***As fases de selecção dos estudos primários devem ser descritas. Em consonância com as boas práticas da Cochrane, é mandatório que o processo de selecção envolva duas fases (fase de rastreio, em que os registos são seleccionados por título e abstract, e fase de inclusão, na qual se procede à leitura integral dos full texts). Em cada uma destas fases, o processo de selecção deve mandatoriamente envolver dois investigadores actuando de forma independente.***	Page 8 (paragraph 3-4)
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators. **– MANDATÓRIO** ***Trata-se de descrever de que forma se procedeu à extracção de dados dos estudos primários. Em consonância com as boas práticas da Cochrane, tal processo deverá envolver dois investigadores de forma independente.***	Page 8 (paragraph 8)
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made. **– MANDATÓRIO** ***Trata-se de descrever as variáveis para as quais foi obtida informação.***	Page 8 (paragraph 8) Page 9 (Table 2)
Risk of bias in individual studies / Risk of bias across studies	12/ 15	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis. **– MANDATÓRIO**	Page 8 (paragraph 9)

		Em todas as revisões sistemáticas, deverá existir um processo de avaliação da qualidade dos estudos primários. No caso de revisões sistemáticas de estudos experimentais/ensaios clínicos aleatorizados, a aplicação dos critérios de risco de viés (Risk of Bias) da Cochrane é altamente recomendada. No caso de revisões sistemáticas de estudos observacionais, poderão ser seguidos os critérios ROBINS ou os critérios dos National Institutes of Health (https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools).	Page 9 (Table 3)
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means). **– FACULTATIVO. APENAS NECESSÁRIO SE FOR FEITA META-ANÁLISE**	NA
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis. **– FACULTATIVO. APENAS NECESSÁRIO SE FOR FEITA META-ANÁLISE**	NA
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified. **– FACULTATIVO. APLICÁVEL APENAS SE FOR FEITA META-ANÁLISE**	NA
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram. **– MANDATÓRIO**	Page 10 (paragraph 1)
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations. **– MANDATÓRIO**	Page 10-21 (Figure 2-11) (Table 4-8)
Risk of bias within and across studies	19/ 22	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12). **– MANDATÓRIO**	Page 18 (paragraph 8-20) Page 21 (Figure 11)
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot. **– FACULTATIVO. APLICÁVEL APENAS SE FOR FEITA META-ANÁLISE**	NA
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency. **– FACULTATIVO. MANDATÓRIO APENAS SE FOR FEITA META-ANÁLISE**	NA
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]). **– FACULTATIVO. APLICÁVEL APENAS SE FOR FEITA META-ANÁLISE**	NA
DISCUSSION			

Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers). **– MANDATÓRIO**	Page 21-24
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias). **– MANDATÓRIO**	Page 24 (paragraph 4-5)
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research. **– MANDATÓRIO**	Page 24/25 (paragraph 8)
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review. **– SEGUIR RECOMENDAÇÕES DA REVISTA**	Page 25 (paragraph 1)

From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit: **www.prisma-statement.org**.

Appendix 2- Transcription regarding each item of PRISMA 2009 checklist

Item 1: Title (Page 5):

"Monitoring fatigue and drowsiness in motor vehicle occupants using electrocardiogram and heart rate - A systematic review."

Item 2: Abstract (Page 5, paragraph 1)

"Background: Fatigue is a complex state that can result in decreased alertness, often accompanied by drowsiness. Driving fatigue has become a significant contributor to traffic accidents globally, highlighting the need for effective monitoring techniques. Various technologies exist to enhance driver safety and minimize accident risks, such as fatigue detection systems that alert drivers as drowsiness sets in. In particular, measuring heart rate (HR) patterns may offer valuable insights into the occupant's physiological condition and level of alertness and may allow them to understand their fatigue levels. This review aims to establish the current state of the art of monitoring strategies for vehicle occupants, specifically focusing on fatigue assessed by HR and heart rate variability (HRV).

Methods: We performed a systematic literature search in the databases of Web of Science, SCOPUS and PubMed, using the terms vehicle, driver, physiologic monitoring, fatigue, sleep, electrocardiogram, heart rate and heart rate variability. We examine articles published between the 1st of January 2018 and the 31st of January 2023.

Results: A total of 294 papers were identified from which 71 articles were included in this study. Among the included papers, 57 utilized electrocardiogram (ECG) as the acquired signal for HR measures, with most ECG readings obtained through contact sensors (n=41), followed by non-intrusive wearable sensors (n=11). The majority of the works rely on subjective self-reported fatigue ratings (n=27) and video-based observer ratings (n=11). Regarding validation, 16 papers do not report validation of any kind. From the included papers, only 13 comprise a fatigue and drowsiness estimation system, 9 with reported validation. Some report acceptable performances, but reduced sample size limits the reach of any conclusions.

Conclusions: This review highlights the potential of HR analysis and non-intrusive instrumentation for continuous monitoring of driver's status and detecting sleepiness. One major issue is the lack of sufficient validation and estimation methods for fatigue, contributing to insufficient methods in providing proactive alarm systems. This area shows great promise but is still far from being reliably implemented."

Item 3: <u>Introduction: Rationale </u>(Page 6, paragraph 1-2; Page 7, paragraph 1)

Throughout the introduction it was explained the rationale of this study. More specifically, we focused on describing the fatigue state which can be stated in page 2 (paragraph 1): “Fatigue is a complex state that can result in decreased mental and physical performance and reduced alertness, often accompanied by drowsiness (K.L. Lal & Craig, 2001) which is feeling the need to sleep.” And in page 2 (paragraph 2): “Fatigue can cause a driver’s attention to decrease, leading to distraction and potentially dangerous driving behaviors, such as speeding, running a red light, and getting out of track (Utomo et al., 2019).”. Then, we approached the importance of detection methods for fatigue in driving context, which can be stated in page 2 (paragraph 2): “(…) Therefore, it is crucial to investigate fatigue detection methods to prevent accidents and promote safe driving practices. This could be particularly important for workers with irregular shift schedules (such as health workers and professional drivers) or anyone who drives on monotonous routes, and for long periods, which may even lead to drowsiness (Harma et al., 2002).”. Then, we approached the role of heart rate and heart rate variability in estimation systems for fatigue and drowsiness, which can be stated in page 3 (paragraph 1): “The HR, is the number of heartbeats in a minute, and the heart rate variability (HRV), consists on the sequence of the time difference between consecutive heartbeats (R to R Intervals, RRI), physiologically regulated by the sympathetic nervous system (ANS) and the parasympathetic nervous system (PNS) from the autonomic nervous system (ANS) (Jiao et al., 2022) (Garcia-Perez et al., 2023). The HRV features are commonly used for drowsiness and fatigue detection as ANS balance changes during stress, extreme fatigue, and drowsiness episodes (Vicente et al., 2016). (…) An important parameter to analyze in HRV is the LF/HF power ratio, which provides insights into the sympathovagal balance and offers a comprehensive assessment of driving fatigue (Patel et al., 2011). Measuring HR from drivers is essential in understanding their fatigue levels.”

Item 4: <u>Introduction: Objectives </u>(Page 7, paragraph 3)

“This review targets motor vehicle occupants (P-population) on a journey, or simulated journey, in a vehicle or simulator while collecting ECG and or HR (I – Intervention or exposure), aiming fatigue monitoring (O – Outcome). Comparisons, namely as validation facing a fatigue reference values, are desirable, but not mandatory, as no golden standard exists. All study designs are admitted.”

Item 5: Methods: Protocols and Registration

Protocol with the registration number PROSPERO 2023 CRD42023400655. Web address:https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42023400655

Item 6: Methods: Eligibility criteria (Page 8, paragraph 2)

"Only studies written in English were considered. Considering both screening and full-text analysis phases, documents were included if they (1) monitor physiological signals during a journey or simulated journey in a vehicle or simulator; (2) monitor fatigue (or equivalently drowsiness or sleepiness) using ECG, HR, HRV or derived indexes; (3) and published between 2018-2023. Exclusion criteria include non-English publications, articles with no abstract available, letters, editorials, comments, abstract only publications, and reviews. An additional exclusion criterion was considered in the full-text analysis: no full text available and studies without implementation (idea only)."

Item 7: Methods: Information Sources (Page 7, paragraph 9)

"We performed a literature search in the databases of Web of Science, SCOPUS, and PubMed until 03rd of February. We examine articles published between 1st of January 2018 and 31st of January 2023, in order to investigate the state of the art of vehicle occupants monitoring strategies regarding fatigue (or equivalently drowsiness or sleepiness), using ECG, HR and HRV readings."

Item 8: Methods: Search (Page 7, paragraph 10; Page 8, paragraph 1)

"To improve query relevance, the search queries were formulated considering the terms in titles, abstracts, keywords, author-keywords, and keywords plus. Queries fundamentally included terms to identify the intended system, referencing vehicle, driver, and physiologic monitoring, among other relevant reference words to find articles of interest and adding terms to specify the search, fatigue, sleep, electrocardiogram, heart rate and heart rate variability." And "After refining the query and performing sensitivity analysis, the final queries are reported in Table 1. The queries needed to be adjusted based on the specific database being used. For instance, PubMed is the only database that provides the option of using MeSH terms."

Item 9: Methods: Study selection (Page 8, paragraph 3-4)

“Screening analysis phase, which involved reviewing titles and abstracts, was performed by two independent reviewers, with the help of a software system, Rayyan, for recording decisions. The two reviewers screened records independently with Blind On. Disagreements were resolved through consensus between the two reviewers.

Full-text analysis phase was performed by four independent reviewers, forming all six possible combinations of pairs, following the strategy:

- the list of retrieved publications was divided into six batches with an equivalent number of publications;
- each batch was assessed by two different reviewers, that performed the data extraction;
- final data were reviewed in a consensus meeting.”

Item 10: Methods: Data collection process (Page 8, paragraph 8)

“Data extraction was part of the full-text analysis phase. The two researchers’ extraction occurred independently, followed by the consensus meeting.”

Item 11: Methods: Data items (Page 8, paragraphs 8; Page 9, Table 2)

“The information structure extracted from publications is reported in Table 2.”. And “Table 2. List of variables considered for data extraction.”

Item 12/15: Methods: Risk of bias in individual studies / Risk of bias across studies (Page 8, paragraph 9; Page 9, Table 3)

“This review focuses on a health-related problem that requires software engineering development and studies. Usual quality instruments and assessment checklists for medical studies are inadequate. Alternative quality assessment instruments specific to software engineering studies have been proposed. The most frequently adopted for systematic reviews, according to (L. Yang et al., 2021), is the 11 criteria checklist by Dybå and Dingsøyr’s (Dybå & Dingsøyr, 2008). Each criteria is evaluated as 1- “yes” or 0 - “no”). These criteria are presented in Table 3. To better adapt to the current review, the criteria 6, was enlarged also to consider comparison with reference, as listed in PRISMA. Those were considered in this review as part of eligibility criteria, information extraction or specific quality analysis by two reviewers. Attending for subjectivity, for each included study, the mean of the two independent scores normalized by the maximum of the scale is considered as a quality assessment.”. And “Table 3.

Quality assessment criteria, Changes with respect to **Dybå and Dingsøyr marked as Italic.**""

Item 13: Methods: Summary measures (NA)

Non-Applicable, since no meta-analysis was performed.

Item 14: Methods: Synthesis of Results (NA)

Non-Applicable, since no meta-analysis was performed.

Item 16: Methods: Additional analysis (NA)

Non-Applicable, since no meta-analysis was performed.

Item 17: Results: Study selection (Page 10, paragraph 1)

"The PRISMA flow diagram model demonstrates the detailed study selection process, as shown in Figure 1. After applying the final query to the three databases, a total of 371 documents were retrieved, which was reduced to 294 publications after eliminating the duplicates found (n=77 duplicates). In the title and abstract screening phase, a total of 194 studies did not meet our inclusion criteria and were excluded. A total of 71 articles were finally included and analyzed."

Item 18: Results: Study characteristics (Page 10-21, Figure 2-11, Table 4-8)

Results from the extracted data are presented through the result section, as follows:

Additional Domains - [Page 10, paragraph 4; Page 12, Figure 3] "Regarding the domains, in addition to fatigue, 42 out of the 71 studies refer explicitly to Drowsiness/Sleep, while 15 included one or more additional domains, as represented in Figure 3."

Sensors and Devices for ECG and HR/HRV - [Page 10, paragraph 5-7; Page 12, paragraph 1; Page 13, Figure 4] "(…) Regarding the assessment of the primary physiological parameter, HR/HRV, four different signal acquired measurements were reported. Most of the publications (n=57) utilized ECG as the acquired signal, followed by photoplethysmography (PPG) (n=20). Some publications (n=7) used both ECG and PPG to obtain HR. Another way to assess HR was through radar-based signal acquisition (n=1), a non-contacting detection of heartbeat signals. Similarly to the auscultation method, one paper used an acoustic pulse signal (n=1) to obtain HR.”. “(…) Figure 4 summarizes the type of sensor used per signal acquired measurements for HR/HRV access across the included publications.”. “For ECG readings, most studies utilized instrumentalized sensors with electrodes positioned in the body (n=41). Some of the studies utilized non-intrusive methods of acquiring ECG signals, such as wearable sensors (n=11) and vehicle sensors (n=6). Among the wearable ECG sensors, the chest belt type sensors were the most utilized across multiple studies. (…) Additionally, one study (Yuda et al., 2021) employed a Biometric Smart Shirt (…) while other study (Huang et al., 2019) used an ECG vest. Amid vehicle ECG sensors, 4 studies (…) employed ECG sensors attached to the steering wheel, while 2 (…) utilized ECG sensors installed on the car seat.”. “The wearable type of sensor is predominantly utilized for PPG readings (n=17). Among these, 14 studies utilized wristwatch-type sensors (…) For acoustic pulse signal acquisition, 1 study (Salvati et al., 2021) employed a microsensor inserted into the seat vehicle, and for radar-based signal acquisition, 1 study (Dong et al., 2021) utilized a millimeter wave radar embedded in the vehicle.”

Additional Physiological Parameters - [Page 12, paragraph 1; Page 13, Table 4] “Additional physiological parameters were collected by 23 studies, namely brain activity, respiratory rate, Peripheral Capillary Oxygen Saturation (SpO2) and Skin Conductivity. Table 4 summarizes the acquired signals by the different studies for each targeted biomedical parameter.”

Additional Activities - [Page 14, paragraph 1-3 ; Page 14 Figure 5, Table 5; Page 15, Table 6] “Additional data monitored were collected by 44 studies, namely driver’s behavioral-based data and vehicle operational performance-based data, as shown in figure 5. Regarding driver’s behavioral-based data, studies have focused on facial expressions parameters and body posture (…) For recording these data several sensors were used, specifically a camera with a video recording of driver’s face, eye tracker technology, electrooculography (EOG), electromyography (EMG) and body position sensor. Table 5 summarizes the sensor variant employed for capturing behavioral-based data. Regarding vehicle operational performance-based parameters, Table 6 represents the different variables extracted from the papers that describe the motion and behavior of a vehicle.”

Health Status and Lifestyle factors - [Page 15, paragraph 1; Page 16, Figure 6] “Regarding health status and lifestyle factors (…) Most studies (n=40) reported that eligible participants were required to have good overall health, without any diseases, and maintain high sleep quality. Concerning subject’s lifestyle factors, multiple studies implemented a range of criteria, such as have a valid driver's license (n=37), refrain from sedative or stimulant substances (n=36), maintain a regular sleep schedule (n=17), and not take chronic medication (n=6). Figure 6 summarizes the health status and lifestyle conditions across the included papers.”

Special Physiological Framework / Experiment Environment - [Page 15, paragraph 2; Page 16, Table 7] “Several studies included in the review utilized a specialized physiological framework (…) Within these frameworks, 23 studies focused on inducing driving fatigue, 19 studies incorporated sleep-deprived conditions, 6 studies examined the effects of shift work and 1 study induced distraction. (…) Table 7 summarizes the controlled environment in which the studies with special physiologic frameworks were conducted.”

Source of Data - [Page 16, paragraph 1; Page 17, Figure 7] “The data source of the included papers is presented in Figure 7. Most studies (n=63) collect new datasets through real or simulated environments. Some studies utilized data from an existing dataset experiment on real or simulated environments (n=4), public databases on real or simulated environments (n=3), and other databases not from real or simulated environments (n=3). There were 3 studies that did not provide clear information about the data source.”

Extension and Type of Validation; Sample Size; Participants Age and Gender - [Page 17, paragraph 1-2; Page 17, Figure 8] “The extension setup across the included papers is presented in Figure 8. Most studies (56%) employed a simulation environment, either in a realistic driving simulator (19%) or in a driving simulator room (28%). Real-world/naturalist environment was employed by 38% of the studies, and 6% had a setup experiment unclear. Validation is missing, referred but not reported or only illustrative (sample size below 10 subjects) for 16 (23%) of the included studies. A sample of more than 30 subjects was considered by 20 studies (28%), and only one study included more than 100 subjects (Y. Jiao et al., 2022). Across all studies data from 1075 males and 351 females was reported, with 15 studies not reporting gender. The ages of subjects are mainly reported using range (33 studies) or mean (20 studies), with 12 not reporting the age of the subjects. The maximum mean value reported is 45 years old, while reported age only included subjects over 50 years old in 17 studies. Differences between age groups are analyzed in 5 studies, all with small samples.”

Data Processin, Golden Standard; Performance for fatigue detection; TLR of the Technology - [Page 18, paragraph 1-5; Page 19, Figure 9; Page 20, Table 8; Page 21, Figure 10] “The summary of the data processing methods is presented in Figure 9. The majority of the studies (51%) explored one or more machine learning methods (…). Nevertheless, more than 39% only employed descriptive statistics and thresholding approaches. Monitoring fatigue was an eligibility criteria, thus found in all included papers. Nevertheless, only 13 presented an estimation and/or alert system for fatigue and drowsiness, as described in Table 8. For 29 studies, no fatigue scale reference to validate the methods was reported. The ground truth for fatigue is summarized in Figure 10 and it was mainly obtained from subjective self-ratings (27 studies) or video-based trained observer ratings (11 studies). Only 52 (73%) of the studies reported any kind of performance of the proposal, with 13 (18%) comparing two or more methods/models/approaches. Regarding the 13 studies that proposed fatigue and/or drowsiness estimation, only 10 reported validation (Table 8). Regarding technology readiness levels (TRL), 61 studies were considered to describe effective research and development, with ongoing or to be done laboratory validation, corresponding to TLR levels of 3 - Experimental proof of concept (Project Plan) - or TLR 4 - Technology validated in a lab (development). For 7 studies, there was no proof of concept, following in TLR level 2- Technology concept formulated, while 2 studies evidence validation in a relevant environment - TLR level 5.”

Item 19/22: Results: Risk of bias within and across studies (Page 18, paragraph 8-10; 12; Page 21,Figure 11)

"One major issue is the lack of sufficient validation. Very few articles have proper validation, and some do not report validation. The limited sample size of many studies compromises the results' reproducibility and generalization. It also restricts the potential benefits of personalization in fatigue detection systems. Additionally, most study participants were young males, neglecting older age groups and females. This leads to biased participant samples and limits the generalization of the results. In some articles, gender and age are not even considered. Regarding ground truth, the majority rely on subjective self-reported fatigue ratings (e.g., KSS scale) or video-based observer ratings. The main drawbacks of the KSS scale are that the subjective feeling does not always reflect the actual sleepiness level. Due to the lack of ground truth data, it is challenging to quantify the accuracy of fatigue detection methods precisely. (…) Additional limitations found in the studies include limited knowledge of participants' health status and personal habits; absence of a non-exposed control group; insufficient description of the physiological states classification (e.g., transition states not evaluated); poor statistics description; and unclear data and testing setting." As explained in section 2, from the 11-point quality assessment a mean score normalized by 11 (maximum possible) was obtained. The minimum- maximum scores were, respectively, 18,2% and 90,0%, with mean (standard deviation) of 64,8% (17,6%). In Figure 11 is presented the distribution of the quality assessment score."

Item 20: Results: Results of individual studies (NA)

Non-Applicable, since no meta-analysis was performed.

Item 21: Results: Synthesis of results (NA)

Non-Applicable, since no meta-analysis was performed.

Item 23: Results: Additional analysis (NA)

Non-Applicable, since no meta-analysis was performed.

Item 24: Discussion: Summary of evidence (Page 21-24)

This item is fulfilled throughout the discussion sections. Here are some examples: "The most direct method to measure HR is through ECG. ECG signals are widely recognized as the most reliable and stable for real-time HR measurements (Hu et al., 2009). (…) As expected, most of the studies (80%) utilized ECG as the acquired signal. From these, 20% of the studies acquired the ECG signal through wearable technology (…) PPG acquired by wearable wristwatch-type sensors, as considered by 70% of those (…) These devices have been reported to be able to correctly estimate HR (Schuurmans et al., 2020)."

"(…) Several studies included in this review employed EEG readings to aid in predicting the fatigue state of drivers. Besides brain activity, some studies evaluate the breathing patterns and respiratory variability to observe the impact of fatigue on respiratory function. In the studies (Jing et al., 2020) and (Murugan et al., 2020), oxygen saturation levels (Sp02) were considered as an additional physiological parameter for fatigue detection. In some studies, researchers utilized electrodermal activity (EDA) as a measure to gain insights into changes in sympathetic arousal and infer about the cardiovascular balance. Additional biomedical monitoring represents extra costs and burdens for the monitoring, with a risk of lower user acceptance. However, it may allow a better fatigue estimation and modelling give rise to a more timed alarm for drowsiness. In this revision, it was not possible to find strong evidence of that, possibly due to the poor validation of most proposals."

" Driver's behavioral-based data and vehicle operational performance-based data were collected by 62% of the studies with most of them (56%) focused on evaluating the driver's facial expressions through eye movement and yawning episodes detection. To record these data, the studies employed non-intrusive sensors, such as camera sensors with eye tracker technology embedded in the vehicle. Eye trackers require eyes to be visible, open, and unobstructed with glasses, hair or any other object. As other systems based on facial landmarks struggle to differentiate between changes in eye position and head movements relative to the camera (Vijayalaxmi et al., 2020)"

"Understanding the data sources is crucial in evaluating the reliability and generalizability of the findings presented in the studies. Most studies (89%) collect new dataset through real or simulated environments. This approach allows for a more accurate assessment of human behavior, performance, and physiological responses in a controlled yet realistic setting. The data collected in such environments provide valuable insights into the specific context being studied, enhancing the validity and applicability of the findings to real-world situations."

"Although monitoring fatigue was a requirement in all the included papers, only 13 (18%) of them presented an estimation and/or alert system for fatigue and drowsiness. (Ebrahimian et al., 2022) introduced a 3-level and 5-level classification of drowsiness, achieving an accuracy rate of 91% and 67%, respectively, over 30 male subjects. Similarly, in (Kundinger & Riener, 2020) a 2 or 3 level classification of drowsiness was proposed, achieving high accuracies (>99%) and an F-measure of 0.99 for both classifications, over 30 subjects, considering 2 age groups. (…) Furthermore, an alerting system for fatigue detection was introduced in (Caceres et al., 2021), (Abbas, 2020a) and revealed an overall device effectiveness and accuracy of 80% and 93.4%, respectively, but data sets were two small (10 and 4 subjects) to allow strong conclusions. These results show the potential for high-accuracy applicability of this type of system detection, but still to be demonstrated in more complete validation protocols."

"The quality assessment resulted in only 25% of the included papers scoring above 75%. This expresses mainly the lack of clear description of methods, data and validation and the insufficiency of the latter."

Item 25: Discussion: Limitations (Page 24, paragraph 4-5)

"The main limitations identified in the included studies can be summarized in seven points:

- Simulation environments used instead of real-world settings, affecting the accuracy of fatigue quantification.
- Lack of proper validation and limited sample sizes compromising reproducibility and generalizability of the results.
- Bias towards young male participants, neglecting older age groups and females.
- Reliance on subjective self-reporting and video-based observer ratings as ground truth, which makes it challenging to precisely quantify the accuracy of fatigue detection methods.
- Insufficiency of fatigue estimation systems and focus on detection rather than proactive alarm systems.
- Use of intrusive instrumentalized electrocardiography (ECG) for measuring heart rate rather than non-intrusive measurements.
- Unclear classification testing settings, data analysis and statistical description.

These limitations also reflect the low technology readiness levels (TRL) predominant with only 2 studies evidencing validation in relevant environments - TLR level 5 - and none above."

Item 26: Discussion: Conclusions (Page 24/25, paragraph 8)

"ECG is an effective tool for assessing driver's HR and HRV, enabling the evaluation of the autonomic balance in the cardiovascular system. By analyzing the LF/HF power ratio in HRV, we can gain insights into the driver's state of arousal and determine their fatigue and drowsiness status. ECG can be acquired non-intrusively, using wearable and in vehicle sensors, to accurately assess the HR of the drivers. This innovative technology represents a significant advancement, as it becomes more user-friendly, enhances its acceptability and practicality for users, and facilitates its implementation in motor vehicle industries. Moreover, other technologies such as PPG were also used for HR estimation. Both HR from ECG and from other sources seem to be reliable. Nevertheless, HR by itself may not be enough to allow precise fatigue estimation and can generate false alarms. Further research, in particular fully validation protocols are needed to determine the full value of HR for fatigue quantification and drowsiness detection, by itself or combined with additional information.”

Item **27:** Funding (Page 25, paragraph 1)

This work was supported by the Project BBAI- Brain Behavior analysis using the most advanced Artificial Intelligence and Computer Vision (ref: NORTE-01-0247-FEDER-069809) , Agência Nacional de Inovação S.A., P2020 **|** COMPETE **-** Projetos em Copromoção

Appendix 3- Diagnostic Guidelines for authors

SAFETY SCIENCE

AUTHOR INFORMATION PACK

TABLE OF CONTENTS

DESCRIPTION

Safety Science serves as an international medium for research in the science and technology of humanand industrial safety. It extends from safety of people at work to other spheres, such as transport, energy or infrastructures, as well as every other field of man's hazardous activities.

Safety Science is multidisciplinary. Its contributors and its audience range from social scientists to engineers. The journal covers the physics and engineering of safety; its social, policy and organizational aspects; the assessment, management and communication of risks; the effectiveness of control and management techniques for safety; standardization, legislation, inspection, insurance,costing aspects, human behavior and safety and the like.

Papers addressing the interfaces between technology, people and organizations are especially welcome.

Safety Science will enable academic researchers, engineers and decision-makers in companies, government agencies and international bodies, to augment their information level on the latest trendsin the field, from policy-makers and management scientists to engineers.

The journal focuses primarily on original research papers across its whole scope, but also welcomesstate-of-the-art review papers and first-hand case histories on accidents and disasters of special significance and discussion papers on hot topic

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INTRODUCTION

Safety Science serves as an international medium for research in the science and technology of humansafety. It extends from safety of people at work to other spheres, such as transport, leisure and home, as well as every other field of man's hazardous activities.

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Safety Science will enable academic researchers, engineers and decision makers in companies, government agencies and international bodies, to augment their information level on the latest trendsin the field, from policy makers and management scientists to transport engineers.

The journal focuses primarily on original research papers across its whole scope, but also welcomesstate-of-the-art review papers and first hand case histories on accidents and disasters of special significance. The emphasis is on safety risks, as distinct from health risks, but may include both.

The editors would like to draw the attention of potential authors to a paper by Shannon, Robson & Guastello,"Methodological criteria for evaluating occupational safety intervention" [Safety Science, Volume 31, Issue 2, March 1999, Pages 161-179]. This gives some very useful indications of the sortof criteria which the journal uses to judge papers presented for publication. The paper is partly basedon the experiences of reviewers in the past, and the shortcomings they have found in manuscripts sent to them for assessment. We hope that you find the paper useful in planning research and in writing it up in a suitable form for publication.

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Hale A.R., Hovden J., 1998. Management and culture: the third age of safety. A review of approachesto organizational aspects of safety health and environment. In: Williamson, A., Feyer, A.-M. (Eds.),Occupational Injury: Risk, Prevention and Injury. Taylor & Francis.

Harborview Medical Center Injury Prevention and Research Center, 1997. Systematic Reviews of Childhood Injury Prevention Interventions. http://weber.u.washington.edu/_hiprc/index_left.html(Oct. 22, 1997).

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