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The psychobiology of using automated driving systems: A systematic review and integrative model

Gunther Meinlschmidt[a,b,c,*], Esther Stalujanis[a,d], Marion Tegethoff[d]

[a] Division of Clinical Psychology and Cognitive Behavioral Therapy, International Psychoanalytic University, Stromstrasse 1, D-10555 Berlin, Germany
[b] Department of Psychosomatic Medicine, Faculty of Medicine, University of Basel and University Hospital Basel, Hebelstrasse 2, CH-4031 Basel, Switzerland
[c] Division of Clinical Psychology and Epidemiology, Department of Psychology, University of Basel, Missionsstrasse 60/62, CH-4055 Basel, Switzerland
[d] Division of Clinical Psychology and Psychiatry, Department of Psychology, University of Basel, Missionsstrasse 60/62, CH-4055 Basel, Switzerland

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ABSTRACT

Using vehicles with engaged automated driving systems (ADS) ('highly automated driving', HAD) will substantially impact on future society's mobility, yet the current understanding of human psychobiology related to HAD is still limited. Hence, we synthesized evidence on the psychobiology of subjects using HAD, informing an integrative model of the psychobiology of HAD, and providing guidance for reporting future research on this topic.

We included (non-)randomized studies assessing human peripheral biology markers of in-vehicle-users in real or simulated driving environments, using vehicles with vs. without engaged ADS, published in English until April 2018. We systematically searched Web of Science, SCOPUS, and PubMed. The search consisted of a combination of terms describing HAD and psychobiological parameters. Risk of bias was assessed regarding randomization, blinding, incomplete outcome data, selective outcome reporting, and other potential causes. We extracted data using predefined data fields.

Four out of five studies included in this review (N = 194 subjects) reported associations of use of vehicles with vs. without engaged ADS with various psychobiological parameters, including heart rate, respiratory sinus arrhythmia (RSA), indicators of electrodermal activity (EDA), and masseter electromyography (EMG). Heart rate tended to be reduced during HAD along with increased EDA and EMG, with no clear indication for changes in RSA.

We cannot exclude substantial risk of bias, among others because the status of engagement of ADS was mostly non-randomized. Yet, findings suggest that HAD goes along with tractable changes in peripheral biology. Informed by the conceptual endophenotype approach (Hellhammer et al., 2018, *Psychoneuroendocrinology*), we propose the Embodied Driving (EMBODD) model that describes how HAD reshapes vehicle use experience, and highlight how to make future ADS equipped vehicles successful regarding user's health. Based on the review, we suggest reporting guidelines for future research on the psychobiology of HAD.

1. Introduction

1.1. Cars as contextual artificial elements of modern mobility

From an evolutionary perspective, active locomotion, that is self-propelled movements to dislocate from one place to another, is a key capability of many animals, including humans (Zug, 2017). Beyond that, using passive locomotion, a type of mobility in which the organism depends on its environmental living context for transportation, is a common phenomenon in animals. Notably, humans have additionally created artificial vehicles as means of transportation with exceeding speed, range, and qualities, but also different demands and risks, as compared to their bipedal terrestrial and aquatic locomotive capacities. These vehicles can be conceptualized as an artificial element of their living environment, requiring specific psychobiological adaption to ensure their functional use without substantial risks.

1.2. Health risks of using cars

Among the most prevalent vehicles as means of transportation for

* Corresponding author at: Division of Clinical Psychology and Cognitive Behavioral Therapy, International Psychoanalytic University, Stromstrasse 1, D-10555 Berlin, Germany.
E-mail address: gunther.meinlschmidt@unibas.ch (G. Meinlschmidt).

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humans worldwide are cars (Schafer and Victor, 2000). Using these cars goes along with substantial health risks, such as injuries related to accidents. Notably, it has been argued that 60–80% of car accident-related costs in Europe (i.e., 96–128 billion Euros per year) are linked to the psychophysical condition of the driver, including consequences of unsafe behaviors of the driver, and the driver's health conditions, such as sleep quality and sleep disorders, depressive and other mental disorders, including alcohol and other substance use disorders, health emergencies, and even pronounced emotions (anger, excitement, etc.) (Rahman et al., 2015; Vivoli et al., 2006). In short, driver's psychobiology and driver's health risks are closely related – already when using conventional (non-automated) cars.

1.3. Tasks required to use cars and the introduction of driving automation systems

Functional use of cars to make trips commonly requires three sets of tasks: (1) operational tasks, such as steering, accelerating, decelerating, and monitoring the vehicle and the roadway, (2) tactical tasks, such as responding to events, determining when to perform maneuvers, such as changing lanes or turning, or when to enhance conspicuity, via lighting, signals, and gesturing, (3) and strategic tasks, such as trip scheduling and determining destinations and waypoints (On-Road Automated Driving (Orad) Committee, 2018). Together, operational and tactical driving tasks form the dynamic driving tasks, defined as "all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic" (On-Road Automated Driving (Orad) Committee, 2018), and including tactile as well as functional effort of the driver. With the advent of automated driving, dynamic driving tasks are increasingly taken over by driving automation systems (On-Road Automated Driving (Orad) Committee, 2018) (see Fig. 1).

The introduction of vehicles equipped with automated driving systems (ADS) will substantially impact on modern society's mobility during the next decades (Bansal and Kockelman, 2017; Meyer et al., 2017; Pettigrew, 2017), with virtually ubiquitous direct and regular contact between the general population and ADS-equipped cars and other vehicles. This may come with certain opportunities, including increased accessibility of using cars (Meyer et al., 2017) and the possibility to use travel time for other purposes than driving, such as activities to improve health (Paredes et al., 2017).

1.4. Driving automation systems and drivers' psychobiology

At first glance, the introduction of ADS is freeing the driver's psychobiology from certain requirements. Notably, increasing driving automation goes along with reduced mental workload and increased freely allocable situational awareness (de Winter et al., 2014). Yet, from a psychological perspective, a broad range of mental functions are required when using ADS-equipped vehicles, including amongst others trust, risk perception, mentalization, decision making, sensory and visceral perceptions, and related attributions (Othersen, 2016; Shariff et al., 2017). Even more, using ADS-engaged vehicles goes along with specific demands: Especially the necessity that the vehicle user stays receptive, that she/he is able to reliably and appropriately focus her/his attention in response to a stimulus, is of paramount importance, especially when using a vehicle at driving automation level 3, requiring users to be 'fallback-ready' in case the vehicle requests that the user takes over dynamic driving tasks. In line with the concept of automation induced complacency or automation complacency, users may even perform worse when relying on the support of ADS. With regard to human error related risks and costs, these may be reduced in the long run by introducing ADS. Yet, it has been argued that during conditional

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Fig. 1. Summary of SAE International's Levels of Driving Automation for On-Road Vehicles (SAE international's J3016, version Jan 2014).

driving automation (level 3 driving automation), knowledge and monitoring of the psychobiology of vehicle users is of special importance, given their remaining role as drivers in case of fallbacks (Rahman et al., 2015).

1.5. Driving automation systems and users' emotions, as well as potential mental barriers

There are first indications that highly automated driving may elicit certain emotions. A few studies assessed emotional processes related to highly automated driving, For example, large overall hesitations towards adoption of ADS-equipped vehicles have been reported, with nearly half of respondents choosing decisions towards vehicles exclusively requiring conventional driving (Haboucha et al., 2017). Further, substantial anticipated worries related to highly automated driving became apparent (Kyriakidis et al., 2015). Anticipation of being more frightened by ADS-equipped cars was linked with a diminished positive association between highly automated driving benefit evaluations and individual willingness to use ADS-equipped cars (Hohenberger et al., 2017).

Beyond negative emotions, driving can also elicit positive emotions and favorable mental processes. For conventional driving, elicited emotions including joy, perceived internal locus of control, self-efficacy, autonomy, and many more (Bergstad et al., 2011; Desmet, 2012; Gatersleben, 2007; Lois and López-Sáez, 2009; Sheller, 2004) have been reported. It may be speculated that using vehicles with engaged ADS as compared to conventional driving differs in terms of elicited positive emotions and mental processes, amongst others, because with engaged ADS driving, the agency of driving transfers from the user to the vehicle.

In line with the notion that driving automation systems may elicit certain emotions and in contrast to the assumption that ADS-equipped cars can be used without relevant limitations (Maurer et al., 2016), the introduction of ADS-equipped cars may also introduce new emotional or other mental barriers for certain potential users. The quality and extent of such barriers still need to be scrutinized. Yet, the history of the introduction of other mobility-related technologies, such as aviation, may be informative. Already in the early 20th century, non-transient fear and anxiety related to the use of airplanes (then termed 'aeroneurosis') has been described, which is still experienced by a non-negligible part of the population (Oakes and Bor, 2010). Such fear of flying is not only characterized by mental symptoms but also by psychobiological characteristics (Wilhelm and Roth, 1998), in line with the notion of psychobiological functions being related to a range of psychopathological processes (Clark et al., 2017). In line with this notion, improving our knowledge of the psychobiology related to the use of ADS-engaged cars may provide the basis for future research towards a better understanding of potential mental barriers towards the use of ADS-equipped vehicles and related health risks. Taken together, using ADS-engaged vehicles increases human mobility opportunities, but at the same time introduces new mental and psychobiological demands. Further, disturbances of many of these mental and psychobiological functions are of relevance for a range of psychopathological processes, suggesting that they may represent a link between highly automated driving and potential mental barriers and health risks. Hence, scrutinizing the psychobiology related to highly automated driving will be of increasing importance in the upcoming years.

1.6. Objectives

The objectives of this article were (1) to systematically review the available evidence regarding the psychobiology of subjects when using vehicles with engaged ADS, (2) informing an integrative model of the psychobiology of highly automated driving use, and (3) providing guidance for reporting future research on this topic.

2. Methods

2.1. Eligibility criteria

Eligibility criteria for inclusion in the synthesis were as follows: Types of studies & design: (1) randomized or non-randomized studies, (2) comparing use of a vehicle with an engaged ADS [defined as driving automation levels 3–5, (On-Road Automated Driving (Orad) Committee, 2018), cf. Fig. 1] with use of a vehicle without engaged ADS (defined as driving automation levels 0–2), (3) published in English, (4) up until April 2018; Types of participants & settings: Assessing (5) human subjects, (6) driving in an (on-road motor) vehicle: car or truck, (7) in either a real-world or simulated scenario; Types of outcomes: (8) at least one peripheral biological parameter, with parameter selection substantially expanding a list of parameters applied by a previous systematic review that addressed a different topic (yoga and mindfulness-based stress reduction) with regard to stress-related physiological measures (Pascoe et al., 2017).

2.2. Information sources and search

We identified studies by searching electronic databases. This search was applied to Web of Science (Core Collection), SCOPUS, and PubMed. The last search was run on 25 April 2018. The search terms were a combination of terms describing use of ADS-equipped vehicles and terms describing psychobiological parameters, limiting hits to humans. The full electronic search strategy for each source is provided as online Supplemental material 1.

2.3. Study selection

Eligibility assessment was performed first by screening titles and abstracts and then having two reviewers independently assessing full-text articles for eligibility in an un-blinded, standardized manner. Disagreements between reviewers were resolved by consensus.

2.4. Data collection

We developed a data extraction sheet and refined it following extraction of data from the first three studies. One review author extracted the following data from included studies and a second author checked the extracted data. Disagreements were resolved by discussion between the two extracting authors; if no agreement could be reached, it was planned the third author would decide.

2.5. Data items

Information was extracted from each included study on: (1) characteristics of study participants (including age, sex, general driving experience, and highly automated driving experience), (2) characteristics of study content [including type of vehicle, setting (real or simulated vehicle use), driving automation level (reported level, or if not reported: estimated level according to SAE driving automation levels), driving environment, (3) theoretical model on which the study is based (if reported), and (4) characteristics of study design (including independent variables, randomization procedures, dependent variables / outcome parameters).

2.6. Assessment of risk of bias in individual studies

One author assessed risk of bias at the study level in a non-blinded way, regarding randomization, blinding, incomplete outcome data, selective outcome reporting, and other biases. We extracted data using predefined data fields.

2.7. Study synthesis & risk of bias across studies

Given the rather low numbers of identified studies and the heterogeneity in study design and content between identified studies, no quantitative meta-analyses or quantitative risk of bias assessments were conducted. Instead, study findings were qualitatively synthesized, focusing on the associations between driving automation level and biological parameters or differences between driving automation levels regarding biological parameters/outcomes. The risk of bias across studies was qualitatively assessed.

3. Results

3.1. Study selection

A total of five studies were identified for inclusion in the review. The search of Web of Science, SCOPUS, and PubMed revealed a total of 2557 citations. After adjusting for duplicates, 2481 citations remained. Of these, 2212 studies were discarded after reviewing the title or abstract. The full-text of the remaining 56 citations was examined in more detail. It appeared that 51 studies did not meet the inclusion criteria as described. Five studies met the inclusion criteria and were included in the synthesis of the systematic review. No unpublished relevant studies were obtained. (See flow diagram, Fig. 2). Of note, we did not include a study (Sasai et al., 2015) that measured peripheral physiological parameters in passengers that were explained "that the experimental vehicle driven by the experimenter is assumed as an autonomous vehicle" as (1) no real or simulated vehicle use at driving automation levels 3–5 was present, despite respective explanation, and (2) a comparison condition with vehicle use at driving automation levels 0–2 was lacking.

3.2. Characteristics of included studies

3.2.1. Study participants

The five identified studies (Carsten et al., 2012; Drnec and Metcalfe, 2016; Ruscio et al., 2017; Waytz et al., 2014; Zheng et al., 2015) contributed a total of $N = 194$ subjects (information on number of participants lacking for one study) for this systematic review (for details, see Table 1): In sum, participants of three (Ruscio et al., 2017; Waytz et al., 2014; Zheng et al., 2015) out of four studies that provided respective data were rather young, on average below 40 years of age, with two (Carsten et al., 2012; Zheng et al., 2015) out of four studies that provided respective data assessing a primarily or exclusively male sample, and participants of two (Carsten et al., 2012; Zheng et al., 2015) out of two studies that provided respective data consisting of rather experienced drivers, with at least ten years of driving experience on average. Notably, no information on experience of using ADS-equipped vehicles was provided, but given that relevant market introduction of cars capable of driving automation level 3 or higher has not yet occurred, it can be expected that such experience was negligible.

3.2.2. Study content

Details on study content are provided in Table 1. All studies used driving simulators with virtual scenarios, simulating either cars (four studies) (Carsten et al., 2012; Drnec and Metcalfe, 2016; Ruscio et al., 2017; Waytz et al., 2014) or trucks (one study) (Zheng et al., 2015). None of the studies explicitly reported the driving automation level that was simulated; using the information provided in the articles and based on the criteria for the different driving automation levels put forth by the On-Road Automated Driving (Orad) Committee, (2018), we concluded that two studies assessed scenarios equivalent to driving automation level 3 (Drnec and Metcalfe, 2016; Ruscio et al., 2017) and three studies assessed scenarios equivalent to driving automation levels 4–5 (Carsten et al., 2012; Waytz et al., 2014; Zheng et al., 2015). Driving environments always included straight street sections and curves, as

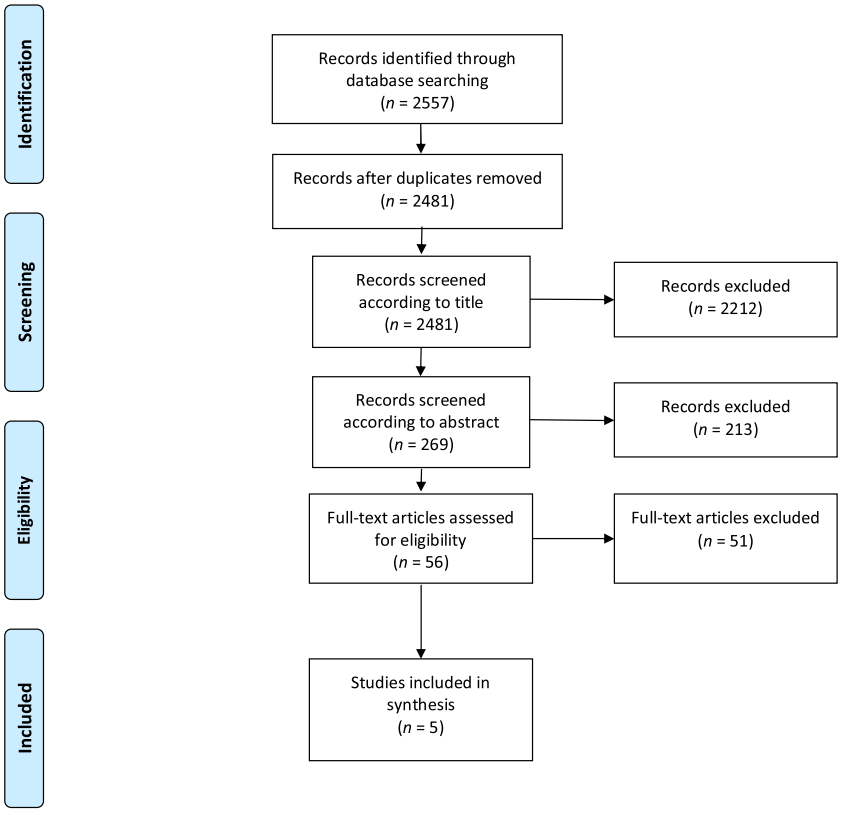

Fig. 2. Flow of information through the different phases of the systematic review.

Table 1
Characteristics of participants and content of the studies identified through the systematic search.

Author	Year	N	Age	Sex	General driving experience	Highly automated driving experience (in-vehicle use of ADS-operated vehicles)	Vehicle (real or simulated)	Setting	SAE level when ADS engaged	Driving environment	Theoretical model
Carsten et al.	2012	49	• Longitudinal-control group (n = 25): Mean ± SD: 47.2 ± 11.1 years • Lateral-control group (n = 24): Mean ± SD: 48.4 ± 10.1 years	90% male, 10% female	Years since passing the driving test (all high-mileage drivers) • Longitudinal-control group: Mean ± SD: 28.0 ± 11.3 years • Lateral-control group: Mean ± SD: 27.9 ± 11.6 years	NR	Car	Driving simulator	NR; (estimated: SAE level 4+)	Three-lane motorway with straight sections and curves, with other traffic	NR
Drnec et al.	2016	NR	NR	NR	NR	NR	Car	Driving simulator	NR; (estimated: SAE level 3+)	One full lap around a two-lane course, with other vehicles (changing speed), wind gusts, and pedestrians	(Trust in automation)
Ruscio et al.	2017	35[1]	Mean ± SD: 37 ± 15 years	44% male, 56% female	NR	NR	Car	Virtual scenario	NR; (estimated: SAE level 3; take over requests)	Different take-over requests combined with dangerous and/or unexpected driving situations	'Malleable attentional resources allocation theory'
Waytz et al.	2014	100	Mean: 26.39 years	48% male, 52% female	Assessed via 'driving history questionnaire'; data not presented in article	Assessed via 'driving history questionnaire' (?); data not presented in article	Car	Driving simulator	NR; (estimated: SAE level 4+)	Virtually unavoidable accident clearly caused by the other driver	(Anthropomorphism as important determinant of trust in technology)
Zheng et al.	2015	10	Mean ± SD: 32.9 ± 12.9 years	100% male	Mean ± SD: 11.2 ± 10.9 years	NR	Truck	Driving simulator	NR; (estimated: SAE level 4+)	Truck following other truck at different distances	NR

[1] 35 participants contributed data to analyses, out of 41 recruited (information on age and sex based on 41 subjects); Abbreviations: Automated driving system, ADS; N, number of participants in the study that contributed to analyses; NR, none / not reported; SAE, SAE international's J3016, taxonomy and definitions for terms related to driving automation systems [On-Road Automated Driving (Orad) Committee, 2018], cf. Fig. 1; SD, standard deviation.

Table 2
Design characteristics and results of the studies identified through the systematic search.

Author	Year	Independent variables	Randomization	Dependent variables / Outcome Parameters	Main results	Comment
Carsten et al.	2012	**WS-Factor 1 'Level of automation':** 'non-automated level' vs. semi-automated level (ACC, i.e. 'support in longitudinal control' or LKS, i.e. 'support in lateral control) vs. 'fully-automated level' (ACC and LKS)	**Factor 1:** not randomized	HR (as indicator of overall workload)	Repeated-measures ANOVA, with post-hoc t-tests for comparisons between levels of automation: ● Longitudinal-control group: HR differed across conditions: fully-automated lower than semi-automated; fully-automated lower than non-automated. ● Lateral-control group: HR differed across conditions: fully-automated not significantly different from semi-automated; fully-automated not significantly different from non-automated.	No results with analyses including subjects of both groups reported
Drnec et al.	2016	**WS-Factor 1 'Automation type'**: full control vs. speed only control **WS-Factor 2 'Automation reliability'**: low vs. high ➔ 'non-automated run' as baseline condition	NR	● ECG ● GSR	No results on biological data reported	
Ruscio et al.	2017	**WS-Factor 1 'Driving condition':** 5 conditions: 'driving single task', 'no warning / expected', 'no warning / unexpected', 'reliable warning', 'misleading warning' (+ additional level 'no warning / danger' condition to test for vigilance)	**WS-Factor 1:** levels 2-4: randomized (no details provided)	● Mean HR ● RSA as indicator of parasympathetic activity ● EDA index (SCR) as indicator of sympathetic activity	HR: Repeated-measures MANOVA and post-hoc univariate ANOVA: Difference in mean HR across driving conditions; HR increased (from resting baseline) less in 'no warning / unexpected', 'reliable warning', and 'misleading warning' conditions as compared to the 'driving single task' condition, but was not significantly different in the 'no warning / expected' condition as compared to the 'driving single task' condition. RSA: Repeated-measures MANOVA and post-hoc univariate ANOVA: Difference in RSA across driving conditions; RSA reactions (from resting baseline) were not significantly different when comparing 'no warning / expected', 'misleading warning', and 'reliable warning' conditions as compared to the 'driving single task' condition. (There was no reaction from baseline in the 'no warning / unexpected' condition) EDA: Repeated-measures MANOVA and post-hoc univariate ANOVA: Difference in SCR across driving conditions; SCR increased (from resting baseline) more in 'no warning / unexpected' and 'misleading warning' conditions as compared to the 'driving single task' condition, but not in 'no warning / expected' (note: interpretation by Ruscio) and 'reliable warning', condition as compared to the 'driving single task' condition.	
Waytz et al.	2014	**BS-Factor 1 'Condition':** Normal condition (without automated driving features) vs. Agentic condition (automated driving features) vs. Anthropomorphic condition (automated driving & anthropomorphic features)	**BS-Factor 1:** randomized (no details provided)	● HR change pre to post collision ● Startle response to collision: videos of participants, subjectively rated regarding startle response (0 = not at all startled to 10 = extremely startled) Note: HR change parameter and startle response were combined as one indicator ('behavioral trust')	Orthogonal contrasts (between subject t-Test): No difference in 'behavioral trust' between agentic and normal condition	HR results not reported separately;

(*continued on next page*)

Table 2 (*continued*)

Author	Year	Independent variables	Randomization	Dependent variables / Outcome Parameters	Main results	Comment
Zheng et al.	2015	**WS-Factor 1 'Distance':** Automated operation with 4,8, and 12 m gap distance vs. Manual driving with 25 m gap distance (reference); **WS-Factor 2 'Driving state':** Driving state variable vs. constant (reference)	**WS-Factor 1:** only 4, 8, and 12 m gap size randomized (no details provided) **WS-Factor 2:** place and time of deceleration randomized (no details provided)	• Palmar perspiration (RMQ); • Masseter EMG (RMQ)	Two-way repeated measure ANOVA: Similar for Palmar perspiration & Masseter EMG: • Main effect Driving state: RMQ increased with lower distance; • Main effect gap distance: RMQ higher with lower distance; Interaction effect: gap distance differences stronger in variable driving state.	Note: Automated operation vs. Manual driving not randomized

Abbreviations: ACC, adaptive cruise control; ANOVA: analysis of variance; BS, between-subject; ECG, electrocardiography; EDA, electrodermal activity; EMG, electromyography; GSR, galvanic skin response; HR, heart rate; LKS, lane-keeping system; MANOVA, multivariate analysis of variance; NR, none/not reported; RMQ method, Root-mean-quad method; RSA, respiratory sinus arrhythmia; SCR, skin conductance reactivity; WS, within-subject.

well as other traffic, often included pedestrians, and sometimes included other unpredictable factors, such as wind. One study included dangerous driving environments (Ruscio et al., 2017) and one study included unavoidable accidents (Waytz et al., 2014).

3.2.3. Theoretical model on which the study is based and characteristics of study design

One study explicitly referred to a theoretical model ('Malleable attentional resources allocation theory') (Ruscio et al., 2017), which is unspecific for use of ADS-equipped vehicles, while two studies addressed the concept of trust (trust in automation; anthropomorphism as important determinant of trust in technology) (Drnec and Metcalfe, 2016; Waytz et al., 2014) (see Table 1).

With regard to the independent variable(s), three studies compared vehicles use at driving automation levels 3–5 (highly automated driving) with driving at driving automation level 0 (no automation) only (Ruscio et al., 2017; Waytz et al., 2014; Zheng et al., 2015), one study compared vehicle use at driving automation level 3–5 with vehicle use at driving automation level 1 (semi-automated) only (Drnec and Metcalfe, 2016), and one study compared vehicles use at driving automation level 3–5 with driving at driving automation level 1 and driving at driving automation level 0 (Carsten et al., 2012). Whether these conditions were randomized was reported in four out of five studies, being randomized in one study (Waytz et al., 2014) and not being randomized in three studies (Carsten et al., 2012; Ruscio et al., 2017; Zheng et al., 2015). Of note: two (Ruscio et al., 2017; Zheng et al., 2015) of the latter three studies conducted some randomization of the independent variable, which however did not include randomization of the comparison between vehicle use at highly automated or non-automated level. Biological outcome parameters included heart rate (three studies) (Carsten et al., 2012; Ruscio et al., 2017; Waytz et al., 2014), respiratory sinus arrhythmia (RSA) as indicator of parasympathetic activity (one study) (Ruscio et al., 2017), electrodermal activity (EDA) [skin conductance reactivity (SCR)/galvanic skin response/palmar perspiration] as indicators of sympathetic activity (three studies) (Drnec and Metcalfe, 2016; Ruscio et al., 2017; Zheng et al., 2015), electrocardiography (ECG) (one study) (Drnec and Metcalfe, 2016), and masseter electromyography (EMG) (one study) (Zheng et al., 2015). (For details on independent variables, randomization and biological outcomes, see Table 2).

3.3. Risk of bias within and across studies

At least certain risk of bias was present in all five studies (see Table provided as online Supplemental material 2), most importantly because of no or only partial randomization, and because of lack of reported information. Notably, in one study (Zheng et al., 2015), variation between vehicle use at highly automated level or non-automated level was confounded by variation in gap distance between the own (simulated) truck and the preceding vehicle, which was due to the aim of this study which was to scrutinize whether use of trucks at highly automated level with substantially reduced distance between vehicles would lead to an increase in stress biology, as compared to non-automated driving levels, with regular (and much larger) distances between vehicles. We were unable to estimate whether risk of bias across studies, such as bias caused by missing data from the included studies (selective reporting bias), or publication decisions conditional on study results (publication bias) may have occurred, as (1) protocols of the included studies were not preregistered or published elsewhere before conducting of the studies, and (2) we only conducted qualitative syntheses, precluding respective quantitative procedures, such as visual or formal (e.g., Egger's test) analyses of 'funnel plots'.

3.4. Results of individual studies and synthesis of results

Results of the individual studies are provided in Table 2. With

regard to heart rate, studies tended to indicate either lower heart rate related to vehicles use at highly automated driving levels, at least when driving under unexpected conditions or when receiving warnings (Carsten et al., 2012; Ruscio et al., 2017) or provided no indication for differences in heart rate (Waytz et al., 2014). EDA / Palmar perspiration / SCR and masseter EMG tended to be higher when using vehicles at highly automated driving levels (Ruscio et al., 2017; Zheng et al., 2015), and there was no clear indication for differences in RSA (Ruscio et al., 2017).

4. Discussion

4.1. Summary of evidence

Overall, the evidence we systematically reviewed is not sufficiently robust to clearly determine the psychobiology related to highly automated driving. Yet, there was suggestive evidence that heart rate is reduced when ADS are engaged. At the same time there was weak evidence for increased EDA, indicative of increased sympathetic nervous system activity and – together with increased masseter EMG – for psychological or physiological arousal. There was no evidence for changes in RSA, an indicator of parasympathetic nervous system activity, and lack of data for electrocardiography ECG.

4.2. Strengths and limitations

4.2.1. Strengths and limitations at study level

The studies included in this review have several strengths: First, all studies applied a driving simulator as study setting, allowing control of unintended variation in the driving environment and facilitating biological assessments. Yet, we cannot determine to which extend findings generalize to real-world vehicle users. Yet, we cannot determine to which extent findings generalize to real-world vehicle users. Notably, consumer market introduction of cars capable of ADS level 3 is just emerging, which will pave new ways to scrutinize our research question in a real-world setting. And second, the simulated driving environments were diverse and included (1) low- and high-risk traffic scenarios, as well as (2) vehicle accidents, thereby increasing generalizability of findings to real-world driving environments. But included studies have also several limitations: First, sample sizes were small to medium, with disproportionate overrepresentation of males and a tendency for rather young study participants, as compared to the general driving population in industrialized countries, limiting generalizability of findings. Second, with regard to study design, full randomization was rare, which introduces substantial risk of bias. Third, notably, only one study was explicitly theory-based, applying the 'Malleable attentional resources allocation theory' that is unspecific for automated driving scenarios, which encouraged us to propose an integrative model of the psychobiology of highly automated driving (see Section 3.3) as basis for future research in the field. And fourth, incomplete reporting regarding many relevant pieces of information across all five studies impeded conducting this systematic review, with one study completely lacking information on results regarding psychobiological parameters. To foster improvement of reporting quality of future studies, we provide guidance in form of reporting recommendations for research on the topic (see Section 4.4).

4.2.2. Strengths and limitations at the systematic review level

There are also strengths and limitations at the level of the systematic review process. First, we applied a rather sensitive (and unspecific) combination of search terms, aiming at increasing the probability to identify relevant studies, which comes along with the disadvantage of having to exclude a large number of irrelevant articles. Second, we only included articles published in English, which however is the key language of publications in the field. Unfortunately, we did not have the opportunity to screen for studies published in Mandarin, given that China is currently one of the most relevant markets for automated mobility. Third, due to study heterogeneity, we were unable to conduct a quantitative synthesis of study results in form of a meta-analysis as well as quantitative estimation of biases.

4.3. The Embodied Driving (EMBODD) model

As mentioned above, most identified publications did not report an explicit theory or model on which the studies were based. Therefore, we here propose a theoretical model of ADS use as basis for future research in the field: the Embodied Driving (EMBODD) model. We develop the model on the basis of the conceptual endophenotype approach, described by Hellhammer et al. (2018). This approach puts at its core a conceptual understanding of psychobiological systems, including the recognition of their functional role within an environmental context. It is in line with the view that mental functions (thought process and content, mood, emotional regulation, reality orientation, perception, etc.) are comprehensible only in their social context (Tandon et al., 2015). This 'contextual functionality' is the purpose of a psychobiological system with its constitutive elements in the context of the environmental milieu. The milieu, in turn, is best described by its phylogenetic and ontogenetic history, current features, and adaptational demands (Rauh and Margolis, 2016). So how does this translate to the psychobiology of highly automated driving use? As starting point, we describe the environmental context or milieu of vehicle use. Phylogenetically, one may argue that this relates back to a combination of three features: (1) active locomotion, (2) passive locomotion (see Section 1), and (3) tool use. Active locomotion can be characterized by two components: First, it is highly dependent on the moving organism's energy storages and resources and its readiness to release energy and to transform it into automotive kinetic energy. Second, active locomotion requires a high degree of receptivity of the organism, allowing collecting with high frequency information on the environment, enabling appropriately directing the use of this energy. In contrast, passive locomotion puts rather little energetic demand on the organism itself. Still, it may require a high degree of receptivity, allowing the organism to appropriately collect environmental information as basis for the decision when, to which extent, and how to use the kinetic energy (i.e., travel options) provided by the environmental context. The required degree of receptivity will most likely depend on the dynamics of the environmental kinetic energy and other aspects of the environment, especially whether its velocity (speed and direction of motion) and progression is predictable or not. Above a certain level of predictability, the organism may conserve the spared energy or use it for other purposes, for example, to regenerate or for other energy-dependent actions. Notably, the advantage of tool use [i.e., using or modifying an inanimate object in some way to cause a change in the environment, thereby facilitating one's achievement of a target goal (Beauchamp and Frey, 2011)], is to achieve goals that would not be achievable without the tool, or to achieve them faster, with less risk, or with spending of less energy. Successful tool use requires many higher-level mental (and in some cases social) functions, including receptivity, attention, planning, learning and memory, mentalization, and goal-directed behavior. Each of these three features, active locomotion, passive locomotion, and tool use, can be related to the activity of three psychobiological systems or contextual endophenotypes. The terms for these three biological systems (glandotropy, ergotropy, and trophotropy) were selected to reflect their functional roles within the evolution of stress responsive systems (for details, see Hellhammer, 1983; Hellhammer et al., 2018): Glandotropy refers to the activity of the different central and peripheral components of the hypothalamic pituitary adrenal (HPA) axis that are associated with mobilization of energy, prevention of an disinhibited stress response, and psychological states such as anticipation, worry, lack of control, and ego involvement. Ergotropy refers to catecholaminergic/sympathetic functions associated with arousal, mental or physical work, and alertness. Trophotropy refers primarily to central

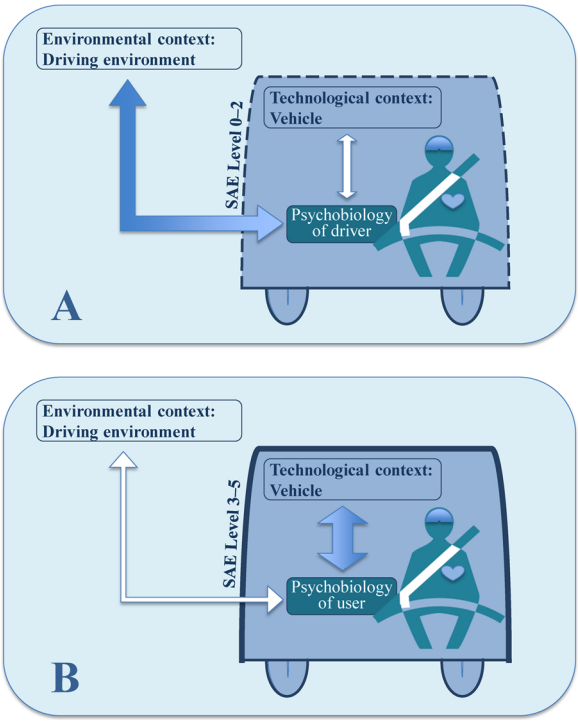

Fig. 3. Outline of the Embodied Driving (EMBODD) model. Panel A: In-vehicle use of a car with no engaged automated driving system (driving automation level 0–2); Panel B: In-vehicle use of a car with an engaged automated driving system (driving automation level 3–5).
Abbreviations: SAE, SAE international's J3016, taxonomy and definitions for terms related to driving automation systems [On-Road Automated Driving (Orad) Committee, 2018, cf. Fig. 1].

and parasympathetic functions that underlie regeneration, recovery, and protection against stress overload. All these functions are complex and are regulated by multiple other neurobiological processes. It can be expected that active locomotion will primarily involve the ergotropic as well as the glandotropic system; Passive locomotion will involve to different degrees the ergotropic system and at the same time may allow or trigger the trophotropic system; And tool use will primarily involve the ergotropic system.

So how do these phylogenetic descriptions match with today's highly automated driving? Let's first describe the environmental context of a highly automated driving constellation. Under both, conventional driving and ADS-engaged in-vehicle use conditions, the user's context is constituted by two nested compartments: The first (inner) compartment, the primarily technological context, is constituted by the vehicle and its features, while the second (outer) compartment, the environmental context, is constituted by the driving environment (see Fig. 3). The inner compartment involves demands towards the user exerted by technology. The outer compartment involves demands towards the vehicle and its user, exerted by the driving environment and characterized amongst other as 'operational design domain' (ODD), which is "the specific conditions under which a given driving automation system or feature thereof is designed to function, including, but not limited to, driving modes" (On-Road Automated Driving (Orad) Committee, 2018). During in-vehicle use of ADS-engaged vehicles, we argue that the user with its mental and psychobiological activity is embodied in these two contextual compartments, with embodiment, describing a relational dynamic that exists between the biological organism and its environment (Quick et al., 2000; Sheller, 2004). Notably, each driving automation level shapes the demands exerted by both compartments onto the embodied vehicle user. During conventional driving (at driving automation level 0), demands exerted by the outer compartment are closely related to demands exerted by the inner compartment and requiring a respective psychobiological reaction of the user (comparable to psychobiological states related to active locomotion, with pronounced ergotropic yet moderate or little energetic/glandotropic component). Driving at automation level 1 and 2 gradually dampens this relation. For example, a driving environment demanding reduction of speed will trigger an automatically initiated breaking reaction of the vehicle, demanding the driver to monitor this vehicle reaction but not demanding any (kinetic energy dependent) initiation of action to activate the breaks herself/himself (reducing the glandotropic component). With in-vehicle use at driving automation level 3–5, this relational dynamic between demands exerted by the driving environment and the embodied vehicle user is further dissociated, up to driving automation level 5, when the driving environment is exerting little or no demand onto the vehicle user (no glandotropic demands, variable ergotropic demands, and potential for trophotropic activation). Notably, this decreased coupling of the relation between the outer compartment and the embodied vehicle user may not only apply to demands but also to other relational dynamics, such as emotions fostered by experiencing and exerting control of the driving environment (see Section 1). Notably, with higher level of automation there may be new opportunities for the organism to direct her/his behavior (for example relaxation related to trophotropic activity), but there may also be new and different demands exerted by the vehicle or other and new aspects of the inner environment (e.g., communication with other passengers or out-of-vehicle subjects), which in many cases will determine the primarily active psychobiological systems of the user, especially given that the 'background'-demands by the outer environment on the user diminish or become even absent with increasing driving automation level. This is the core of the EMBODD model (see Fig. 3): A decreased coupling of relational dynamics between the psychobiology of the embodied vehicle user and the outer compartment of the driving environment, with increasing level of driving automation, along with an increased coupling of relational dynamics between the psychobiology of the embodied vehicle user and the inner compartment of its context. This tentative model is theoretically derived and its predictions, such as changes in covariation between characteristics of the compartments and the psychobiology of the vehicle user across levels of driving automation are empirically testable. It has the potential to inform how the embodied vehicle use experience can be improved and optimized, amongst other with regard to functionality, subjective perception, emotions, and health.

4.4. Recommendations for reporting research on the psychobiology of using ADS

Improving quality of research reporting is of paramount relevance to develop our knowledge regarding the psychobiology of using ADS. In health research, a large number of reporting guidelines have been issued, providing detailed recommendations regarding good reporting practice for different study types, most prominently under the umbrella of the EQUATOR (Enhancing the QUAlity and Transparency Of health Research) Network (Simera et al., 2010) (see http://www.equator-network.org). Similarly, members of other disciplines, including engineering, have proposed guidelines to improve the quality and impact of research (Jedlitschka et al., 2008, 2014; Kitchenham et al., 2008). In general, these reporting guidelines, selecting the one that best fits with the study type applied should be considered. More specifically, we recommend considering some topic-specific aspects and items when reporting research on the psychobiology of using ADS. We provide a list of respective items in Table 3. Beyond that, with regard to use of terminology, we recommend referring to published terminology recommendations, taxonomies, and classification systems from the fields of health, biology, driving automation, and other relevant areas (see World Health Organization, WHO, International Classification of Disease, http://www.who.int/classifications/icd/en/) (Automated Driving System Committee, 2016; Cowley et al., 2016; Kok et al., 2016;On-Road

Table 3
List of items to include when reporting a study on the psychobiology related to highly automated driving[1].

Section	Topic	Driving Automation System (DAS)-related items	Example	Comment
Title	Title	Mention that the topic relates to research involving DAS and use appropriate terms, e.g., "Driving Automation System" for any SAE driving automation level (levels 0–5) or "Automated Driving Systems (ADS)" for SAE driving automation levels 3–5.	"Number of Automated Driving System(ADS)-issued requests to intervene predict the cortisol awakening response in users of ADS-equipped cars: A closed cohort study"	The term "autonomous driving/mobility/car/vehicle" is discouraged[1]
Abstract	Structured Summary	Consider including selected DAS-related items outlined below.	–	–
Introduction	Objectives	When providing a statement of objectives (either as specific hypotheses or as questions that the study was designed to address), include information on relevant DAS-related items outlined below.	"Our primary objective was to estimate the association between a current diagnosis of specific phobia and the proportion of distance travelled with ADS-engaged vehicles in in-vehicle users of ADS-equipped motorized on-road vehicles."	–
Methods/ Results	Participants (Vehicle users)	Information on drivers license (e.g., current status, type of license, years since obtaining license); Information on experiences of using motorized on-road vehicles (e.g., distance travelled per year, etc.); information on experiences of using vehicles with certain driving automation systems engaged (e.g., total in-vehicle distance travel with ADS-operated motorized on-road vehicles); further vehicle-use related experiences, depending on the study question (e.g., holding a vehicle ready for a certain driving automation level; previous involvements and role in traffic accidents, etc.)	"All study participants held at least an EU driving license, category B, obtained on average (mean ± SD) 10.2 ± 4.6 years ago. During the past 12 months, the average self-reported in-vehicle distance travelled at driving automation levels 0–2 was (mean ± SD) 15,000 km ± 4760 km, with an average self-reported in-vehicle distance travelled at driving automation level 3 of (mean ± SD) 1500 km ± 940 km. No vehicle use at driving automation levels 4 and 5 was reported."	Consider using a driving history questionnaire[2]; Consider using available taxonomy recommendations and definitions[3] for consistent use of the terms for vehicles users: e.g., driver, conventional driver, remote driver, passenger, fallback-ready user, driving operation dispatcher, etc.
	Vehicle	Information on type and characteristics of (on-road motorized) vehicles included in the study. The recommended level of detail of reported information depends on the study question and the feasibility to collect / availability of respective data. Level of detail may range from information on vehicle category to automobile model specifications and specific features and characteristics of the vehicle, the latter especially relevant in case of concept cars. A special focus may be spent on description of the driving automation systems the vehicle is equipped with. In case of using a driving simulator, sufficient details on the applied hard- and software (including mock-vehicle), as well as configurations of the simulator shall be provided, preferably with referral to the real-world vehicle the system is aiming to simulate.	"We considered time spent in vehicles of UNECE types L and M."	Consider using standard nomenclatures, for examples nomenclatures for vehicle types [e.g., UNECE Classification and Definition of Vehicles (see http://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29classification.html)
	Engaged automated driving level / DAS-features	Specify automated driving levels and/or the DAS-features that are engaged (including time engaged, initiated by whom, under which situations/ODDs, etc).	"In the control group, participants operated the vehicle at driving automation level 0 for 10 min."	Vehicles may be capable of operating under different driving automation levels. Hence it is important do specify at which driving level the vehicle is operated (in addition to the driving levels it is capable).
	Setting	Specify, whether the vehicle moves in a real-world, in a simulated (e.g., driving simulator) or in a mixed (augmented reality) scenario. (In case of remote use of vehicles, also describe the environment of the remote user).	"Visitors were invited to take part in our study, consisting of a 30 min driving simulator session, followed by …"	

(*continued on next page*)

Table 3 (*continued*)

Section	Topic	Driving Automation System (DAS)-related items	Example	Comment
	Driving environment	Describe the (real or simulated) driving environment in sufficient detail to replicate the study. Provided information may include characteristics and conditions of the roadway, weather, traffic, other agents (pedestrians), level of risk, (un)expected events, etc. Technically, this information is related to the ODD, defined as "operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics."[3]	"The virtual scenario consisted of driving on a 2-lane straight rural road at normal weather conditions. After a random interval of 30 to 50 s, following vehicles overtook on the side opposite to that appropriate to the direction of traffic travelling at a speed that varied randomly between 120 and 140 km/h) and then maintained a close and constant leading distance (between 30 and 40 m). At random intervals ranging from 5 to 10 s after end of overtaking, the now leading vehicle abruptly decelerated for 3 s until moving at 20 km/h less than the speed of the vehicle of the participant at the end of overtaking."	In case of virtual driving environments, consider providing information on the scenario in a video (or other data) format.
	Psychobiological assessments	Describe all relevant information to replicate the psychobiological assessments, including (if applicable) information on time and content (including related instructions) at which the data or specimen is collected; procedures of data/sample collection; equipment/material used to collect data/samples; processing, quality check, and storage of the data/samples; mathematical, biochemical, and statistical analyses (including information on quality characteristics of the analyses); as well ase reference values.	➔ *For examples, please refer to studies published in established journals, reporting on respective psychobiological assessments.*	Refer to respective guidelines for application of certain psychobiological parameter, if available[4].
	Other	Subjective perceptions and other human factors regarding vehicle use, DAS and DAS-related experiences, driving environment / ODD, etc. may be of relevance, depending on the study question, should be reported as required.	–	Consider using available taxonomy recommendations and definitions[5] for consistent use of terms related to human factors.
Discussion	Generalizability	Discuss generalizability of findings with regard to vehicle user, vehicle, driving automation level, setting (e.g. generalizability from simulated to real-world driving), driving environment / ODD, etc.	"One limitation is the potential lack of representativeness of vehicle users agreeing to participate in the study; however, the characteristics of study participants with regard to age, sex, years since obtaining driving license, and conventional driving experience were very similar to those of participants of a recent representative survey on vehicle use in Switzerland."	–
	Implications	In addition to implications for future research and health care (clinical implications), consider discussing implications for policy makers, NGOs, companies and industry, as well as respective decision makers.	–	–

Abbreviations: ADS, Automated Driving System; DAS, Driving Automation System; NGO, non-governmental organization; ODD, operational design domain; SAE, SAE international's J3016, taxonomy and definitions for terms related to driving automation systems[2]; UNECE, United Nations Economic Commission for Europe.

[1] When using vehicles at SAE driving automation levels 4 and 5, the human users of the vehicles are under most circumstances correctly referred to as passengers or dispatchers, not as drivers.

[2] e.g., Dingus et al. (2015).

[3] see On-Road Automated Driving (Orad) Committee, 2018.

[4] e.g., Stalder et al. (2016).

[5] e.g., Automated Driving System Committee (2016).

Automated Driving (Orad) Committee, 2018).

4.5. Implications

Our review has several implications for future research: We provide a theoretical framework and reporting guidelines for future studies in the field. Further, synthesized evidence of the here identified studies point out to the relevance of variation in ergotropic activity for highly automated driving. However, future research is needed that thoroughly scrutinizes different potentially relevant psychobiological systems and their covariation with features of the outer and inner compartment of the environment of the embodied vehicle user (see Section 4.4) across driving automation level and features. Notably, we only identified studies using psychophysiological methods. However, there is one recent article in press (published after the last search conducted for the systematic review and hence not included in our data synthesis), in which the authors (Arakawa et al., 2018) amongst others successfully applied psychoneuroendocrinological methods (i.e., assessing salivary alpha-amylase) to compare the physiological states of drivers during automated driving and while resuming manual control of the vehicle, concluding that drivers, once accustomed to automated driving, may experience stress upon switching to manual control (for detailed information, see online supplemental material 3). Notably, by assessing the psychoneuroendocrinology of highly automated driving, Arakawa and colleagues open up a new area of research.

From an engineering, manufacturer, and developer perspective, our review points out to the potential of taking into account human psychobiology, not only in terms of improving human-machine interactions, but by adopting an integrative view on how ADS can be designed and applied to improve users subjective experiences, emotions, and health, bringing ADS-equipped vehicles from lab to street for the sake of all potential vehicle users. For example, choice of driving automation level has been primarily discussed as driven by technology and ODDs. However, the here proposed EMBODD model suggests that beyond that, driving automation levels may be chosen on the background of the ODD, as new tool for the in-vehicle user to support her/him in attaining an intended psychobiological state, with potential benefit for her/his subjective vehicle use related perception, emotions, and well-being. Thereby, considering the psychobiology of ADS users may pave new ways to improve vehicle-use related perception, performance and potentially even health, even though we are just about to begin understanding mental and psychobiological processes related to the use of highly automated driving.

4.6. Conclusion

Based on a systematic review on the psychobiology of highly automated driving, we have synthesized evidence suggesting that using vehicles with engaged ADS goes along with tractable changes in peripheral biology. Informed by the conceptual endophenotype approach (Hellhammer et al., 2018, *Psychoneuroendocrinology*), we have put forth the EMBODD model, which may inform how the embodied ADS-engaged vehicle use experience can be improved and optimized, amongst other regarding functionality, subjective perception, emotions, and health of the drivers and passengers. To foster this new area of research, we have suggested some reporting recommendations and are exited to observe how this emerging field will develop.

Conflict of interests

None

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Appendix A. Supplementary data

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