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How to keep drivers engaged while supervising driving automation? A literature survey and categorisation of six solution areas

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ABSTRACT

This work aimed to organise recommendations for keeping people engaged during human supervision of driving automation, encouraging a safe and acceptable introduction of automated driving systems. First, heuristic knowledge of human factors, ergonomics, and psychological theory was used to propose solution areas to human supervisory control problems of sustained attention. Driving and non-driving research examples were drawn to substantiate the solution areas. Automotive manufacturers might (1) avoid this supervisory role altogether, (2) reduce it in objective ways or (3) alter its subjective experiences, (4) utilize conditioning learning principles such as with gamification and/or selection/training techniques, (5) support internal driver cognitive processes and mental models and/or (6) leverage externally situated information regarding relations between the driver, the driving task, and the driving environment. Second, a cross-domain literature survey of influential human-automation interaction research was conducted for how to keep engagement/attention in supervisory control. The solution areas (via numeric theme codes) were found to be reliably applied from independent rater categorisations of research recommendations. Areas (5) and (6) were addressed by around 70% or more of the studies, areas (2) and (4) in around 50% of the studies, and areas (3) and (1) in less than around 20% and 5%, respectively. The present contribution offers a guiding organisational framework towards improving human attention while supervising driving automation.

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Attention; engagement; supervisory control; automated driving; human monitoring of automation

Relevance to human factors/Relevance to ergonomics theory

A good amount of human factors research has already previously been devoted to examining human vigilance in supervising automated process (both by experimental investigation and literature review synthesis). However, given recent advances and accidents with humans

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supervising driving automation, an applied literature survey and categorization of solution areas has been undertaken to organize promising directions for the mutual benefit of both academic theory (which attention solution themes are more/less common in various supervisory operator domains) and to automotive system designers (what could work for them towards keeping their drivers engaged during supervision of autonomous driving).

Background

Addressing human driving errors with automation technology

Traffic safety literature has predominately implicated human behaviour and cognition as principal factors that cause motor vehicle crashes and fatalities. Treat et al. (1979) performed 2,258 on-site and 420 in-depth accident investigations and found that human errors and deficiencies were a cause in at least 64% of accidents, and were a probable cause in about 90–93% of the investigated accidents. Treat et al. (1979) identified major human causes as including aspects such as improper lookout, excessive speed, inattention, improper evasive action and internal distraction. The National Highway Traffic Safety Administration (NHTSA 2008) conducted a nationwide survey of 5,471 crashes involving light passenger vehicles across a three year period (January 2005 to December 2007). NHTSA (2008) determined the critical reason for pre-crash events to be attributable to human drivers for 93% of the cases. Critical reasons attributed to the driver by NHTSA (2008) included recognition errors (inattention, internal and external distractions, inadequate surveillance, etc.), decision errors (driving aggressively, driving too fast, etc.) and performance errors (overcompensation, improper directional control, etc.).

Consequently, Advanced Driving Assistance Systems (ADAS) and Automated Driving Systems (ADS) are commonly motivated as solutions to address transportation safety problems of human errors (Gao, Hensley, and Zielke 2014; Kyriakidis et al. 2015; NHTSA 2017). SAE International (SAE) originally released a standard J3016_201401 (SAE 2014) that conveyed an evolutionary staged approach of five successive levels of driving automation ranging from '*no automation*' to '*full automation*' (herein referred to as SAE Level 0–5). While the SAE standard has been revised several times to its most current version available as of June 2018 (SAE 2018), its principal levels have been retained and continue to be a common reference point for the automotive automated/autonomous vehicles (AVs) research domain. Automotive manufacturers have already begun to release various SAE Level 2 '*Partial Automation*' systems within their on-market vehicles, which allow combined automatic execution of both lateral and longitudinal vehicle control under specific operational design domains. At SAE Level 2, drivers are still expected to complete object and event detection and response duties while retaining full responsibility as a fall-back to the driving automation (SAE 2018).

New roles, new errors: supervisors of mid-level driving automation

A complicating issue along the path to fully autonomous self-driving cars exists for the SAE Level 2 partial automation systems in regard to driver supervisory engagement and retention of responsibility. Owners' manuals, manufacturer websites and press releases of recent on-market SAE Level 2 systems were collected as background material to understand how the industry is presently addressing this issue. A sample of recently released SAE Level 2 driving automation systems and their Human Machine Interfaces (HMI) regarding human disengagement is organised in Table 1. This overview suggests that vehicle manufacturers

Table 1. Partially automated driving releases (~2017)[#].

Make	Model	System	Terms for driver state of engagement	Engagement input modality[a]	Engagement output modality[b]	Inattention escalation intervals
Volvo Cars	XC90, S90, V90	Pilot assist II	Attention, judgment	VLa VLn VMsc	AU VI TOC	0
GM, Cadillac	CT6	Driver attention system (super cruise)	Attention, awareness, supervision, engagement	VI	AU VI TA TOC	>1
Tesla	Model S, Model X	Autopilot Tech Package v. 8.0	Alert, safely, in control, hands-on, mindful, determine appropriate, be prepared	VLa	AU VI TOC	5
Audi	A4, Q7	Traffic jam assist	Be in control, ready, responsible, assessing, attention	VLa VMsc	AU VI TOC	>1
BMW	750i, 7 series	Active driving assistant plus	Be in control, responsible, correctly assess traffic situation, adjust the driving style to the traffic conditions, watch traffic closely, actively intervene, attentively	VLa	AU VI (TA) TOC	1
Infiniti	Q50S	Active lane control	Be alert, drive safely, keep vehicle in travelling lane, control of vehicle, correct the vehicle's direction	(VLa)	(AU) (VI)	−1
Daimler, Mercedes-Benz	S65 AMG	Distronic plus with steering and active lane-keeping assist	Adapt, aware, ensure, control, careful observation, be ready, maintain safety	VLa VMsc	AU VI (TA) TOC	1

[#]sources of information.

- Volvo Cars
  - http://volvornt.harte-hanks.com/manuals/2017/S90_OwnersManual_MY17_en-US_TP22301.pdf
  - http://volvo.custhelp.com/app/answers/detail/a_id/9769/~/new-features-available-as-of-november-2016
- GM, Cadillac
  - http://media.gm.com/media/us/en/cadillac/news.detail.html/content/Pages/news/us/en/2017/apr/0410-super-cruise.html
  - https://www.youtube.com/watch?v=Shm3GY_JG-w
- Tesla
  - https://www.tesla.com/sites/default/files/model_s_owners_manual_north_america_en_us.pdf
- Audi
  - http://ownersmanual.audiusa.com/
  - http://www.audi.com/en/innovation/piloteddriving/assistance_systems.html
  - https://www.youtube.com/watch?v=T8ESfICGnAc
  - https://www.youtube.com/watch?v=RMj4H4ybEkc
- BMW
  - https://www.bmwusa.com/owners-manuals.html
  - http://www.bmw.com/en/topics/fascination-bmw/connected-drive/driver-assistance.html
  - https://www.youtube.com/watch?v=RKAE-ANKIBY
  - https://www.youtube.com/watch?v=7fqXJcscjzw
- Infiniti
  - https://owners.infinitiusa.com/content/manualsandguides/Q50/2017/2017-Q50-owner-manual-and-maintenance-info.pdf
- Daimler, Mercedes-Benz
  - https://www.mbusa.com/mercedes/service_and_parts/owners_manuals#!year =2017&class = S-Sedan
  - http://techcenter.mercedes-benz.com/en/distronic_plus_steering_assist/detail.html
  - http://techcenter.mercedes-benz.com/en_ZA/steering-pilot/detail.html
- Unofficial demonstration/review reports
  - https://www.youtube.com/watch?v=Rjvl57BlDp0
  - https://www.caranddriver.com/features/semi-autonomous-cars-compared-tesla-vs-bmw-mercedes-and-infiniti-feature-2016-bmw-750i-xdrive-page-4
  - https://www.youtube.com/watch?v=isZ3fSbE_pg
  - https://www.youtube.com/watch?v=C7xV9rMajNo

[a]Input modalities (vehicle from driver): VLa = vehicle lateral, steering, etc.; VLn = vehicle longitudinal, brake, gas, etc.; VMsc = vehicle misc. seat buckle, weight on seat, door lock, etc.

[b]Output modalities (vehicle to driver): AU = audio; VI = visual; TA = tactile/haptic/vestibular; TOC = transition of control, change in functionality/level, etc.

do share some concern for the topic of human supervisory oversight of their driving automation. Notably, such concerns appear mostly in arguably passive (e.g. instructional guidelines and warnings), indirect (e.g. surrogate sensing of attention/involvement) and/or reactive (e.g. post-incident alerting) manners.

Most manufacturers kept their descriptions of driver engagement responsibilities and requirements during use of their SAE Level 2 systems at a higher level than commonly found in research communities (e.g. manufacturers did not commonly use aberrant driver state terminology such as *'drowsiness', 'distraction', 'inebriation',* etc.). Instead, manufacturer examples included abstracted aspects like always being aware of and acting appropriately in traffic situations or being '*in control*'. Some notable specifics for the remaining driver responsibility include Mercedes' detailing of vehicle speed, braking, and staying in the lane (Mercedes-Benz 2017, p. 177), a few statements from BMW that hands must be kept on the steering wheel (BMW 2017), and repetitive remarks from Tesla regarding their hands-on requirements (Tesla 2017, p. 73), including an entire sub-section entitled '*Hold Steering Wheel*' (Tesla 2017, p. 74).

Across the various inputs that are interpreted as aberrant driver engagement/readiness (e.g. inadequate braking levels, unbuckled seatbelts, open doors and driver-facing cameras), the most common classification was that of measures associated with lateral vehicle control (i.e. steering wheel touch/torque and/or lane position). GM/Cadillac currently stands out as the only one so far to use a visual modality of a driver-facing camera to ascertain driver inattention. The consequential output modalities of auditory, visual and transitions of control (ToC) were found to be used by all manufacturers in their reactive HMI strategies. One manufacturer officially mentioned use of a tactile modality alert (GM/Cadillac) while a few others (Mercedes, BMW) were found in unofficial reports (MercBenzKing 2016; Sherman 2016).

By counting stages beyond a first warning (i.e. escalation intervals), Tesla was found to use the highest number of escalations in their reactive HMI. At least five escalations were observable from online Tesla owner videos (e.g. Black Tesla 2016; Super Cars 2017). Descriptions and approximated timings of the following escalations are in regards to coming after the initial warning of a grey filled textbox with wheel icon and '*Hold Steering Wheel*' message at the bottom of the dashboard instrument cluster.

1) +2 seconds after first warning — dashboard instrument cluster border pulses in white with an increasing rate;
2) +15 seconds after first warning — one pair of two successive beeps;
3) +25 seconds after first warning — two pairs of two successive beeps;
4) +30 seconds after first warning — at the bottom of the instrument cluster, a red filled textbox plus triangle exclamation point icon with two line written messages of 'Autosteer Unavailable for the Rest of This Drive' on line one, and 'Hold Steering Wheel to Drive Manually' on line two in smaller font, along with a central image of two red forearm/hands holding a steering wheel that replaces the vehicle's lane positioning animation, with the same previous pairs of successive beeps repeatedly sounding in a continuous manner, and the vehicle gradually reducing speed
5) +37 seconds after first warning — all alerts from previous level remain, two yellow dots are added at the beginning of each forearm, and the vehicle hazard blinkers are activated

A few manufacturers could be determined as having more than one escalation (GM/Cadillac, Audi), a few others as exactly one escalation (BMW, Daimler/Mercedes-Benz)

and Volvo appeared to have a single first level/stage warning with no further escalation. Infiniti appeared to have no HMI reactive to driver disengagement/misuse of their Level 2 system (Active Lane Control). All but one manufacturer (Infiniti) were found to use at least the visual modality in their first stage of warning against driver disengagement.

Introduction of solution grouping framework

Proactive solution strategies for human engagement in supervisory control

To complement the passive, indirect and/or reactive approaches presently available in the aforementioned on-market industry examples, a set of proactive solution strategies towards human engagement in supervisory control might be helpful. Longstanding human factors and ergonomics principles have previously suggested risks in relying on humans as monitors of automated (e.g. invariant, predictable, monotonous, etc.) processes over extended periods (Bainbridge 1983; Greenlee, DeLucia, and Newton 2018; Hancock 2017a; Mackworth 1950; Molloy and Parasuraman 1996). Thus, it was expected that many solutions might exist across the academic literature and could benefit from a qualitative framework for organising trends and patterns in their recommendations.

A natural starting point to the difficulties in human supervisory control of driving automation is to avoid the supervisory role outright (e.g. skip SAE Level 2). Logically, softer versions of such a hard stance might also be realisable in either objective or subjective ways. Objectively, the amount of time or envelope of automated functionality could be reduced. Subjectively, the supervisory experience of responsibility could be refashioned with altered perceptions of the human's role towards shared or even fully manual authority. Furthermore, extensive research conducted under multiple paradigms of psychological theory might suggest approaches out of different schools of thought. The behaviourism paradigm centres around conditioning learning theories and suggests associative stimuli and/or stimulus-response pairing principles to promote the desired behaviour and discourage that which is undesirable. The cognitivism paradigm focuses on internal information processes and advises ways to support limited mental resources, representations and awareness. Lastly, ecological approaches emphasise inclusion of external considerations of the task and the environment surrounding the worker/learner towards enhanced relational performance from a broader systems-level view.

In summary, a grouping framework of six proactive solution areas is proposed to help answer the question '*How do we keep people engaged while supervising (driving) automation?*' In each case, the solution areas are introduced first in a general manner of various automation domains, before exemplifying relevancy specifically for engagement in supervisory control of driving automation.

Solution Area (1): Avoid the role of sustained human supervision of automation
- Suspend/repeal/skip levels of automation requiring human oversight and backup
  - '*just don't do it*'

Solution Area (2): Reduce the supervising role along an objective dimension
- Change the amount of time or envelope of automated operations
  - '*don't do it as much*'

Solution Area (3): Reduce the supervising role along a subjective dimension

- Share responsibilities and/or alter the end user experience and impressions
  - '*do it without drivers having to know about it*'

Solution Area (4): Support the supervising role from the behaviourism paradigm
- Condition the desired target behaviours through training and selection
  - '*make or find drivers who do it better*'

Solution Area (5): Support the supervising role from the dyadic cognitivism paradigm
- Inform designs to support cognitive processes and mental models
  - '*focus on internal mental constructs*'

Solution Area (6): Support the supervising role from the triadic ecological paradigm
- Inform designs to leverage external environment contexts and task considerations
  - '*focus on external task/environment factors*'

Solution area (1): avoid the role of human supervision of automation

The most parsimonious proactive solution could be to avoid subjecting drivers to the unnatural requirement of monitoring automated processes. Decades of human factors and ergonomics research have echoed that this is not something humans do well. A resounding result from Norman Mackworth (1948) was that despite instruction and motivation to succeed in a sustained attention task (used as an analogy to the critical vigilance of WWII radar operators watching and waiting for enemy target blips on their monitor screens), human detection performance dropped in relation to time-on-task. Thousands of reports have since been published on the challenges of human vigilance, also known as '*sustained attention*' (Cabrall, Happee, and De Winter 2016; Craig 1984; Frankmann and Adams 1962). Bainbridge (1983) observed the irony that human supervisory errors are expected when operators are left to supervise an automated process put in place to resolve manual control errors. Humans were described as deficient compared to machines in prolonged routine monitoring tasks, as seen in the MABA-MABA (Men Are Better At – Machines Are Better At) list by Fitts (1951), and such characterisations persist today (De Winter and Dodou 2014). In a review of automation-related aircraft accidents, Wiener and Curry (1980) suggested that it is highly questionable to assume that system safety is always enhanced by allocating functions to automatic devices rather than human operators. They instead consider first-hand whether a function *should* be automated rather than simply proceeding because it *can* be.

Driver responses have been found to be negatively impacted when having to respond to simulated automation failures while supervising combined automatic lateral and longitudinal driving control (De Waard et al. 1999; Stanton et al. 2001; Strand et al. 2014). From elaborated operator sequence diagram models, Banks, Stanton, and Harvey (2014) indicated that far from reducing driver workload, additional sub-system tasks associated with monitoring driving automation actually would increase cognitive loads on a driver. Banks et al. (2018) analysed on-road video observations of participants operating a Tesla Model S in Autopilot mode (i.e. SAE Level 2 driving automation). They found that drivers were not properly supported in adhering to their new monitoring responsibilities, and were showing signs of complacency and over-trust. Accordingly, Banks et al. (2018) discussed a possibility that certain levels of driving automation (DM, driver monitoring) need not be implemented even if they are feasible from a technical point of view, and that a simplified set of roles of only DD (driver driving) and DND (driver not driving) could be preferred from a human factors role/responsibility point of view.

> '…*it seems more appropriate at the time to accept that the DD and the DND) roles are the only two viable options that can fully protect the role of the human within automated driving systems. This in turn means that either the human driver should remain in control of longitudinal and/or lateral aspects of control (i.e. one of the other) or they are removed entirely from the control-feedback loop (essentially moving straight to SAE 4)'. (p. 144).*

Solution area (2): reduce the role along an objective dimension

In the mid-1990s, several key studies suggested a less strict avoidance approach in the human supervision of automation. Various schemes for alternating periods of manual and automated control were investigated, for example by, Parasuraman, Mouloua, and Molloy 1996; Scallen, Hancock, and Duley 1995; and Endsley and Kiris 1995. In Parasuraman, Mouloua, and Molloy (1996), adaptive control conditions where control was temporally returned to a human operator showed subsequent increases in monitoring performance compared to a non-adaptive full automated condition. In Scallen, Hancock, and Duley (1995), adaptive switching between manual and automated control was investigated at short time scale intervals (i.e. 15, 30 and 60 seconds). Objective performance data indicated better performance with shorter rather than longer cycles. However, such benefits were associated with increased workload during the shorter cycle durations (i.e. the participants did better only at the cost of working harder and prioritising a specific sub task). Thus, the authors concluded that if the goal of the operator is to maintain consistency '*on all sub-tasks, at all times*' then the performance immediately following episodes of short automation warrants particular concern: i.e. '*the results support the contention that excessively short cycles of automation prove disruptive to performance in multi-task conditions*'. In Endsley and Kiris (1995) the level of automated control was investigated. Rather than manipulating the length of time of automated control, a shift from human active to passive processing was deemed responsible for decreased situation awareness and response time performance. Manual control response times immediately following an automation failure were observably slower compared to baseline manual control periods. However, the effect was less severe under partial automation conditions compared to the full automation condition.

In Merat et al. (2014), a motion-based driving simulator experiment study was conducted with adaptive automation. They compared a predictable fixed schedule for triggering ToC to manual control with a real-time criterion which switched to manual based on the length of time drivers were looking away from the road. The authors concluded that better vehicular control performance was achieved when the automated to manual ToC was predictable and based on a fixed time interval.

Solution area (3): reduce the role along a subjective dimension

Rather than altering the objective amount of automated aid as in solution area (2), automation system design can also focus on the driver's psychological subjective experience or perception of responsibility and/or capability. In other words, manual human operator behaviour is not replaced in solution area (3) but augmented, extended and/or accommodated. Such subjective shaping might take the form either as help (e.g. automatic backup) or even as hindrance (e.g. to provoke positive adaptive responses). Schutte (1999) introduced the concept of '*complemation*' to describe technology that is designed to enhance humans by augmenting their innate manual control skills and abilities rather than to replace them. With such complementary technology, many of the sub-tasks that could be automated are

deliberately not automated, so that the human remains involved in the task. Flemisch et al. (2016) relayed similar theoretical concepts and design approaches where both the human and the machine should act together at the same time under a '*plethora*' of names, such as shared control, cooperative control, human-machine cooperation, cooperative automation, collaborative control, co-active design, etc. Young and Stanton (2002) proposed a Malleable Attentional Resources Theory positing that the size of relevant attentional resource pools can temporally adapt to changes in task demands (within limits). Thus, cognitive resources may actually be able to shrink/grow to accommodate various decreases/increases in *perceived* demands (e.g. even while retaining objective protections in the background).

Janssen (2016) evaluated simulated automated driving as a backup and found improved lateral performance and user acceptance (workload and acceptance) compared to adaptive automated-to-manual ToC. Mulder, Abbink, and Boer (2012) improved safety performance and decreased steering variation in a fixed-base driving simulator through the use of haptic shared control. By requiring and retaining some level of active control from the human driver (i.e. amplification of a suggested torque), the shared control model was expected by Mulder, Abbink, and Boer (2012) to maintain some levels of engagement, situation awareness, and skill as compared to the supervisory control of automation.

A concept of promoting increased care in driving from the end-user by a seemingly reductive or even counter-productive human-automation interface design can be found in Norman (2007). In order to keep human drivers informed and attentive, the proposition suggested that more requirements for human participation might be presented than is really needed. In other words, an automated driving system can encourage more attention from the human supervisor by giving an appearance of being less capable, of doing less or even doing the wrong thing. Norman (2007) exemplified this framework of '*reverse risk compensation*' by reference to Hans Monderman (1945–2008) and then to Elliot, McColl, and Kennedy (2003). In Monderman's designs, the demarcations, rules and right of ways of a designed traffic system are purposefully diminished/removed in favour of shared spaces. The idea is to provoke end-users (drivers, pedestrians, cyclists, etc.) to collectively combat complacency and over-reliance on rules/assumptions by being forced to look out for themselves (and one another). Norman (2007) cited results from Elliot, McColl, and Kennedy (2003) where artificial increases in perceived uncertainty resulted in driver adoption of safer behaviours such as increased information seeking and heightened awareness. In sum, Norman (2007) described an interesting potential of designed automated processes in futuristic cars where there could be an approach of shaping psychological experiences.

> '…*we can control not only how a car behaves but also how it feels to the driver. As a result, we could do a better job of coupling the driver to the situation, in a natural manner, without requiring signals that need to be interpreted, deciphered, and acted upon … The neat thing about smart technology is that we could provide precise, accurate control, even while giving the driver the perception of loose, wobbly controllability*'. (p. 83).

Solution area (4): support the role from the behaviourism paradigm

A historical psychological perspective on shaping people to behave as desired can be traced back to the early 1900s behaviourism learning models of Ivan Petrovich Pavlov ('*classical conditioning*') and Burrhus Frederic Skinner ('*operant conditioning*'). Broadbent and Gregory (1965) attributed prolonged watch detriments to a shift in response criterion whereby operators might be better persuaded towards reacting to doubtful signals (e.g. manipulation of payoff). More recently, the term '*gamification*' has been defined as the '*use of game design*

elements in non-game contexts' (Groh 2012) and was recognised in positive and negative ways to exemplify conditional learning aspects (Terry 2011). In gamification, interface designs utilise the mechanics and styles of games towards increased immersion. Related approaches include an emphasis on skills either acquired over practice (e.g. training focus) and/or from innate pre-dispositions (e.g. personnel selection, individual differences, etc.). Neuro-ergonomic approaches in Nelson et al. (2014) improved vigilance task performance via transcranial direct current stimulation. Parasuraman et al. (2014) identified a genotype associated with higher skill acquisition for executive function and supervisory control. Sarter and Woods (1993, p. 118) advised directions to support awareness through '*new approaches to training human supervisory controllers*', and Gopher (1991) suggested potential promise via the enhancement of '*skill at the control of attention*'.

Behaviouristic dispositions are also observable in the automotive domain concerning increased driver vigilance with ADAS. Similar to the aforementioned investigations of selection interest (e.g. neurological disposition for enhanced cognitive executive control), automotive research recommendations have included the implementation of training programmes and/or gamified concepts. This solution area aims to enhance operators without enough attentive skills or executive control for sustained focus, to instead obtain such skill/focus via extra practice, immersion and/or motivation. Diewald et al. (2013) reviewed '*gameful design*' and saw promise for its use for in-vehicle applications (e.g. navigation, safety and fuel efficiency). For driving safety, virtual money/points and virtual avatar passengers were identified as rewards/punishments tied to onboard diagnostics of driving styles. In Lutteken, Zimmermann, and Bengler (2016), a simulated highly automated highway driving vehicle performed longitudinal and lateral control while the human driver controlled lane changes as a manager of consent. A gamified concept consisting of partner teaming, virtual currency points that could be earned/spent, and time scores was found to motivate and increase the desired cooperative driver behaviours. In a test-track study, Rudin-Brown and Parker (2004) found increased response times to a hazard detection task while using adaptive cruise control (ACC). Rudin-Brown and Parker (2004) concluded that response times to the ACC failure were related to drivers' locus of control and suggested driver awareness training as a potential preventive strategy that could minimise negative consequences with using novel ADAS. The TRAIN-ALL (European Commission co-funded) project had the objective to develop training schemes and scenarios for computer-based training in the use of new ADAS (Panou, Bekiaris, and Touliou 2010). Panou, Bekiaris, and Touliou (2010) evaluated various ADAS training simulations so that trainees would learn how to optimally use ADAS without overestimating their functionality and maintain appropriate knowledge of their limitations.

Solution area (5): support the role from the dyadic cognitivism paradigm

The internal human mind is the focus of solution area (5). The chapter '*The Human Information-Processer*' of Card, Moran, and Newell (1983) described a model of communication and information processing where sensory information flows into working memory through a perceptual processor, working memory consists of activated chunks in long-term memory and the most basic principle operation consists of cycles of recognising and acting (e.g. resulting in commands to a motor processor). In accord with this seminal work, cognitive user-centric interface design theory and practices (e.g. Johnson 2010) have generally used metaphors and constructs to align content, structure and functions of computerised systems with content, structure and functions of human minds: attention (Sternberg 1969; Posner 1978), workload (Ogden, Levine, and Eisner 1979; Moray 1982), situation awareness

(Endsley 1995), (mental-spatial) proximity compatibility principle (Wickens and Carswell 1995), and multiple (modality) resource theory (Wickens 1980, 1984). Similar mentally focussed accounts persist for the topic of sustained attention and monitoring. Parasuraman (1979) concluded that loads placed on attention and memory are what drive decrements in vigilance. See et al. (1995) argued for the addition of a sensory-cognitive distinction to the taxonomy of Parasuraman (1979), where it was emphasised that target stimuli that are (made to be) more cognitively familiar would reduce vigilance decrement consequences. Olson and Wuennenberg (1984) provided information recommendations for user interface design guidelines regarding supervisory control of Unmanned Aerial Vehicles (UAVs) in a list that covered cognitive topics of transparency, information access cost minimisation, projections, predictions, expectations and end-user understanding of automation. Sheridan et al. (1986) described the importance of mental models in all functions of supervisory control, including aspects for monitoring (e.g. sources of state information, expected results of past actions and likely causes of failures) and intervening (options and criteria for abort and for task completion). Lastly, the highly cited human trust of automation theory from Lee and See (2004) underscored arriving at *appropriate* trust via cognitive aspects of users' mental models of automation: understandable algorithms, comprehensible intermediate results, purposes aligned to user goals, expectancies of reliability and user intentions.

The importance of mental process components is shared by SAE Level 2 simulator studies (Beggiato et al. 2015; De Waard et al. 1999; Strand et al. 2014) and theoretical accounts (Beggiato et al. 2015; Li et al. 2012). De Waard et al. (1999) were concerned with reduced driver alertness and attention in the monotonous supervision of automated driving. They found emergency response complacency errors in about half of their participants and advocated providing feedback warnings pertaining to automation failures (e.g. clear and salient status indicators). Strand et al. (2014) appealed to an account of situation awareness to explain their findings of higher levels of non-response as well as decreased minimum times to collision when simulated driving automation was increased from an ACC to an ACC plus automatic steering system. Beggiato et al. (2015) used both a driving simulator study (post-trial questionnaires and interviews as well as eye gaze behaviour) and an expert focus group to investigate information needs between SAE Levels 0, 2 and 3, where they found the level 2 to be more exhausting than the other conditions due to the continuous supervision task. Beggiato et al. (2015) concluded that in contrast to manual driving where needs are more oriented around driving-task related information, for partially and highly automated driving requested information is primarily focussed on status, transparency and comprehensibility of the automated system. Li et al. (2012) conducted a survey of recent works on cognitive cars and proposed a staged/levelled alignment of automation functions (e.g. perception enhancement, action suggestion and function delegation) with driver-oriented processes (stimuli sensation, decision making and action execution) (c.f. Eriksson et al., in press; Parasuraman, Sheridan, and Wickens 2000).

Solution area (6): support the role from the triadic ecological paradigm

A broad ecological systems view is represented by solution area (6). This perspective relates vigilance problems to an artificial separation of naturally coupled observation-action-environment ecologies. As an extension to information processing approaches, the chapter '*A Meaning Processing Approach*' of Bennett and Flach (2011) described a semiotics model dating back to work of Charles Peirce (1839–1914) that widens a dyadic human-computer

paradigm into a triadic paradigm of human-computer-ecology with functionally adaptive rather than symbolically interpretive behaviour. Flach (2018) observed that minds tend to be situated, in the sense that they adapt to the constraints of situations (like the shape of water within a glass). Gibson (1979) promoted a theory of affordances not as properties of objects but as direct perception of ecological relations and constraints. Particularly in the chapter '*Locomotion and Manipulation*', Gibson (1979) suggested that the dichotomy of the '*mental*' apart from the '*physical*' is an ineffective fallacy. Gibson promotes units of direct perception to be not of things, but of actions with things. Moreover he conveys that such affordances are not available equally in some universal manner, but instead are relatively bounded in a holistic manner. Wickens and Kessel (1979) accounted for a manual control superiority because of a task ecology of continual sensing and correcting of errors together (active adaptation) where additional information (i.e. physical forces) is provided beyond those available from prolonged sensing alone without continual action. Neisser (1978) dismissed accounts of humans as passive serial information processors and instead promoted an indivisible and cyclic account of simultaneous processes. Thus, from such a point of view, vigilance tasks could be considered as problematic because of artificial assumptions and attempts to separate perception and action (i.e. thinking before acting, perceiving without acting, etc.) and to unnaturally isolate a state of knowledge at a singular specific point in time or sensory modality.

Such ecological approaches that emphasise the importance of direct perception and informed considerations of adaptation to specific work domains (tasks and situations) are evident in common across multiple human factors and psychological theories: cognitive systems engineering (Rasmussen, Pejtersen, and Goodstein 1994), situation awareness design (Endsley, Bolte, and Jones 2003), ecological psychology (Vicente and Rasmussen 1990), situated cognition (Suchman 1987), embodied minds (Gallagher 2005), the embedded thesis (Brooks 1991; O'Regan 1992) and the extension thesis (Clark and Chalmers 1998; Wilson 2004). Flach (1990) promoted the importance of ecological considerations by emphasising that humans naturally explore environments, and thus models of human control behaviour have been limited by the (frequently impoverished) environments under which they were developed. He relayed that an overly simple laboratory tracking task '*turns humans into a trivial machine*' and that real natural task environments (of motion, parallax and optic arrays, etc.) are comparatively information rich with relevant '*invariants, constraints or structure*'. Chiappe, Strybel, and Vu (2015) supported a situated approach by observing that '*operators rely on interactions between internal and external representations to maintain their understanding of situations*' in contrast to traditional models that claim '*only if information is stored internally does it count as SA*'. Mosier et al. (2013) provided examples that the presence of traffic may affect the extent to which pilots interact with automation and the level of automation they choose and operational features such as time pressure, weather and terrain may also change pilots' automation strategies as well as individual variables such as experience or fatigue. They found that vignette descriptions of different situational configurations of automation (clumsy vs. efficient), operator characteristics (professional vs. novice) and task constraints (time pressure, task disruptions) led pilots to different predictions of other pilots' behaviours and ratings of cognitive demands. Hutchins et al. (2013) promoted an integrated software system for capturing context through visualisation and analysis of multiple streams of time-coded data, high-definition video, transcripts, paper notes and eye gaze data in order to break through an '*analysis bottleneck*' regarding situated flight crew automation interaction activity. In an UAV vigilance and threat detection task,

Gunn et al. (2005) recommended sensory formats and advanced cuing interfaces and accounted for the reduced workload levels they obtained via a pairing of detections to immediately meaningful consequential actions in a simulated real-world setting (i.e. shooting down a target in a military flight simulation) rather than responses devoid of meaning.

Leveraging external contextual information can be found in several recent driving automation theory and experimental studies. Lee and Seppelt (2009) convey that feedback alone is not sufficient for understanding without proper context, abstraction and integration. Although technically an SAE Level 1 system, ACC also contains supervisory control aspects (i.e. monitoring of automated longitudinal control) and Stanton and Young (2005) concluded that ACC automation designs should depart from conventions that report only their own status, by offering predictive information that identifies cues in the world and relations of vehicle trajectories. Likewise, Seppelt and Lee (2007) promote and found benefits of an ecological interface design that makes limits and behaviour of ACC visible via emergent displays of continuous information (time headway, time to collision and range rate) that relates the present vehicle to other vehicles across different dynamically evolving traffic contexts. In terms of an SAE Level 2 simulation, participants in Price et al. (2016) observed automated lateral and longitudinal control where vehicle capability was indicated via physically embodied lateral control algorithms (tighter/looser lane centre adherence) as opposed to via typical visual and auditory warnings. Consequently, drivers' trust was found to be sensitive to such a situated communication of automation capability. Pijnenburg (2017) improved vigilance and decreased mental demand in simulated supervisory control of SAE Level 2 driving automation via a naturalistic interface that avoided arbitrary and static icon properties in its visual design. A recent theory of driving attention proposed not to assume distraction from the identification of specific activities alone but instead underscored a definition that requires relation in respects to a given situation (Kircher and Ahlstrom 2017). After conducting several driver monitoring system (DMS) studies, a concluding recommendation from a work package deliverable of a human factors of automated driving consortium project was to '*incorporate situated/contextualized aspects into DSM systems*' (Cabrall et al. 2017).

Literature Survey Aims

In the previous section, a qualitative grouping framework of six solution areas was introduced to identify trends and group proactive approaches towards human engagement while supervising automated processes. The aim of the following literature survey was to investigate whether the proposed solution areas might be represented in best practice recommendations and conclusions of influential and relevant works from a variety of human operator domains. Additionally, we aimed to identify trends between the solution areas: would some be more commonly found than others?; which might be more/less favoured by different domains?

Methods of literature survey

Inclusion criteria

A scholarly research literature survey was conducted concerning the topic of keeping prolonged operator attention. In line with the terminology results of the automotive on-market survey (Table 1), our search terms were crafted to diminish potentially restrictive biases: of preferential

terminology (vigilance, situation awareness, signal detection theory, trust, etc.), of operationalisation of performance (response/reaction time, fixations, etc.), of state (arousal, distraction, mental workload, etc.) or of specific techniques/applications (levels of automation, autonomous systems, adaptive automation, etc.). Instead, a more general Google Scholar search was performed with two presumably synonymous terms '*engagement*' and '*attention*':

- keeping engagement in supervisory control
- keeping attention in supervisory control

The proactive term (i.e. '*keeping*') was included at the front of the queries to attempt to focus the literature survey away from reactive research/applications (e.g. concerning measurement paradigms).

Google Scholar was used to reflect general access to semantically indexed returns from a broad set of resources as sorted for relevancy and influence in an automatic way. Literal search strings within more comprehensive coverage of specific repository resources were not presently pursued because the present survey was aimed initially for breadth and accessibility rather than database depth or prestige. Comparisons to a more traditional human-curated database (i.e. Web of Science) have concluded that Google Scholar has seen substantial expansion since its inception and that the majority of works indexed in Web of Science are available via Google Scholar (De Winter et al., 2014). Across various academic and industry research contexts, not all stakeholders might share equivalent repository reach, whereas Google Scholar is purposefully engendered as a disinterested and more even playing field. For such a democratic topic of driving safety risks while monitoring driving automation (i.e. that have already been released onto public roadways and might pose dangers for everyone in general), organisation of accessible guideline knowledge collectible from a broad-based Google Scholar resource seemed an appropriate first place methodological motivation ahead of future studies that might make use of more specific in-depth databases.

The 100 titles and abstracts of the first 50 results per each of the two search terms were reviewed to exclude work not pertaining to human-computer/automation research. Furthermore, several relevant and comprehensive review works that were returned in the search (e.g. Sheridan 1992; Chen, Barnes, and Harper-Sciarini 2011; Merat and Lee 2012; etc.) were not included for categorisation on the basis that their coverage was much wider than the present purposes of organising succinct empirical recommendations. Exclusions were also made for works that appeared to focus more on promoting or explaining supervisory control levels or models of automation rather than concluding design strategies to the problem of operator vigilance while monitoring automated processes. One final text was excluded where raters had trouble applying a solution area on the basis that it dealt with remote human operation of a physical robotic manipulator. The research did not seem to share the same sense of human-automation supervisory control as seen in the other texts. The remaining set of 34 publications are listed in Appendix A in reverse chronological order.

Solution area categorisations via numeric theme codes

To investigate the reliability of organising the body of published literature with the proposed solution areas, confederate researchers (i.e. human factors PhD student (co-) authors on the present paper) were tasked as raters to independently categorise the conclusions of the

retrieved research papers. For the sake of anonymity, the results of the three raters are reported with randomly generated pseudonym initials: AV, TX and CO. Raters were provided an overview of the solution areas with numeric theme codes (i.e. Theme 1–6) and tasked with assigning a single top choice code for each of the publications of the inclusion set. The task was identified to the raters as '*to assign a provided theme code number to each of the provided publications texts based on what you perceive the best fit would be in regards to the authors' conclusions (e.g. solution, strategy, guideline, recommendation)*.' Raters were also instructed to rank order any additional theme codes as needed. A survey rather than a deep reading was encouraged, where the raters were asked to sequentially bias their reading towards prioritised sections and continue via an additional as-needed basis (e.g. abstract, conclusions, discussion, results, methods, introduction, etc.) in order to determine the solution area that the author(s) could conceivably be most in favour of. A frequency weighting-scoring system per each theme code was devised where 1 point would be assigned for first choice responses, 0.5 points for second choice responses and 0 points otherwise.

Results of rater categorisations

Inter-rater reliability

First and second choice (where applicable) theme codes from each rater for each publication are presented in Appendix B. For first choice theme codes, statistical inter-rater Kappa agreement was computed via the online tool of Lowry (2018) with standard error computed in accordance with the simple estimate of Cohen (1960). The Kappa between AV and TX was 0.25, with a standard error of 0.11. The Kappa between AV and CO was 0.23, with a standard error of 0.11. The Kappa between TX and CO was 0.21, with a standard error of 0.09. Such Kappa statistic results (i.e. in the range of 0.21–0.40) may be interpreted as representing a '*fair*' strength of agreement when benchmarked by the scale of Landis and Koch (1977) which qualitatively ranges across descriptors of '*poor*', '*slight*', '*fair*', '*moderate*', '*substantial*' and '*almost perfect*' for outcomes within six different possible quantitative ranges of Kappa values.

Initially suggestive of a low level of percentage agreement, only six out of the 34 publications received the same first choice coded theme categorisation across all three raters. However, randomisation functions were used to generate three chance response values (i.e. 1–6) for each of the 34 publications and repeated 100 different times. Thus, it was determined that the chance probability of achieving full agreement for 6 or more publications was less than 1%. In comparison, full agreement by random chance was observed for 0 publications to be 40%, for 1 publication to be 37%, for 2 publications to be 15%, for 3 publications to be 6%, for 4 publications to be 1%, for 5 publications to be 1%, and for 6 or more publications to be <1%. Simulations with up to 1 million repetitions verified such a range of chance performance across 0–6 publications: 38%, 37%, 18%, 5%, 1%, <1%, 0%.

Furthermore, matched categorisations between any two rather than all three of the raters was considered. As such, 27 out of the 34 publications received the same first choice coded theme categorisation between at least two raters. As with the preceding full agreement analyses, random chance probabilities of two-way agreement were also computed from 100 sets of 3 random values for each of the 34 publications. The chance probability of achieving two-way categorisation agreement for 27 or more publications was also determined to be less than 1%.

In comparison, random chance two-way agreement was observed for between 31 and 34 publications to be less than 1%, for 26–30 publications to be less than 1%, for 21–25 publications to be 5%, for 16–20 publications to be 42%, for 11–15 publications to be 46%, for 6–10 publications to be 7% and for 5 or fewer publications to be less than 1%. Simulations with up to 50,000 repetitions verified such chance performance across the ranges of 31–34, 26–30, 21–25, 16–20, 11–15, 6–10 and 0–5 respectively as 0%, <1%, 3%, 41%, 50%, 5%, and <1%.

Theme frequency

Weighted frequency scores (i.e. from aggregated first and second choice responses across raters) for each theme code and per each publication are listed in reverse chronological order in Table 2. Theme 5 appears to be the most common solution area, followed closely by 2 and 6. In contrast, Theme 1 appears to be the rarest, followed by Theme 3. While the majority of publications received heavy score weightings distributed across several themes, a highest likelihood single theme was recognisable for 28 of the 34 references (82%), as a result of the first and second choice rater aggregation scoring scheme. Theme 2 of objective reduction of amounts of human supervisory control of automation was found to be the most frequent first choice solution area labelled by two out of the three raters (i.e. AV and CO), whereas TX most often identified Theme 5 pertaining to support of internal cognitive processes and mental models. Theme 5 was also the most frequent second choice for TX and AV. Theme 6 regarding the use of external contexts and task considerations was the most frequent second choice of CO.

All publications of the included thematic analysis set were informally organised into primary operational domain(s) of concern (i.e. what job or service was the human supervisory control of automation investigated in). Most likely solution areas from weighted raters' first and second choice applied theme codes were determined per publication. Domains and most likely themes are combined in reverse chronological order in Table 3. In general, it can be observed that for the included publications, the domain areas have shifted over the decades from more general laboratory and basic research and power processing plants towards more mobile vehicle/missile applications and most recently especially with remotely operated vehicles. Although of limited sample size, some general domain trends might be observed. For example, it appears that uninhabited aerial vehicle (UAV) operations predominately favoured Theme 2 with also some consideration for Theme 6. In contrast, uninhabited ground vehicle (UGV) operations presently indicated only Theme 4. Earlier work with space, power plants and general basic research showed a mix mostly of Themes 5 and 6. Aviation areas with pilots and air traffic control had a split of Themes 4 and 5. Missile air defence consisted of Theme 4 and Theme 2. Lastly, two automobile studies were present in the returned results: the first involving a fairly abstracted driving decision task (with a resulting likely categorisation of Theme 2), and the second evidencing a split categorical rating assignment between Theme 2 and Theme 5.

Discussion

Evolution of cross-domain concern

With a proliferation of automation also comes an increase in human supervision of automation (Sheridan,1992) because automation does not simply replace but changes human

Table 2. Weighted frequency scores for aggregated first and second choices by each inter-rater for each publication reference. Highest weights per publication are outlined.

Ref ID	Weight of Theme 1	Weight of Theme 2	Weight of Theme 3	Weight of Theme 4	Weight of Theme 5	Weight of Theme 6
1	0.0	2.0	0.0	0.0	2.0	0.0
2	0.0	1.0	0.0	0.0	0.5	2.5
3	0.0	2.0	0.0	1.0	0.5	0.5
4	0.0	1.5	0.0	0.0	0.5	2.5
5	0.0	0.0	0.0	2.0	1.5	0.5
6	0.0	0.5	0.0	1.5	1.0	1.0
7	0.0	0.0	0.0	3.0	0.5	0.0
8	0.0	2.0	0.0	0.5	1.0	0.0
9	0.0	2.5	0.0	0.5	1.5	0.0
10	0.0	2.5	0.0	0.0	1.0	0.0
11	1.0	1.0	0.0	0.0	1.0	0.0
12	0.0	2.0	0.0	0.0	0.5	1.0
13	0.0	0.0	0.0	1.0	1.5	2.0
14	0.0	2.5	0.0	0.0	0.0	2.0
15	0.0	3.0	0.5	0.0	0.0	0.5
16	0.0	0.0	0.0	3.0	0.0	0.5
17	0.0	0.0	0.0	0.5	1.0	3.0
18	0.0	2.0	0.0	0.0	1.0	0.5
19	0.0	1.0	0.0	0.0	1.0	1.0
20	0.0	0.0	1.0	0.0	1.0	2.0
21	0.0	2.0	0.5	0.0	1.0	0.5
22	0.0	0.0	1.5	0.0	1.0	1.5
23	0.0	1.0	0.0	2.0	0.5	0.0
24	2.0	2.5	0.0	0.0	0.0	0.0
25	0.0	1.0	0.0	2.0	0.5	0.0
26	0.0	0.0	0.0	0.5	2.0	1.5
27	0.0	0.0	0.0	3.0	0.5	0.5
28	0.0	0.0	0.0	0.0	1.0	2.5
29	0.0	0.0	1.0	0.0	0.5	2.0
30	0.0	0.0	0.0	1.0	3.0	0.0
31	0.0	0.0	1.0	0.0	1.5	1.0
32	0.0	1.0	0.0	0.0	1.5	1.5
33	0.0	0.0	0.0	0.0	2.0	1.5
34	0.0	0.5	0.0	2.0	2.0	0.0
Total:	3.0	33.5	5.5	23.5	34.0	32.0

activity. Such changes often evolve in ways unintended or unanticipated by automation designers and have been predominately regarded in a negative sense as in '*misuse*', '*disuse*' and '*abuse*' (Parasuraman and Riley 1997) and/or as '*ironies*' (Bainbridge 1983). Whether or not significant human supervisory problems will manifest in a proliferation commiserate with automation propagation is likely to be a function of the automation's reliability in the handling of the problems inherent in its' domain area. Human supervisors of automation are needed not only because a component might fail (e.g. electrical glitch) but also

Table 3. Primary operator domains of publications with identified likely thematic solution category from aggregate inter-rater first and second choice weighted scores.

Ref ID	U(x)V	UAV	UGV	USV	UUV	Pilot	ATC	Missile	Auto-mobile	Naval Vessel	Space	Power Plant	General	Radar	ComCon
1									2/5						
2		6													
3	2	2			2										
4	6														
5			4												
6			4												
7							4								
8	2	2		2											
9	2	2			2										
10		2													
11		1/2/5													
12								2							
13		6													
14		2													
15		2											2		
16								4							
17		6													
18	2	2													
19	2/5/6														
20															6
21	2	2													
22							3/6						3/6		
23													4		
24									2						
25						4									
26						5									
27								4							
28												6			
29							6			6				6	
30						5									
31												5	5		
32													5/6		
33											5				
34													4/5		

ATC = ground-based air traffic control; Automobile = automotive cars, trucks, etc.; ComCon = general military command/control, tactical operations; General = laboratory, basic research; Missile = air defence command and control; Naval vessel = battleship, aircraft carrier, etc.; Pilot = flight-deck, cockpit; Power Plant = hydro, nuclear, electric, gas, oil, etc.; Radar = military asset defence of airfield, ship, etc.; Space = spacecraft, satellites, etc.; UAV = uninhabited aerial vehicles; UGV = uninhabited ground vehicles; USV = uninhabited surface vehicles, ships; UUV = uninhabited underwater vehicles; U(x)V = uninhabited vehicles, robots.

because the situation might exceed the automatic programing. Originally, computers and their programmes were physically much larger and constrained to determinable locations within predictable and enclosed environments. As computers have become physically smaller their automated applications could be more practically incorporated into vehicles. Vehicles, however literally move across time and space and hence are subject to many environmental variants. Advances in supervisory control automation have been originally appropriate and suitable to vast expanse domains (outer space, the oceans, the sky) because they are difficult for humans to safely and commonly inhabit. Thus, such domains typically suffer from impoverished infrastructures and are subject to signal transmission latencies where automation must close some loops itself. Such automatic closures are benefited further by the absence of masses of people because compared to machines, people create more noise and uncertainty with many different kinds of unpredictable and/or imprecise behaviours.

Likewise, driving automation was first showcased on highly structured freeways (Ellingwood 1996), out in the desert and within a staged urban environment on a closed air force base (DARPA 2014) before progressing towards more open operational design domains. Subsequently, driving automation market penetration has tended to begin first within more closed campus sites and scenarios with lower levels of uncertainty (e.g. interstate expressways) before proceeding into other contexts of increasing uncertainty and/or complexity (e.g. state highways, rural roads and urban areas). Thus, while the present search terms for keeping attention/engagement in supervisory control returned only two studies in the automotive area, more might be expected in the future to the extent that 1) automated vehicles continue to need human supervisors (e.g. how structured and predictable vs. messy and uncertain are the areas in which they drive) and 2) how much attention/engagement of human supervisors of automated driving might be expected to wane or waver.

Convergence and contribution

When restricted to a single choice, seemingly few applied theme codes were found to be in common agreement across all three independent raters. However, non-chance agreement was still obtained both in terms of standard inter-rater reliability Kappa statistics and percentage agreement analyses. Furthermore, thematic categorisation agreement was enhanced by the allowance of rater second choices, which seems plausible, as empirical research conclusions can of course be of compounding nature. For example, Stanton et al. (2001) address the design of future ADAS by advocating for future research that '*could take any of the following forms: not to automate, not to automate until technology becomes more intelligent, to pursue dynamic allocation of function, to use technology to monitor and advise rather than replace, to use technology to assist and provide additional feedback rather than replace, to automate wherever possible*'. Saffarian, De Winter, and Happee (2012) proposed several design solution areas for automated driving: shared control, adaptive automation, improved information/feedback and new training methods. Specifically for the topic of SAE Level 2 'partially automated driving', Casner, Hutchins, and Norman (2016) lament their expectations for vigilance problems in their conclusions that '*Today, we have accidents that result when drivers are caught unaware. Tomorrow, we will have accidents that result when drivers are caught even more unaware*'. Furthermore, they anticipate dramatic safety enhancements are possible when automated systems share the control loop (such as in backup systems like brake-assist and lane-keeping assistance) or adaptively take it as needed from degraded driver states (i.e. distraction, anger, intoxication). Casner, Hutchins, and Norman (2016) also conclude that designers of driver interfaces will not only have to make automated processes more transparent, simple and clear, they might also periodically involve the driver with manual control to keep up their skills, wakefulness and/or attentiveness. Lastly, Seppelt and Victor (2016) suggest new designs (better feedback and environment attention-orienting cues) as well as '*shared driving wherein the driver understands his/her role to be responsible and in control for driving*' and/or fully responsible driving automation that operates without any expectation that the human driver will serve as a fall-back.

The proposed solution areas overlap with many of the compounded review conclusions above from Stanton et al. (2001), Saffarian, De Winter, and Happee (2012), Casner, Hutchins, and Norman (2016) and Seppelt and Victor (2016). From the present literature survey, what is added is a grouping framework that might more fully encapsulate the conclusions of empirical

results from both the broad body of human factors, ergonomics, and learning theory as well as human driving automation interaction research. Furthermore, the solution areas were purposefully organised in a hopefully digestible and memorable way. The first three themes describe avoidance either in a hard sense or different versions of a soft stance: objective or subjective reductions. The latter three themes describe solutions under familiar learning theory paradigms in chronological order: behaviourism, cognitivism and ecological constructivism.

Identifying a 'best' or 'preferred' theme of proactive strategy is not expected to be a discretely resolvable answer. Instead, the relative advantages and disadvantages should probably best be reflected upon in light of contextual considerations. Furthermore, due to their qualitative nature, the themes are not directly orthogonal from one another. Themes 2 and 3 could be conceived of as softer avoidance versions of a stricter skip-over stance of Theme 1. Theme 6 can be seen to expand from Theme 5 not as an opposing contrast but as an elevating extension that can still subsume cognitive and human-centred concepts. Themes 5, 2 and 6 were the top three most common solution areas found in the present survey.

Solution area (1): avoid the role of human supervision of automation

For Theme 1, it might be easier to hold close to a viewpoint of avoiding supervisory control of automation in theoretical or laboratory-oriented research. A sizeable body of human factors and ergonomics science literature supports such a standpoint that human bias and error is not necessarily removed via the introduction of automation, but instead, humans can generally be shown to be poor monitors of automation. However, industry examples also exist of both traditional and start-up automotive manufacturers (i.e. Ford and Waymo) opting to skip mid-level driving automation where a human is required to continuously supervise the processes (Ayre 2017; Szymkowski 2017). The low coverage of this theme in the present survey (see Table 2) is probably more an artefact of the present survey rather than evidence of its unimportance or non-viability—more discussion is provided in the limitations section.

Solution area (2): reduce the role along an objective dimension

Regarding Theme 2, temporal restrictions based upon scheduled durations of automation use might be a practical starting place to initially implement mechanisms to reduce the objective amount of human supervision of driving automation. For combatting fatigue associated with conventional driving control during long trips, many modern day vehicles come equipped with timing safety features. Such rest reminders function by counting the elapsed time and/or distance of a single extended trip (e.g. hours of continuous operation since ignition on) and consequently warn/alert the driver for the sake of seeking a break or rest period. Because time-on task has been traditionally identified as a major contributing factor to vigilance problems (Greenlee, DeLucia, and Newton 2018; Mackworth 1948; Teichner 1974), time-based break warnings and/or restrictions as with general driving fatigue countermeasures, might be practically worthwhile to apply on scales specific for human supervisory monitoring of SAE Level 2 driving automation. Compared to other contributing components to vigilance decrements (cf. Cabrall, Happee, and De Winter 2016), the duration of watch period is expected to be an attractive dimension for human-automation interaction system designers due to its intuitive and simplistic operationalisation even despite its potential to interact with other vigilance factors.

Solution area (3): reduce the role along a subjective dimension

Theme 3 of altering the perception towards increased danger or uncertainty and thus necessitating greater care from end-users could be problematic for automotive manufacturers that would reasonably expect to maintain positive rather than negative attributions of their products and services. However, an altered experience might carefully be crafted to direct attribution of uncertainty away from the vehicle and towards aspects of the environment or others (see Norman 2007, 83–84). For example, advanced driving automation of SAE Level 2 (simultaneous lateral and longitudinal control) might operate on an implicit level to support a driver who believes that he/she alone has control authority/responsibility (e.g. in line with how previous lower level driver assistance systems such as electronic stability control have been successfully deployed in the background). Discussion of its relatively low amount of coverage in the present survey (see Table 2) is provided in the limitations section.

Solution area (4): support the role from the behaviourism paradigm

Theme 4 is perhaps the most widely known in the general population and especially that behaviouristic aspect of manipulating or shaping behaviour through rewards and punishments. Caution, however, is warranted, as effects have been previously shown to be limited in lasting power and reach. For example, Parasuraman and Giambra (1991) found that while training and experience can help to reduce vigilance decrements, its benefits were not as observable in older populations: practice alone is insufficient to eliminate age differences. Notably, elderly populations are commonly regarded as primary users and beneficiaries of automated/autonomous ADAS (cf. Hawkins 2018). Furthermore, the practical viability of Theme 4 should be noted with consideration of the fact that a large proportion of the vigilance decrement phenomena exhibited in historic experiments was undertaken by young, highly trained and motivated operators. By comparison, the present literature survey was concerned with uncovering proactive knowledge further generalisable and applicable to laypeople who might not be used to or amenable to rigours of professional training when it comes to driving (e.g. recurrent training, reading of documentation, attention to help resource media/material, etc.).

Solution area (5): support the role from the dyadic cognitivism paradigm

Theme 5 cognitive science approaches have become prominent and favoured over the last few generations. Established human-automation research guideline approaches are on the rise (i.e. information processing models, awareness/attention, user/human centred design, etc.) alongside the popular success of companies like Google that promote their top maxim as '*Focus on the user and all else will follow*' (Google 2018). With the launch of a subsidiary company called "*Ford Autonomous Vehicles LLC*", the Ford Motor Company is self-reportedly embedding a deeper product-line focus where '*the effort is anchored on human-centred design*' (Ford 2018).

Solution area (6): support the role from the triadic ecological paradigm

Theme 6 pertaining to leveraging and augmenting information in the environment and task itself (e.g. situated, ecological, extended cognition, etc.) is expected to gain traction commensurate with technological progress of increased access to ambient data that might have been too cost-prohibitive in previous decades. For example, more recent times have

seen an acceleration of accessibility from the miniaturisation of recording equipment and availability of ubiquitous sensing and computing power. As automation applications continue to grow into new operational areas and expand beyond closed control system process considerations (especially as with vehicles which by definition move from one place to another), recognition of environmental and task dependencies are also expected to grow.

Limitations

The presently proposed framework to group answers to the potential problems of degraded driver engagement while monitoring driving automation were not derived from a formal and systematic procedure. Instead, the themes were construed in an abductive reasoning manner while trying to organise and relate timely operational concerns (monitoring responsibilities in SAE Level 2 driving automation) with both established and more recently emergent research literature. Assimilation of these solution areas was desirable, considering the long-standing history of general vigilance issues of prolonged human supervisory attention over any automated processes. However, such a framework cannot claim to be the only one conceivable, and the identified themes could be argued to reflect only idiosyncratic knowledge, reasoning and partial/imperfect readings of a more full body of literature. For example, Themes 1 and 3 were scarcely used categorisations by any of the raters within the present literature survey. Besides clear challenges presented by a small sample size of only 34 publications, other explanations are available as to the absence of Themes 1 and 3 among the rater responses. As foreshadowed first by Billings (1991) and repeated by Endsley and Kiris (1995), the rapid release and continual roll-out of automation (then for aviation, now for automotive applications) might obviate a so-called '*too academic*' position of strict avoidance (i.e. Theme 1). Thus, it is conceivable how an approach area as Theme 1 might be under-represented in the literature as being both either too obvious and/or too obsolete. For example, the proactive literature search terms (e.g. of keeping engagement/attention in supervisory control) might reasonably not be expected to return publications that are predominately oriented towards the first solution area of avoiding the supervisory role. In contrast, Theme 3 might be too abstract or unusual (or even arguably unethical as a feature of deception) to be directly arrived at and associated with the terms of '*supervisory control*'. While shared control and backup automation are far from being alien concepts, the logical complement of changing a subjective experience with automation (Theme 3) to that of changing an objective amount of automation (Theme 2) might be for some too unfamiliar as a grouping umbrella perspective. Furthermore, because humans are still humans, whether supervising automated processes of performing other kinds of vigilance and/or sustained attention work, it should be noted that, although presently left out of scope, many of the other literature search returns regarding proactive solutions to human attention/engagement in supervisory of monitoring control/work might be expected to transfer interesting lessons learned even if from non-operator domains: educational classrooms, business offices, creative work, medical hospitals, geriatric care, etc.

Conclusions

A wealth of literature suggests categorical approaches to proactive strategies for addressing potential degradation of driver monitoring performance in human supervisory control of

driving automation. A qualitative framework of six themes to group solutions have been presently proposed in order to answer a research question of '*how do we keep people engaged while supervising (driving) automation*'. These themes were motivated from human factors and psychological learning theory literature and found to be recognisably applied by raters to categorise empirically grounded human-automation interaction research recommendations. The present themes were devised as short-hand formulations that might be easy to remember. Such abstracted organisation frameworks are expected to be useful in order to more easily draw comparisons both within and across domains. For example, as a sort of lay of the land overview, the solution areas might serve like a map for automation research/design practitioners to locate where their present approaches (i.e. to human vigilance in supervising driving automation) currently reside and what other alternative areas might be interesting to explore. Additionally, underlying concepts can thus be more easily entertained to provide common groundwork benefits across seemingly disparate themes.

General lessons learned

The body of literature has much to say regarding supervisory control of automation. We encourage readers towards broader review work in general (Sheridan 1992), for unmanned robot-vehicle systems (Chen, Barnes, and Harper-Sciarini 2011) and for evolving driving roles specifically (Merat and Lee 2012). Across these review works (and across the six presently identified themes), a consensus benefit would appear to be meta-information requirements to combat uncertainty regarding human involvement in supervising automation (e.g. information about control utility, situated automation capability, performance predictions, etc.). Specific findings from these publications are highlighted below to substantiate this position.

Sheridan (1992) provides a definitive reference for supervisory control that brings together a variety of theories and technologies across decades of his experimental research within the area. In his concluding chapter, he warns of alienation of operators from their work/responsibilities as an underlying cause and concern to be combatted through designs that allow an operator to retain her/her sense of responsibility and accountability. He considers the future of supervisory control in relation to the task entropy (i.e. the complexity or unpredictability of task situations to be dealt with). He offers a way forward through an assumption that humans know best when the automation should apply based on how readily the required information can be modelled.

> *'The human decision maker is necessary for the information that is not explicitly modelable … Some, perhaps most, decision situations the human operator will encounter require only information that is modelable. She will make mistakes in such decisions, and can benefit from a decision aid for these cases, and in such cases the decision aid can be validated … Assume the human can properly decide when the situation includes elements the decision aid can properly assess, and for which elements the decision aid should be ignored' (p. 359).*

Chen, Barnes, and Harper-Sciarini (2011) cover a multitude of related research concerning human performance issues (e.g. multitasking performance, trust in automation, situation awareness and operator workload) and innovative technologies designed to reduce potential performance degradations surrounding human supervisory control of automated robot-vehicles. They review interface/tool design developments of multimodal display/controls, planning, visualisation, attention management, trust calibration, adaptive automation and

intelligent agent and human-robot teaming. Chen, Barnes, and Harper-Sciarini (2011) relay sub-roles within supervisory tasks from Sheridan (2002) that append aspects of planning and learning to bookend monitoring and intervening. Such surrounding aspects of gaining experience with when/where to moderate attention strategies in the application of supervisory control echoes those discussed above by Sheridan (1992).

Complicating interactive challenges reviewed by Chen, Barnes, and Harper-Sciarini (2011) include inaccuracies in meta-knowledge that contribute to issues of both automation disuse and over-reliance. On the one hand, humans commonly overestimate the cognitive/perceptual abilities of themselves and others (e.g. metacognitive errors such as change blindness blindness, verbal and visual hindsight bias, self-confirmation bias, cognitive dissonance, etc.) thus inflating their sense of necessity for human involvement. On the other hand, to the extent that operators anthropomorphise hardware/software into human-like team-mates could then likewise exacerbate expectations of capability, encourage complacency and produce over-reliance on automated processes. At the heart of the issue is the concept of trust calibration (i.e. during a supervisory control task, operators intervene only when they have reason to believe their own decisions are superior to the automation system's decisions). Within their review of calibrating human trust of automation, Chen, Barnes, and Harper-Sciarini (2011) suggest that the capabilities and limitations of the automation should be conveyed to the operator whenever feasible because previous research has shown that awareness of context-related nature of automation reliability has significantly increased a rate of correct human detection of automation failures. Beyond aspects of proneness towards false alarms or misses, they suggest additional dimensions of trust: utility, predictability and intent.

Merat and Lee (2012) include a review of driver automation interaction research to guide future designs. Their results include identification of two general design philosophies for automation: substitution vs. support. They conclude that assumptions towards substitution are not seamlessly simple to meet and instead argue that successful designs will depend on recognising and supporting the new roles for drivers. Merat and Lee (2012) provide scenario-based warnings both of conflicting timescales: '*Automation may require drivers to intervene on a scale of milliseconds, but re-entering the control loop may take seconds*' (p. 683), as well as of ironies of automation that '…*can accommodate the least demanding driving situations—encouraging drivers to disengage from driving—but then calls on the driver to address the most difficult situations … Periods when drivers are most likely to fully rely on automation—highway driving—also require the most rapid re-entry of drivers into the control loop.*' (683–684). In consideration of such scenarios, it becomes apparent that interactive meta-information (of humans, vehicles/automation and the driving task environments) would be essential for forming expectations of how well drivers will perform their monitoring duties.

In summary, a general lesson for common benefit to all solution areas would appear to be further characterisations of driving situations towards understanding which are more complex from those that are more routine (i.e. for both humans and for machines). Such kind of information would support designers and end-user expectations in meta-supervisory mental model knowledge of when/where the automation they are tasked with supervising might better/worse perform and why (and likewise for the monitoring performance/requirements of the human supervisor). To the extent that the driving is able to be handled entirely within perfectly formulated sets of rules and logic, then

automated processes should excel and consequences for human oversight would reasonably be diminished. On the other hand, to the extent that driving involves complex socio-cultural norms and violations that are not mathematically well-described and highly interactive with un-modelled context dependencies, human engagement in monitoring becomes more crucial. For example, as relayed by Merat and Lee (2012): '*Even now, the role of the person behind the wheel is often not that of a driver but that of an office worker on a conference call, a mother caring for a child or a teen connecting with friends* (Hancock 2017b)'. As more mutually informed tests are conducted of SAE Level 2 driving automation, between laboratory and on-road research and development, such experiences should serve to provide clearer details, specifics and evidence in place of assumptions. Positive progress towards specific details relevant for human monitoring of driving automation can be recognised from the California Department of Motor Vehicles. The CA DMV has begun to publically share documentation of annual collision and disengagement reports from autonomous vehicle (test) operations within its jurisdiction (California DMV 2018) — 95 collision reports are available between 2015–2018 and 2308 disengagements for the 2017 reporting period. More than just a requirement to enumerate problems, the disengagement documentation also begins an attempt to standardise a communication of circumstances (e.g. who initiated the disengagement, on what kind of road, with a description of facts causing the disengagement). Future research might make use of such details to further inform targeted studies surrounding the topic of human attention in supervision of driving automation. As more information becomes available, such information can be used in line with the first three of our presently identified solution area themes to avoid (1) and/or reduce (2–3) the operational design domains of partial automation that requires human supervision, or by the last three solution area themes to support its operations via e.g. enhanced training (4), feedback and mental models (5) and/or task environment relations (6).

Disclosure statement

No potential conflict of interest was reported by the authors.

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Note: References marked with a hash # indicate publications included in the present literature survey categorisation analysis.

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Appendix A

Inclusion set of categorised human-automation literature conclusions from search for keeping engagement/attention in supervisory control.

Ref ID	Year	First Author	Title
1	2016	Banks	Keep the driver in control: automating automobiles of the future
2	2014	Clauss	Implications for operator interactions in an agent supervisory control relationship
3	2013	Cummings	Boredom and distraction in multiple unmanned vehicle supervisory control
4	2012	Breda	Supervisory control of multiple uninhabited systems-methodologies and enabling human-robot interface technologies (Commande et surveillance de multiples …
5	2012	Chen	Supervisory control of multiple robots: Effects of imperfect automation and individual differences
6	2012	Chen	Supervisory control of multiple robots in dynamic tasking environments
7	2012	Pop	Using engagement to negate vigilance decrements in the NextGen environment
8	2010	Cummings	Modelling the impact of workload in network centric supervisory control settings
9	2010	Hart	Assessing the impact of low workload in supervisory control of networked unmanned vehicles
10	2010	Shaw	Evaluating the benefits and potential costs of automation delegation for supervisory control of multiple UAVs
11	2007	Cummings	Operator scheduling strategies in supervisory control of multiple UAVs
12	2007	Cummings	Developing operator capacity estimates for supervisory control of autonomous vehicles
13	2007	Cummings	Automation architecture for single operator-multiple UAV command and control
14	2007	Johnson	Testing adaptive levels of automation (ALOA) for UAV supervisory control
15	2007	Miller	Designing for flexible interaction between humans and automation: Delegation interfaces for supervisory control
16	2006	Hawley	Training for effective human supervisory control of air and missile Defence systems
17	2006	Scott	Assisting interruption recovery in supervisory control of multiple UAVs
18	2005	Parasuraman	A flexible delegation-type interface enhances system performance in human supervision of multiple robots: Empirical studies with RoboFlag
19	2003	Parasuraman	Human control of multiple robots in the RoboFlag simulation environment
20	2002	Blasch	JDL Level 5 fusion model: user refinement issues and applications in group tracking
21	2002	Ruff	Human interaction with levels of automation and decision-aid fidelity in the supervisory control of multiple simulated unmanned air vehicles
22	2000	Hoc	From human-machine interaction to human-machine cooperation
23	1999	Manly	The absent mind: further investigations of sustained attention to response
24	1995	Endsley	The out-of-the-loop performance problem and level of control in automation
25	1995	Pope	Biocybernetic system evaluates indices of operator engagement in automated task
26	1995	Sarter	How in the world did we ever get into that mode? Mode error and awareness in supervisory control
27	1993	Lockhart	Automation and supervisory control: A perspective on human performance, training, and performance aiding
28	1992	Ackerman	Understanding supervisory systems
29	1992	Gersh	Cognitive engineering of rule-based supervisory control systems: Effects of concurrent automation
30	1992	Sarter	Mode error in supervisory control of automated systems
31	1987	Gaushell	Supervisory control and data acquisition
32	1986	Norman	Attention to action: Willed and automatic control of behaviour
33	1986	Sheridan	Human supervisory control of robot systems
34	1984	Sheridan	Research and modelling of supervisory control behaviour. Report of a workshop

Appendix B

First and second choice (where applicable) thematic category as identified by each rater for each publication reference. First choice overlap agreement by at least two raters is shaded.

Ref ID	AV first choice	TX first choice	CO first choice	AV second choice	TX second choice	CO second choice
1	5	5	2	2	2	–
2	6	6	2	–	5	6
3	2	2	4	–	5	6
4	6	6	2	5	2	6
5	4	5	4	5	6	–
6	6	5	4	4	2	–
7	4	4	4	–	5	–
8	2	5	2	–	4	–
9	2	5	2	4	2	5
10	2	5	2	–	2	–
11	1	5	2	–	–	–
12	2	2	6	–	5	–
13	5	6	4	6	5	6
14	2	6	2	6	2	6
15	2	2	2	3	6	–
16	4	4	4	–	6	–
17	6	6	6	5	4	5
18	2	5	2	–	6	–
19	6	5	2	–	–	–
20	3	6	6	5	5	–
21	2	5	2	6	–	3
22	5	6	3	6	3	–
23	2	4	4	–	5	–
24	2	1	2	1	2	1
25	2	4	4	–	5	–
26	5	5	6	6	–	4
27	4	4	4	5	6	–
28	5	6	6	6	–	–
29	6	6	3	–	5	–
30	5	5	5	4	–	4
31	6	5	3	5	–	–
32	6	5	2	5	6	–
33	6	5	5	–	6	–
34	5	5	4	4	4	2
Mode:	2	5	2	5	5	6