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From Mackworth's clock to the open road: A literature review on driver vigilance task operationalization

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ABSTRACT

Objective: This review aimed to characterize tasks applied in driving research, in terms of instructions/conditions, signal types/rates, and component features in comparison to the classic vigilance literature.

Background: Driver state monitoring is facing increased attention with evolving vehicle automation, and real-time assessment of driver vigilance could provide widespread value across various levels (e.g., from monitoring the alertness of manual drivers to verifications of readiness in transitions of control between automated and manual driving). However, task requirement comparisons between the classic vigilance research and vigilance in car driving have not to date been systematically conducted.

Method: This study decomposed the highest-cited vigilance literature of each full decade since the 1940s for the situational features of the renowned vigilance decrement phenomenon originating from Mackworth (1948). A consensus set of 18 different situational features was compiled and included for example an (1) isolated (2) subject ... perceiving (3) rare (4) signals ... against (10) frequent (11) noise ... in a (17) prolonged (18) task. Next, we reviewed 69 experimental vigilance task operationalizations (i.e., required signal detection and response) within 39 publications concerned with driving vigilance. All vigilance tasks were coded as "driving vigilance tasks" or "non-driving vigilance tasks" based on the perceptual signal and response action both belonging to normal driving activity or not. Presence, absence, and unreported presence/absence of each of the 18 features was rated for each task respectively as "overlap", "contrary", and "unspecified". In conjunction, instructions/environmental conditions, signal definitions, signal rates, and summaries of the experimental vigilance tasks were extracted.

Results: A majority of driving vigilance tasks was performed in simulators (69%) compared to on-road (28%) and watching videos (3%) along with large differences in task conditions. Participants had to maintain fixed speed/lane positions in the simulators in higher proportion (74%) than on the road (36%) where they had only to drive "normally" and/or by loose conventions like "according to the law" more often (55% versus 15%). Additionally, presence of other traffic was found more often on-road (91%) than in simulators (48%). A specification of signals to detect and react to was found present within/for driving less often (59%) than alongside/in conjunction with driving (100%). Likewise, rates of signals (i.e., frequency of signal occurrence) were reported more often for non-driving vigilance tasks (80%) than in driving vigilance tasks (21%). For driving vigilance tasks, the highest overlap was 12 of the 18 features present (67%). On average, results showed relatively low levels of classic feature overlap (36%) with high rates of unspecified feature presence (46%) for driving vigilance tasks compared to non-driving vigilance tasks with higher classic feature overlap (64%) and fewer features unspecified (13%).

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Conclusion and application: There is little overlap between the well-known and often cited vigilance decrement phenomenon and published experimental tasks of driving vigilance. Major differences were also found in the instructions/environmental conditions of simulator versus on-road experimental driving vigilance tasks. What driving vigilance practically is in the real-world thus remains a promising area for future research. We recommend that researchers apply approaches which account for more real-world driving features to better expose and address uncertainty regarding driving and vigilance.

1. Introduction

1.1. Timely value of vigilance operationalization for advancing driving automation

Automobile accidents have severe costs in terms of both personal safety and financial consequence. For example, from motor vehicle crashes in the United States in 2010, there were 3.9 million non-fatal injuries, 32,999 fatalities, and economic costs totalled around $242 billion (Blincoe, Miller, Zaloshnja, & Lawrence, 2015). Between 2005 and 2007, critical reasons for pre-crash events from a total of 5,361 analyzed crashes in a National Motor Vehicle Crash Causation Survey have been attributed to the driver in an overwhelming majority (95%) compared to vehicles (2%) and to roadway/atmospheric conditions (3%), where 48% of driver causes involved adverse driver readiness states like inadequate surveillance, distraction, inattention (e.g., daydreaming, etc.), following too closely, overcompensation, panic/freezing and/or being asleep (NHTSA, 2008). Presently researchers and industry stakeholders are rapidly progressing technological solutions within vehicles to support safer driving. Developments span a wide range of conceptual and deployed products of manufacturers and suppliers, research consortiums/initiatives, as well as information technology companies and service providers. These automotive technology developments involve a large range of categories such as driver warnings, active control assistance, and temporary or even complete relief of driving authority/responsibility. Encapsulating these developments, the German Federal Highway Institute (BASt), the United States National Highway Traffic Safety Administration (NHTSA) and the International Society of Automotive Engineers (SAE) have each produced scales for distinguishing and categorizing various levels of vehicle driving automation technology ranging from none to full (Gasser & Westhoff, 2012; NHTSA, 2013; SAE, 2014). Crucially, issues and value of knowing how to measure driver vigilance can be found throughout these aspirations and technologies in all except the absolute highest automation levels (i.e., with no human involvement at all). Definitions of vigilance are provided next before elaborating on this point.

Colloquially, the adjective ‘vigilant’ might only evoke images of dutiful security positions ranging from the sentinels in front of Buckingham Palace to anyone’s own local neighbourhood watch program. More formally but also more broadly, Merriam-Webster and Dictionary.com respectively define vigilant as “alertly watchful especially to avoid danger” and “keenly watchful to detect danger; wary ... ever awake and alert; sleeplessly watchful” fitting many more situations, that is, seemingly any involving purposeful watching with some adverse consequence at stake. Most well cited (and maintaining a broad coverage area), the seminal operational research definitions of *vigilance* classically stem from the British scientist Norman Mackworth. Within his classic WWII radar era article “The breakdown of vigilance during prolonged visual search” subjects were tasked to watch an experimental clock hand for specific sized movements (Mackworth, 1948). Mackworth first cites the usage of the term vigilance from the esteemed neurologist Sir Henry Head as “both a physiological and psychological readiness to react.” Immediately after which, Mackworth then treats *vigilance* as “a useful word to adopt, particularly in describing a psychological readiness to perceive and respond, a process which, unlike attention, need not necessarily be consciously experienced” (Mackworth, 1948, p. 6). Thus, the present analysis follows in broadly treating vigilance tasks as any involving the ability to meet required perception and response demands.

In the context of driving, difficulties in drivers meeting required perception and response demands may be influenced from a variety of overlapping effects and mechanisms, such as widely investigated and closely related constructs of driver fatigue, driver distraction and hazard perception. Fatigue can be characterized both as a physiological sleepy or drowsy state of a driver detectable from signature activities regarding the eyes, head, and face (Ji, Zhu, & Lan, 2004), as a psychological state of subjectively experienced disinclination to continue performing the task at hand (Brown, 1994), or relating to both physiological and psychological processes reflecting a general decreased capacity to perform (Thiffault & Bergeron, 2003). Definitions of driver distraction include not only shifts of attention away from driving stimuli/tasks (Steff & Spradlin, 2000) but also incorporate aspects of consequence (i.e., impact/effect), sources internal/external to the vehicle (i.e., activity/event/object/person) and modality types (i.e., auditory, biomechanical, cognitive, visual, or a combination) (Pettitt et al., 2005; Young & Regan, 2007). Hazard perception is a natural combination of both dangerous situations on the road ahead (Horswill & McKenna, 2004) as well as a skill developed through experience for recognizing and responding to such hazards in decreasing amounts of time (Wetton et al., 2010). Whether these constructs (and even more like workload, attention, arousal, stress, etc.) are considered independent/orthogonal, e.g., drivers may exhibit reduced vigilance (distraction) even in non-fatigued states (fully awake) and suffer performance decrements in states of both over- and underload or whether they are dependently tied, e.g. vigilance decrement as direct effect of fatigue/sleepiness is an open area of relational representation (Heikoop et al., 2015; Stanton & Young, 2000) beyond the scope of this review. However, regardless of the specific boundaries drawn by different terminology usage, such constructs (including the present topic of vigilance) all share extended consideration and coverage of both endogenous factors (i.e., emanating from within) of both physiological and psychological processes as well as exogenous factors (i.e., originating from outside).

Accurate accounts of driving demands are prerequisite to designing roles and responsibilities for various automated and/or human driving agents. The value vigilance stands to contribute across driving and automation is detailed next by taking a step-by-step account of the NHTSA levels of vehicle automation as specific example. In the *NHTSA Definitions of Levels of Vehicle Automation* (NHTSA, 2013), the categories begin with *Level 0 – No Automation* (e.g., lane departure warning) and progress through four more levels: *Level 1 – Function-Specific Automation* (e.g., electronic stability control), *Level 2 – Combined Function Automation* (e.g., adaptive cruise control in combination with lane centering), *Level 3 – Limited Self-Driving Automation* (e.g., the 2012 Google car with human override), *Level 4 – Full Self-Driving Automation* (e.g., the 2014 Google car with no steering wheel, gas pedal, or brake pedal).

Starting with *Level 0*, a distinction is made that regardless of the presence/absence of various warnings (e.g., forward collision, lane departure, blind spot) or automated secondary controls (e.g., wipers, headlights, turn signals, hazard lights, etc.) the driver is in complete and sole command of the primary vehicle controls (brake, steering, throttle, and motive power) at all times and responsible for monitoring the roadway and safe operation of all vehicle controls (NHTSA, 2013). Clearly, responsibility is explicitly given to the driver for watching many aspects of both control devices and the roadway in this level and so safety checks of readiness in these duties of watching could be useful.

In *Level 1*, automation is function-specific (and independent in the case of multiple functions operating simultaneously) where the driver has overall control but can choose to cede limited authority over a primary control, the vehicle can automatically assume limited authority over a primary control, or provide added control in certain normal driving or crash-imminent situations; all of which occur without replacing driver vigilance and assuming driving responsibility from the driver (NHTSA, 2013). Explicitly, vigilance is identified as a requirement of the driver *not* intended to be relieved from the use of the automation and hence, presumably would benefit from real-time verification that the driver is not over-relying on the automation and is sustaining appropriate levels of vigilance.

In *Level 2*, automation of controls can work in unison (i.e., hands off the steering wheel and foot off the pedal at the same time) however the driver is still responsible for monitoring the roadway and safe operation and expected to be available for control at all times (i.e., short notice, no advanced warning) (NHTSA, 2013). When a driver is expected for short and no-notice transitions of control, the real-time assessment of his/her readiness could be critical for safe operations to avoid startle/upset and/or loss of control.

In *Level 3*, the driver is no longer expected to constantly monitor the roadway while driving but instead to rely heavily on the vehicle to monitor for changes with the driver available only for occasional control and with sufficiently comfortable transition times (NHTSA, 2013). If only called upon occasionally for driving control, a driver's level of preparedness to react and respond can be expected to vary within a pre-determined allotted transition time depending on how far removed or closely tied to the driving situation the driver may or may not be.

Lastly, in *Level 4* the driver is excused from an expectation of availability of control for an entire trip. While continual driver readiness to perceive and respond then is not a direct requirement, vigilance may still be useful to assess against risks of driver initiated control actions under inappropriate levels of readiness.

Generally, across any driving automation hierarchy and functional allocation framework, there may be value from accurate driver vigilance operationalization in recognizable ways. For more manual control levels, a driver might fall behind driving task demands for many reasons (e.g., falling asleep, becoming angry, day dreaming, inexperience, stimulus overload, etc.). Early detections of mismatches of driver watchfulness and preparedness to respond to events could be vital precursors to actual performance decrements and hence promote active safety through prevention rather than merely passive safety through mitigation. For partially automated situations where the driver maintains responsibility in case of automation inadequacy (or even for nominal transitions of control) and he/she is tasked to observe, the driver is expected to be ready to uptake control. Methods for actively verifying this preparedness could add value by obviating the vulnerability of merely assuming watchful readiness. Lastly, from partial and into more highly automated situations, a real-time qualification and quantification of driver vigilance can provide practical information regarding how close/far away a driver might be from the driving task demands (especially when they are allowed/encouraged to uptake additional tasks) and so can support requirements for assuring drivers back into the control loop in safe and appropriate ways. All of these aspirations for improved driving safety through none to some levels of automation entail grounding knowledge and operationalization of driving vigilance (i.e., specifically what and how drivers need to be watchful and ready for) and would be expected to be informed by established literature on human capabilities for vigilance in general.

1.2. Classic general vigilance literature

As a starting point for reconciling the above interests and values in the advancing domain of driving task responsibility evolution, the current review seeks to first look back towards classic human factors knowledge regarding the heavily researched vigilance decrement phenomenon (Mackworth, 1948), before progressing forward with future driving vigilance operationalization. We consider a summary of knowledge of the factors contributing to decreases of vigilance *in general* to support practical extrapolation of previously learned lessons to driving tasks *specifically*.

As described above, the automation of human control tasks can create problems in operational practice in addition to its intended benefits. This observation is supported by and established within the classic human factors literature. For example, Lisanne Bainbridge's seminal work "Ironies of Automation" introduces and discusses the ways in which automation of processes may expand rather than eliminate problems with the human operator (Bainbridge, 1983). Specifically, she laments that within an automated system, a former operator may be recast to a monitoring role under which he is expected to take-over if things do not operate correctly. This is a problem because manual control skills that preclude against unstable or imprecise control all degrade without direct practice and use. Furthermore, cognitive strategies for appropriate control in novel or unusual situations rely on sufficient prior exposure and experience with nominal operations, and this exposure is typically remote or occluded with the provision of automated processes. Bainbridge continues by citing Mackworth stating that "we know from many 'vigilance' studies (Mackworth, 1950) that it is impossible for even a highly motivated human being to maintain effective visual attention towards a source of information on which very little happens" (Bainbridge, 1983, p. 776).

Given the potential for grave danger and adverse safety consequences, it should not be surprising that Bainbridge was not alone in these observations and interests. By the 1980s, reviews indicated that there were already at least around one thousand published reports in the literature on the topic of vigilance since WWII (Craig, 1984; Wiener, 1987). Furthermore, concerns were expressed as early as 1962 that with investigators of *vigilance* behaviour "spread over several continents and publishing under the sponsorship of numerous military, industrial and academic organizations, it has become a major problem to keep up with the technical literature" (Frankmann & Adams, 1962, p. 257). As a quick and current confirmatory check only of the topic's proliferation, a Google Scholar search (March, 2015) was made of titles since Mackworth in 1948 and revealed 8,140 results for *vigilance* and 1,540 results for its synonym *sustained attention* in the title only; the sum together of which (minus double-counts for appearances of both terms in the title) stood remaining at 9,652 total results. Indeed by 1987, enough material and interest had amassed on the topic of vigilance and sustained attention that a full special issue of the Journal of the Human Factors and Ergonomics Society was centralized around this topic only; an initiative itself in commemoration of the end already, of at least one entire career spent in pursuit of the same (Warm & Parasuraman, 1987). For example, the recent review of Chan (2008) provides an encompassing account of theoretical aggravators (e.g., lack of reinforcement feedback, inaccurate estimations of signal probability, irregular spatial/temporal and successive presentation of signals and events, etc.) and alleviators (e.g., increase in signal rate, self-paced tasks, greater signal intensity, etc.) of the vigilance decrement. The lessons learned in classic vigilance literature often revolve around general theoretical terminology regarding signals. To apply their solutions to vigilance assessment and decrements in driving, it is then pre-requisite to identify in driving, what exactly constitutes such signals and other relevant and potentially interacting factors or features.

1.3. Vigilance and signal stimuli concerns in the driving literature

In research publications, it is common to see driving vigilance expressed as interest/aim in many different ways. Among others, examples include: labelling driving in part or whole as some kind of vigilance task/test (Inkeri, 2010; Mets et al., 2008; Thiffault & Bergeron, 2003), vigilance as a contributing or critical factor for driving safety (CARRS-Q, 2013; Michael & Meuter, 2006; Vrignon & Rakotonirainy, 2007), driving as including/requiring large amounts of vigilance behaviour/demands (Bloomer, 1962; Boverie, Giralt, & Le Quellec, 2008; Mackie & O'Hanlon, 1977) or driving as being comparable to/resembling a vigilance task (Atchley & Chan, 2011; Chan, 2008; Schmidt et al., 2007). Notably, consideration has also been raised to the unambiguous application of vigilance literature to specific driving scenarios like driver supervision of ACC control (Ervin, Bogard, & Fancher, 2000), the absence of regular engagements and distractions that are available on a normal highway/normal road versus in a tunnel (Jayakumar, Novak, Faber, & Bouchner, 2014) and to the relevancy of focus of vigilance problems on straight roads rather than in curves, where it is highly unlikely for someone to fall asleep (Giusti, Zocchi, & Rovetta, 2009).

It is been previously underscored that no reliable methods yet exist for defining a priori what a driver should be attending to (Hancock, Mouloua, & Senders, 2008). Instead, what (signal-processing) activities are critical for safe driving is seen as an unresolved issue in traffic safety (Regan, Hallett, & Gordon, 2011). Some insights and progress may be gained through retrospective analyses of crash and incident data. However, working backwards through reports and naturalistic driving video footage and coding some information processing activities more critical/correct than others still presents many ambiguous situations (Regan et al., 2011). One area where both ambiguity of driving signals as well as definitions of functional driving vigilance might be expected to be explicitly handled and resolved is under the highly controlled conditions and detailed documentation of experimental research and reporting.

1.4. Research aim and questions of the current literature review

Our review of vigilance tasks in driving vigilance experiments was undertaken to answer to the following questions.

(1) What are (un)common experimental instructions and environmental conditions of driving vigilance tasks?
(2) What are the types of signals operationalized in driving vigilance experiments?
(3) What are the rates of those signals?

(4) How much overlap resides between consensus features of classic vigilance tasks and experimental operationalizations of driver vigilance?
(5) Where overlap is or is not found, what are the most common classic features present/absent?
(6) What other circumstances (additional to the classic features) surround those tasks with the highest amount of overlap?

With answers to these questions, transportation researchers can use knowledge of driver vigilance to achieve better automation designs and hopefully greater levels of driving safety. Knowledge about the degree of overlap between classic vigilance tasks and experimental operationalizations of driver vigilance would allow us to infer when/how we can proceed in an informed manner. Degrees of contradiction and un-specification, on the other hand, would uncover gaps of knowledge to be addressed in future driving research.

2. Methods

2.1. Multi-decade consensus features of classic vigilance tasks

To utilize the findings and conclusions of prior research for applications to a new specific problem (in this case, of driving and driving automation), it is necessary to define shared components and characteristics between the prior and the current problem. A relevant first question becomes: what specific circumstances surround vigilance decrements so that we may make best use of already identified solutions? Returning to the seminal work of Mackworth (1948), the author devotes an entire section entitled "The Specific Problem" (p. 7) to introduce and emphasize the careful control of situational features surrounding the task of interest.

Thus, using Google Scholar, we retrieved the highest cited research with the terms 'vigilance' or 'sustained attention' in the title from each full decade inclusively since and that cites Mackworth in order to establish vetted consensus situational features of the now classic vigilance decrement (i.e., Davies & Parasuraman, 1982; Frankmann & Adams, 1962; Holland, 1958; Mackworth, 1948; Parasuraman, 1979; Sarter, Givens, & Bruno, 2001; Warm, Dember, & Hancock, 1996, chap. 9). Distal research domains outside of human factors and/or engineering psychology, such as from medicine or predator/prey animal behaviour were thus intentionally left out of scope. Common components were found to sufficiently relate a consensus in features namely involving (1) a subject/perceiver who between (2) signals/targets versus (3) noise/non-signifying events had (4) the work/task of perceiving and responding appropriately. In addition to mere presence/absence of these four feature object-nouns, 14 mutually exclusive descriptors were found to modify such objects, that is, feature modifier-adjectives. These were hence compiled in a chronologically additive manner to result in a present day composite of multi-decade theoretical features of vigilance tasks in general (Table 1).

2.2. Search criteria, filtering, and scope reduction

Given finite resources, it would be untenable to aspire to an exhaustive review of every published driving vigilance operationalization. Instead, the goal of the present search was to gather a representative sample for detailed analysis from which

Table 1
Present day composite of multi-decade consensus theoretical features of vigilance decrement situations as feature object-nouns and feature modifier-adjectives extracted from review of top-cited vigilance works of each full decade since Mackworth (1948).

Code	Feature
1	**subject (a.k.a. participant, watcher, perceiver)**
1a	*isolated (a.k.a. alone)*
2	**signal (a.k.a. stimulus, target)**
2a	*few (a.k.a. infrequent, occasional, rare)*
2b	*temporally uncertain (a.k.a. unpredictable, probability not influenced by subject, random)*
2c	*difficult to perceive (a.k.a. small, near perceptual threshold)*
2d	*clearly perceptible when alerted (a.k.a. detectable, defined, unambiguous)*
2e	*short lasting (a.k.a. glimpse, transient)*
2f	*spatially uncertain*
3	**noise (a.k.a. events, neutral, not meaningful, do not signify)**
3a	*very similar to signals*
3b	*frequent, (a.k.a. constantly encountered, high quantity, often)*
4	**task (a.k.a. performance, work, assignment)**
4a	*long duration (a.k.a. sustained, extended, prolonged, lengthy, continuous, in a series)*
4b	*lacking objective feedback of subject's own performance*
4c	*monotonous (a.k.a. same, consistent)*
4d	*successive presentations of signal and noise (a.k.a. a burden to or loading on memory)*
4e	*required response (a.k.a. action to take)*

Note: Feature object-nouns are in bold and feature modifier-adjective are in italics.

to generalize. Accessing Google Scholar through Harzing's Publish or Perish scholarly citation software, a search of publications between the years 1948 and 2014 was conducted where the title had at least one word from a set of "vigilance" terms (vigilance, sustained attention, vigil, vigilant) in combination with at least one word from a set of "driving" terms (driving, driver, drivers, motorist, motorists, automobile, automobiles, car, cars, vehicle, vehicles, road, roads, motorway, motorways). Again, such a search was not engineered to return *all* relevant papers, but instead to ensure with greater chance that the returned sample would retain relevancy on the assumption that presence of target terms in the title connotes importance of that term to the research and hence would be a point for elaboration and description within the text.

Search results of 248, 8, 3, and 11 titles were returned respectively for "vigilance", "sustained attention", "vigil", and "vigilant" in combination with one of the "driving" terms. A total of 181 titles remained rising in frequency over the years (Fig. 1) after 89 exclusions were made from manually reading the title and/or abstract for those that were written in a language other than English (27), were duplicates within the same year (25) and across different years (14), were written about trains (9), did not actually have the search terms in the title (4), used *vigilance* regarding criminal theft (3), used *driving* as a verb of causality/influence and not locomotion (2), used *road* but did not involve driving (1), were about aerial vehicles (1), were about the vigilance of physicians of car accident victims (1), were about the deaths of children in trunks of cars (1), and described a macroscopic level vehicle traffic congestion/flow system (1).

Proceeding through each of these 181 publication title returns, an approximate two-thirds majority ($n = 110$) were retrieved in full text and assessed manually for the aim of isolating experimental driving vigilance tasks. The exclusion criteria previously applied to the title/abstracts was re-applied now in greater resolution in review of full texts, and 28 more removed. Additionally, 43 were set aside that involved either algorithm/prototype validation, naturalistic observational methods or otherwise lacked explicit description of driving task experimental conditions and controlled manipulations. Where multiple experimental tasks were involved under the same title, these were expanded (30 times). Consequentially, a remaining total of 69 experimental vigilance tasks (across 39 different publications, Table 2) were eligible for analysis within the present review of sampling empirical driving vigilance task operationalizations for overlap with consensus theoretical vigilance set ups.

Notably, not all vigilance task operationalizations of the "driving" plus "vigilance" titled experiments were defined as belonging within nominal driving activity. For comparable and meaningful analysis, we found it necessary to further subdivide and classify the 69 experimental vigilance tasks into mutually exclusive driving vigilance tasks ($n = 39$) versus non-driving vigilance tasks ($n = 30$). This division was made on the basis of whether both the perceptual elements to perceive *and* the required response actions of the task were nominally within the realm of driving or not. A representative example of each cell of this 2×2 decision matrix is given next for clarification of this classification judgement and also depicted in Table 3. Furthermore, such a division provided a baseline set of data to compare against instead of just comparing driving vigilance operationalization versus the composite consensus alone.

1. In Inkeri (2010) drivers were instructed to maintain a speed of 120 km/h and a central lane position and so were presumably watchful for deviations that they should correct through use of acceleration or deceleration and steering. In the present analysis, this vigilance task was classified as a driving vigilance task because both the perceptual targets and response actions reside within the notional activity of driving.
2. In Wyon, Wyon, and Norin (1995) driver attention was measured towards essential sources of information of varying degrees of priority within the driving task namely, indications and abnormal execution of most of the instruments, warning lamps, controls as well as auditory horn signals, noises from the engine or a near a rear wheel, and/or blue flashing

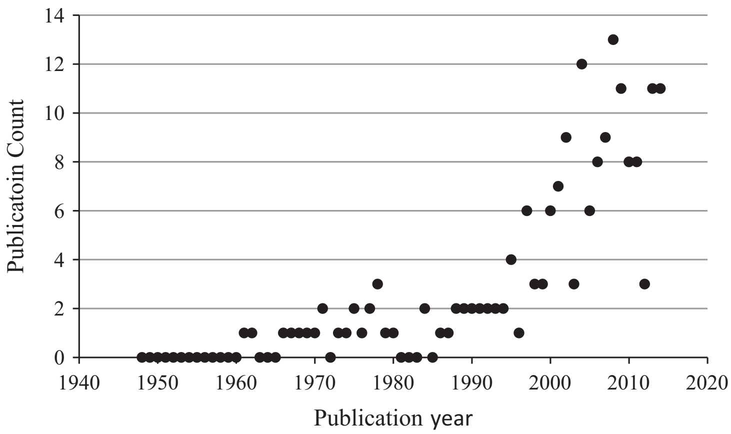

Fig. 1. Publication search returns by year between 1948 and 2014 where the title had both a "vigilance" and a "driving" term in the title and did not meet exclusion criteria.

Table 2
Publication list of present analysis with shorthand "Ref #" index code for use in subsequent tables.

Ref #	Year	First Author	Title
1	2014	Chuang	Kinesthesia in a sustained-attention driving task
2	2014	Correa	Effects of chronotype and time of day on the vigilance decrement during simulated driving
3	2014	Jayakumar	Driver vigilance monitoring–impact of the long tunnels
4	2014	Lin	Wireless and wearable EEG system for evaluating driver vigilance
5	2013	Amato	Effects of three therapeutic doses of codeine/paracetamol on driving performance, a psychomotor vigilance test, and subjective feelings
6	2013	Pei	Effect of driving duration and work schedules on vigilance level and driving performance of bus drivers
7	2013	Ruiz	Measuring the three attentional networks in a vigilance context and their relationship with driving behaviour
8	2011	Atchley	Potential benefits and costs of concurrent task engagement to maintain vigilance
9	2011	Schmidt	The short-term effect of verbally assessing drivers' state on vigilance indices during monotonous daytime driving
10	2010	Inkeri	Fatigue while driving in a car simulator: effects on vigilance performance and autonomic skin conductance
11	2009	Giusti	A noninvasive system for evaluating driver vigilance level examining both physiological and mechanical data
12	2009	Schmidt	Drivers' misjudgement of vigilance state during prolonged monotonous daytime driving
13	2009	Tippin	Visual vigilance in drivers with obstructive sleep apnea syndrome
14	2009	Ueno	An analysis of saccadic eye movements and facial images for assessing vigilance levels during simulated driving
15	2008	Chan	Benefits and cost of dual-tasking in a vigilance task: A laboratory and driving simulator investigation
16	2008	Mets	Effects of seasonal allergic rhinitis on driving ability, memory functioning, sustained attention, and quality of life
17	2008	Preece	Are individuals recovering from mild traumatic brain injury vigilant drivers?
18	2007	Vrignon	Impact of subjective factors on driver vigilance: A driving simulator study
19	2007	Dalton	Effects of sound types and volumes on simulated driving, vigilance tasks and heart rate
20	2007	Howard	The interactive effects of extended wakefulness and low-dose alcohol on simulated driving and vigilance
21	2007	Schmidt	Assessing driver's vigilance state during monotonous driving
22	2006	Bonnefond	Behavioural reactivation and subjective assessment of the state of vigilance—Application to simulated car driving
23	2006	Desai	Vigilance monitoring for operator safety: A simulation study on highway driving
24	2006	Michael	Sustained attention and hypovigilance: The effect of environmental monotony on continuous task performance and implications for road safety
25	2005	Lo	The impact of shift, circadian typology, and bright light exposure on sleepiness, vigilance, and driving performance in hong kong taxi drivers
26	2004	Campagne	Correlation between driving errors and vigilance level: influence of the driver's age
27	2003	Santana	Driver vigilance monitoring – new developments within the AWAKE project
28	2003	Thiffault	Monotony of road environment and driver fatigue: a simulator study
29	2002	Lucidi	The effects of sleep debt on vigilance in young drivers: an education/research project in high schools
30	2002	Roge	Alteration of the useful visual field as a function of state of vigilance in simulated car driving
31	2001	Brice	The effects of caffeine on simulated driving, subjective alertness and sustained attention
32	2001	Roge	Variations of the level of vigilance and of behavioural activities during simulated automobile driving
33	1998	O'Hanlon	Venlafaxine's effects on healthy volunteers' driving, psychomotor, and vigilance performance during 15-day fixed and incremental dosing regimens
34	1995	Findley	Vigilance and automobile accidents in patients with sleep apnea or narcolepsy
35	1995	Wyon	The effects of negative ionisation on subjective symptom intensity and driver vigilance in a moving vehicle
36	1996	Wyon	The effects of moderate heat on driver vigilance in a moving vehicle
37	1978	Guillerman	Effects of carbon monoxide on performance in a vigilance task (automobile driving)
38	1976	Boadle	Vigilance and simulated night driving
39	1967	Brown	Measurement of control skills, vigilance, and performance on a subsidiary task during 12 h of car driving

(police) lights in any of the mirrors. However, the sole response required of the driver was to depress the foot switch, await an audible tone and report at leisure while holding down the foot switch and then releasing it. In the present analysis, this vigilance task was classified as a non-driving vigilance task due to the response action.

3. In Tippin, Sparks, and Rizzo (2009) drivers had to watch for small light targets appearing along the horizon at seven discrete locations and responded with clicking of the high beam control as soon as they detected the target. In the present analysis, this vigilance task was classified as a non-driving vigilance task due to the arbitrary perceptual targets.
4. In Schmidt et al. (2007), drivers were required to detect an auditory tone of 500 Hz and respond by pressing a button fitted to their right thumb. In the present analysis, this vigilance task was classified as a non-driving vigilance task due to the arbitrary nature of both perceptual target and response action.

2.3. Manual coding and annotation

Each of the 69 tasks was manually reviewed by the first author and rated against a simple ternary coding scheme for the presence, absence or unreported presence/absence of each of the 4 feature object-nouns and 14 feature modifier-adjectives seen in the multi-decade consensus circumstance composite (Table 1). Per each task, percentages of "overlap", "contrary", and "unspecified" were calculated by summing the number of features present (true/consistent), absent (false/contradictory), and not reported in enough detail to determine presence/absence (unreported/uncertain) respectively and dividing each sum by the total feature set size of 18 and multiplying by 100%. Furthermore, such ratings were cross-validated with

Table 3
Experimental vigilance task division in driving research into driving vigilance tasks (++) and non-driving vigilance tasks (+−, −+, −−) based on vigilance task perceptual elements and required response actions both belonging to notional activity of driving or not.

Experimental vigilance tasks	Driving response action (+)	Non-driving response action (−)
Driving percept (+)	**Example**, Ref # 10: watch for deviations from a speed of 120 km/h and central lane position (percept, +) correct deviations with acceleration/deceleration/steering (action, +) *driving vigilance task* (+ +) **Full Set**, Ref #s: 1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26, 27, 28, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39	**Example**, Ref # 35: pay attention indications and abnormal execution of most of the instruments, warning lamps, controls, as well as auditory horn signals, noises from the engine or near a rear wheel, and/or blue flashing (police) lights in any of the mirrors (percept, +) depress a footswitch and make a verbal report at leisure (action, −) *non-driving vigilance task* (+ −) **Full Set**, Ref #s: 8, 35, 36, 38, 39
Non-driving percept (−)	**Example**, Ref # 13: watch for small light targets along horizon at seven discrete locations (percept, −) click the high beam control lever (action, +) *non-driving vigilance task* (− +) **Full Set**, Ref #s: 13, 19, 25, 30, 37	**Example**, Ref # 21: detect an auditory tone of 500 Hz (percept, −) press a button fitted to the right thumb (action, −) *non-driving vigilance task* (− −) **Full Set**, Ref #s: 2, 5, 7, 9, 10, 12, 15, 16, 18, 19, 20, 21, 24, 29, 31, 33

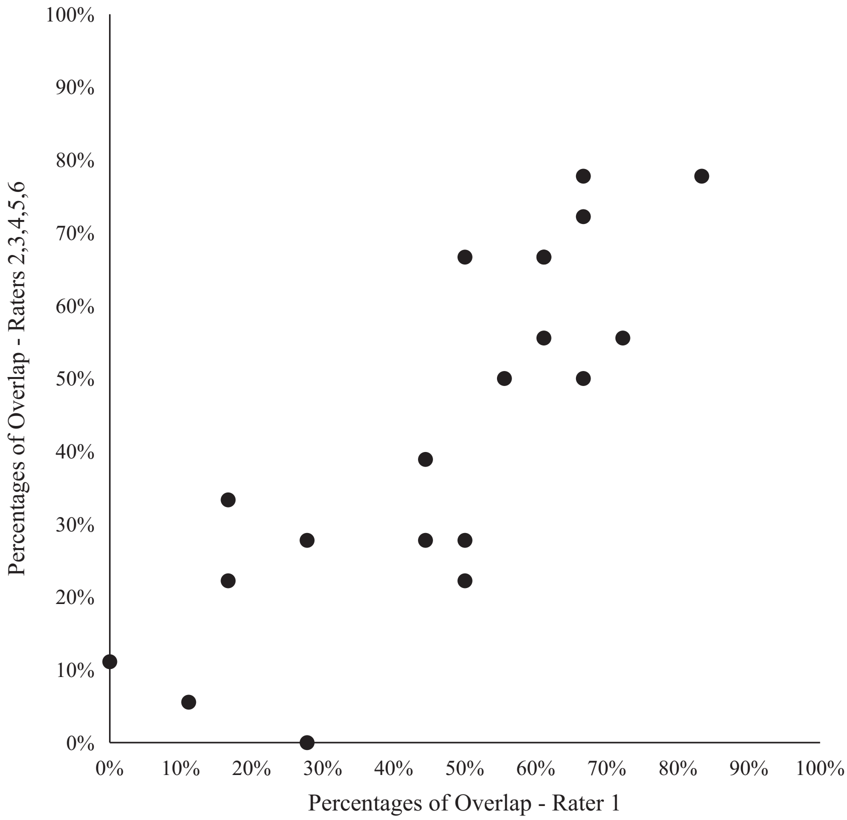

Fig. 2. Correlation ($r = .83$) between the original rater and five other volunteer raters for 20 experimental vigilance tasks regarding that task's overlap with the multi-decade consensus aspects/qualifiers (Table 2). Note: the data point at 61%, 67% (X,Y) represents two overlapping points.

5 additional volunteer raters who redundantly and independently coded a sub sample of 4 tasks each for a total of 20 (approximately 30% of the full set of 69). A strong positive correlation was obtained between the calculated overlap percentages of these tasks rated by the additional volunteers and with those of the original rater on the same tasks ($r = .83$, Fig. 2).

Additional aspects of feature details and environmental conditions of the experiment were also manually reviewed and annotated for each experimental task. Specifically, the present analysis involved a qualitative identification of what the signal of interest was and a quantification of its rate of presentation scaled over one hour. Environmental conditions recorded included whether the experimental tasks took place within a simulator versus a real road; with instructions to hold fixed (or within a fixed range) a specified lateral lane position and/or longitudinal speed value; with instructions to drive "normally" and/or by some established convention/law; with the presence or absence of other vehicle traffic; and during clear visibility conditions (e.g., day time) versus deteriorated visibility (e.g., night time, fog, etc.).

3. Results

3.1. Coverage of experimental instructions and environmental conditions for driving vigilance tasks

Instructions and environmental conditions of the analyzed driving vigilance experimental tasks are presented in Table 4. Overall, a greater majority of experimental driving vigilance research was found to take place with simulators (27 of 39; 69%) compared to real-life roads (11 of 39; 28%) or use of video footage (1 of 39; 3%). Participants of the simulator studies were more often explicitly tasked with maintaining a fixed position (or a position within a fixed range) for longitudinal control (20 of 27; 74%) and/or lateral control (17 of 27; 69%) than were participants of experimental on-road tasks where lateral positions (4 of 11; 36%) and longitudinal positions (2 of 11; 18%) were mandated to be held. Contrastingly, use of more flexible instructional guidance such as "drive normally" and/or by abiding to commonly established norms, laws, and conventions was found to be higher in on road driving vigilance tasks (6 of 11; 55%) compared to simulator tasks (4 of 27; 15%). Furthermore, presence of other traffic (i.e., at least one other vehicle) was found in higher proportion in on-road (10 of 11; 91%) than in simulated tasks (13 of 27; 48%). Lastly, reporting of on-road driving vigilance tasks was found to primarily be of

Table 4
Instructions and environmental conditions of driving vigilance experimental tasks.

Ref #	Road	Sim.	Video	Lat.	Long.	Normally	Alone	Traffic	Day	Night
1		1		1	1	?	1			1
4		1		1	1	?	1			1
3		1		?	?	?		1	1	
5b		1		1	1	?	1		1	
8a		1		1	1	?		1	?	?
8b		1		1	1	?		1	?	?
14		1		1	1	?	?	?	?	?
15c		1		1	1	?		1	?	?
15d		1		?	1	?		1	?	?
18b		1		1	?	?		1	1	
19b		1		?	?	?	?	?	?	?
20a		1		1	1	?		1		1
22		1		1	1	?		1		1
25b		1		1	1	?	1		1	
25c		1		1	1	?	1		1	
31b		1		?	0	1		1	?	?
34		1		1	1	?	?	?	?	?
38a		1		1	1	?		1		1
2b		1		1	1	?	1		1	
10a		1		1	1	?	1		?	?
13a		1		1	1	?		1	?	?
11		1		1	?	?	?	?	?	?
23		1		?	?	?		1	1	
26		1		?	0	1	?	?		1
30a		1		1	?	?		1		1
32		1		?	?	1	1		?	?
28		1		1	0	1	?	?	1	
6	1			?	?	1		1	1	
9b	1			?	?	1		1	1	
12a	1			?	?	1		1	1	
17			1	0	0	?		1	?	?
16a	1			1	1	?		1	1	
21a	1			?	?	?		1	1	
27	1			1	?	?		1	1	
33a	1			1	1	?		1	?	?
35a	1			?	?	1		1	1	
36a	1			?	?	1		1	1	
37a	1			1	?	?	1			1
39a	1			?	0	1		1	1	

Note: Column header indications: "Road" – driving task took place on real life road; "Sim." – driving task took place within a simulated environment; "Video" – driving task took place with videos of driving; "Lat." – subject required to maintain a fixed lane position or hold steady in a set range; "Long." – subject required to maintain a fixed speed or hold steady in a set range; "Normally" – subject asked to drive as normal/usual, by regulation, convention, law, standard, etc.; "Alone" – no other traffic present in driving task situation; "Traffic" – at least one other vehicle present in driving task situation; "Day" – daytime, clear visibility; "Night" – nighttime, fog, reduced visibility. Coding of "1" = true; "0" = false; "?" = unreported.

daytime/clear-visibility conditions (9 of 11; 82%) with lower amounts of consensus features unspecified (2 of 11; 18%). Simulator driving vigilance tasks however, were more evenly split between daytime/clear visibility (8 of 27; 30%) and night-time/reduced visibility (7 of 27; 26%) with higher amounts of consensus features unspecified (12 of 27; 44%).

3.2. Types of signals

Signal type categorization of driving and non-driving vigilance experimental tasks are shown in Tables 5a and 5b, respectively. Across the 69 vigilance tasks from the driving vigilance literature, there were 53 specified signals in total together from Tables 5a and 5b. Fewer signals from within the driving vigilance tasks were found specified (23 signals from 39 tasks; 59%) compared to those of the non-driving vigilance tasks (30 signals from 30 tasks; 100%). The 23 identified driving vigilance signals were found to align under mutually exclusive categories in the following amounts and proportions: lateral or longitudinal deviation (12 of 23 signals; 52%), obstacles (9 of 23 signals; 39%), and light sources (2 of 23 signals; 9%). Contrastingly, the 30 identified non-driving vigilance signals were found to align under modality categories of visual (23 of 30 signals; 77%), auditory (5 of 30 signals; 17%), and multi-modal (2 of 30 signals; 7%). Further detailed descriptions follow for signal types of both the driving and non-driving vigilance tasks.

Regarding the driving vigilance task signals, where the signal to detect was a deviation from maintenance of a prescribed fixed longitudinal speed (or speed range) (9 of 12 fixed position tasks; 75%) a correspondent deviation from a required fixed lateral position was also simultaneously given as a signal (12 of 12 fixed position tasks; 100%). Additionally, externally forced

Table 5a
Signal type specification and sub-categorization of driving vigilance experimental tasks.

Ref #	Specified	Deviations			Obstacles					Light	
		Lane	Speed	Wind	Pull-out	Lead	Ped.	Hazard	?	Mirror	Intersect.
1	1	1									
2b	1	1	1								
4	1	1		1							
5b	1	1	1								
8b	1				1						
10a	1	1	1								
13a	1	1	1								
14	1									1	
11	1								1		
17	1							1			
16a	1	1	1								
15c	1	1	1	1							
15d	1				1						
20a	1					1					
22	1					1					
25b	1										
25c	1						1				1
30a	1					1					
28	1	1	1	1							
33a	1	1	1								
34	1								1		
37a	1	1	1								
38a	1	1									
3	?										
6	?										
9a	?										
8a	?										
12a	?										
18b	?										
19b	?										
21a	?										
23	?										
26	?										
27	?										
31b	?										
32	?										
35a	?										
36a	?										
39a	?										

Note: Column header indications: "Specified" – driving vigilance task signal definition/description specified within the text; "Lane" – a deviation from lateral lane position; "Speed" – a deviation from a longitudinal speed; "Wind" – the deviation included encouragement from an external perturbation, e.g. wind gust; "Pull-out" – a vehicle that pulls out in front of and cutting off subject vehicle; "Lead" – a vehicle the subject vehicle is following; "Ped." – a pedestrian; "Hazard" – described at general level as "a potentially dangerous traffic situation"; "?" – an obstacle without description; "Mirror" – a light source in rear view mirror; "Intersect" – a traffic intersection light. Coding of "1" = true; "?" = not specified.

Table 5b
Signal type specification and sub-categorization of non-driving vigilance experimental tasks.

Ref #	Specified	Multi-Modal	Audio		Visual						
								Object			
										Property	
			Hz	Length	Stim.	Light	Char.	Shape	Bboard	Spat. pos.	Color
2a	1							1			1
7a	1							1		1	
7b	1							1		1	
7d	1							1		1	
5a	1							1			
9a	1		1								
8c	1								1		
10b	1					1					1
13b	1					1					
12b	1		1								
16b	1						1				
15a	1						1				
15b	1						1				
18a	1		1								
30b	1							1			1
30c	1							1			1
37b	1					1					
38b	1					1					
39b	1					1					
19a	1					1					
19c	1							1			
21b	1		1								
20b	1				1						
24	1						1				
25a	1						1				
29	1			1							
31a	1						1				
33b	1					1				1	
35b	1	1									
36b	1	1									

Note: Column header indications: "Specified" – non-driving vigilance task signal definition/description specified within the text; "Multi-Modal" – multiple modalities; "Hz" – specific tone frequency; "Length – specific tone duration; "Stim." – a visual stimulus without description; "Light" – a source of light; "Char." – an alpha, numeric, or symbolic character; "Shape" – a simple shape e.g. circle/square, etc.; "Bboard" – a billboard; "Spat. pos." – specific spatial position; -"Color" – specific color. Coding of "1" = true.

perturbations (e.g., lateral wind gusts) were employed in a few cases (3 of 12 tasks; 25%): once with lateral position holding only and twice with both lateral and longitudinal holding. Obstacles of different kinds were used as driving vigilance signals in the following groups and amounts from greatest to least: vehicle continuously leads ahead (3 of 9 signals; 33%); vehicle with discrete pull out or cut in ahead (2 of 9 signals; 22%); unspecified obstacles (2 of 9 signals; 22%); pedestrian leaves curb (1 of 9 signals; 11%,), and examples of hazards pictured in driving scenes but not detailed in explicit description (1 of 9 signals; 11%). Lastly, in regards to the driving vigilance signals as light sources, one involved a light in a rear view mirror (1 of 2 signals; 50%) and the other a traffic signal light (1 of 2 signals, 50%).

Regarding the non-driving vigilance tasks, purely visual signals most frequently included shapes like circles or squares (8 of 23 signals; 35%); followed by sources of light (7 of 23 signals; 30%) and alpha, numeric, or symbolic characters (6 of 23 signals; 26%); with a single instance of a real life object, that is, a billboard (1 of 23 signals; 4%). Furthermore, only a handful of these included a discrimination of color in defining the signal (4 of 23 signals; 17%). For purely auditory signals, most were of a specified frequency (4 of 5 signals; 80%) with a single instance of signal definition based on duration (1 of 5 signals; 20%). Lastly, existing elements of a vehicle were rarely used and spanned multiple modalities (2 of 30 signals, 7%).

3.3. Rates of signals

Rates of signals for general and classic vigilance tasks have been already identified and discussed at length in the literature. For example by 1971, in his extensive 100+ page monograph "Vigilance: The problem of sustained attention", road and motor vehicle traffic safety researcher Carl Stroh reviews over 35 different publications on the topic of signal frequency and concludes "when signal frequency is raised beyond a reasonable level (60–90 per hour), performance might be improved, but then it is doubtful that we are still dealing with a true vigilance situation" (Stroh, 1971, p. 8). Taking his upper bounds as the present analysis' lower bound, signal rates less than and including 90 per hour were considered presently "few" and those greater than 90 per hour were considered absently "few" and hence not matching in terms of the infrequency of signal characteristic found within the multi-decade consensus composite (Table 1, Feature 2a).

Signal rate categorization and quantifications of driving and non-driving vigilance experimental tasks are shown in Tables 6a and 6b, respectively. A larger amount of unspecified feature adherence/contradiction was found regarding the reported rate of signal presentation for driving vigilance (31 reported signal rates from 39 tasks; 79%) than for non-driving vigilance (6 reported signal rates from 30 tasks; 20%). Where signal rates were specified in driving vigilance, slightly more than half were found to match the aforementioned frequency of "few" (5 of 8 specified signal rates; 63%). In comparison, where signal rate was more often specified in non-driving vigilance tasks, a lower proportion were found to be "few" (7 of 24 specified signal rates; 29%). A comparative depiction of proportional signal rates between the driving and non-driving vigilance tasks as well as breakouts for rates not found to be "few" is given in Fig. 3.

3.4. Percentages of overlap with classic/general vigilance tasks

An overlap percentage was computed from the number of the multi-decade features (Table 1) that were present within each of every vigilance task operationalization. On average, less than half of the consensus features were found to be present overall ($M = 48\%$, $n = 69$) with an average amount of unspecified features of 32%. Averaging separately, however, revealed a lower average overlap for the driving vigilance tasks ($m = 36\%$, $n = 39$) with higher amounts unspecified ($M = 46\%$) compared to the non-driving tasks ($M = 64\%$, $n = 30$) with lower amounts unspecified ($M = 13\%$) as seen in Fig. 4.

3.5. Most common features of overlap, contrary, and unspecified

For both the driving and non-driving vigilance tasks and each multi-decade consensus feature (Table 1), separate sums of the ratings of overlap, contrary, and unspecified were computed (Table 7) to determine what of classic vigilance tasks were

Table 6a
Signal presentation rates per hour of driving vigilance experimental tasks.

Ref #	Few	Rate per hr
1	?	?
2b	?	?
4	0	133.33
5b	?	?
8b	?	?
10a	?	?
13a	?	?
14	?	?
11	1	4.8
17	?	?
16a	?	?
15c	?	?
15d	?	?
20a	?	?
22	?	?
25b	?	?
25c	?	?
30a	1	4.8
28	?	?
33a	?	?
34	?	?
37a	1	20
38a	?	?
3	?	?
6	1	60
9a	1	60
8a	?	?
12a	?	?
18b	?	?
19b	?	?
21a	?	?
23	0	360
26	?	?
27	?	?
31b	0	1560
32	?	?
35a	?	?
36a	?	?
39a	?	?

Note: Column header indications: "Few" – less than or equal to 90 signal presentations per hour; "Rate per hr" = number of signal presentations per hour. Coding of "1" = true; "0" = false; "?" = not reported.

Table 6b
Signal presentation rates per hour of non-driving vigilance experimental tasks.

Ref #	Few	Rate per hr
2a	0	600
7a	0	219.43
7b	0	219.43
7d	0	219.43
5a	0	360
9a	0	102.86
8c	1	12.24
10b	?	?
13b	1	60
12b	0	102.86
16b	?	?
15a	0	348.84
15b	0	120
18a	?	?
30b	1	34.47
30c	0	159.6
37b	?	?
38b	1	30
39b	1	20
19a	1	60
19c	0	540
21b	0	120
20b	0	600
24	0	345
25a	0	200
29	0	144
31a	0	480
33b	1	40
35b	?	?
36b	?	?

Note: Column header indications: “Few” – less than or equal to 90 signal presentations per hour; “Rate per hr” = number of signal presentations per hour. Coding of “1” = true; “0” = false; “?” = not reported.

most held in common, in contradiction or in uncertain terms. In the driving vigilance tasks, the most common feature overlapping with the classic features was that regarding a lengthy duration (i.e., half an hour or longer, Feature 4a) (28 of 39; 72%). In the non-driving vigilance tasks the most common feature in overlap was a tie between the detection of a signal (Feature 2) and the requirement of making a specified response (Feature 4e) (30 of 30; 100%). Regarding contrary features, the most common feature absent and in contradiction for the driving vigilance tasks was the successive presentation of signal and noise (i.e., a burden of memory of the distinction between these provided their non-simultaneous/overlapping occurrences, Feature 4d) (20 of 39; 51%). For the non-driving vigilance tasks the most common feature absent and in contradiction was a tie between the signals being few in frequency (i.e., <90 per hour, Feature 2a) and the signals occurring in spatially uncertain locations (Feature 2f) (17 of 30; 57%). Lastly for unspecified feature presence/absence, the provision of objective feedback of a subject’s own task performance (Feature 4b) was the feature most often rated as unspecified in both driving vigilance (35 of 39; 90%) and non-driving vigilance tasks (20 of 30; 67%).

3.6. Task summaries of the highest amount of overlap

Finally, additional task summaries of those experimental driving vigilance tasks with the highest amount of overlap with the classic consensus general vigilance features are next presented in a four-way tie of 67% overlap each. First, with the lowest amount of unspecified features (6%), drivers were asked to immediately steer back to the center of the original lane once perturbed by random forced departure events while on a simulated night time roadway with no other traffic and cruising at a constant speed of 100 km/hr (Lin et al., 2014). Second, with the next lowest unspecified consensus features of 11%, participants steered towards randomly left/right deviating red tail lights projected at a constant distance ahead “as if following it along a country road at night” while seated in a stationary car cabin but with a forward projection of a moving road of random dot patterns on an extended table surface ahead of their cabin, whose progression was coupled to the input of their accelerator pedal (Boadle, 1976, p. 220). Lastly, in two separately coded driving vigilance tasks from the same publication (Lo, 2005) and both with 17% of the consensus features unspecified, participants had to step on a brake pedal as response to encountering either a pedestrian stepping away from the sidewalk into the driving lane or a traffic light that changed from green to red. These participants were occupational taxi drivers who performed the test while seated in their own stationary real-life taxi with a 15″ laptop displaying a simulated 80 km/hr flowing view of a monotonous road lacking any other traffic or lateral control.

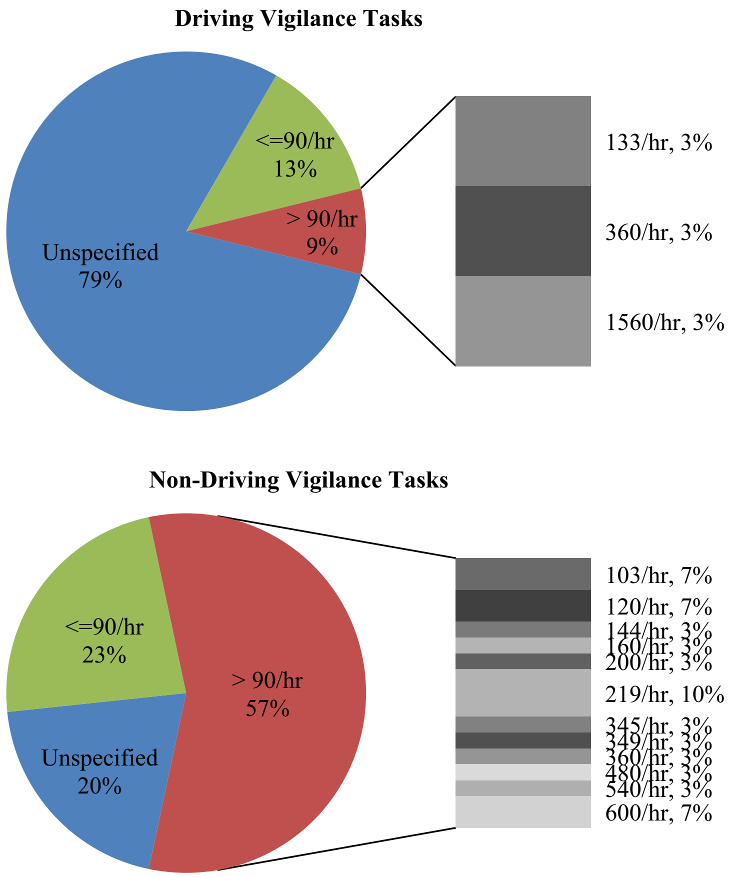

Fig. 3. Specification of signal rates in driving vigilance versus non-driving vigilance tasks and stacked bar delineation for proportions of specific rates when in excess of "true vigilance situations" (i.e., >90/h) (Stroh, 1971, p. 8).

4. Discussion

This review aimed to characterize experimental driving vigilance tasks in terms of common instructions/conditions, signal types/rates, and component features for comparison to the classic vigilance literature. From sampling experimental literature principally concerning both *driving* and *vigilance*, we found task operationalizations that were not highly similar with the full set of multi-decade consensus situational features surrounding the vigilance decrement. The overall results support critical (re)evaluation of *driving* tasks as being construed as *vigilance* tasks in the classic sense.

4.1. Coverage of experimental instructions and environmental conditions for driving vigilance tasks

Our results revealed large and informative differences between the common instruction/conditions used in experimental driving vigilance research, especially along the dimension between the use of simulators or real roads. First, and perhaps unsurprisingly, simulator studies were about twice as common as real-world settings. Furthermore, simulator studies were found to more commonly restrict the driving task into maintaining a specific speed and lane position and hence driving vigilance arises as the perception and response to deviations from such mandates. When operationalized on real roads, drivers were more often flexibly tasked with only general adherence to legal/social conventions for driving. The driving vigilance here, might then be differently construed as the perception and response to deviations from safety or normality. Additionally, a large component of driving safety can reasonably be expected to include the presence/absence of other vehicles, which was about twice as commonly available in the real-world versus the simulator studies. Real-world studies, however, were seen to more commonly be restricted to conditions of near perfect visibility compared to simulator studies which more evenly exposed driving participants to both day/clear and night/fog environment.

4.2. Types of signals

Similar challenges for the topic of driving vigilance were found from the analysis of signal types in experimental driving vigilance tasks. First, explicit descriptions of the driving specific signals a participant should be ready to perceive and

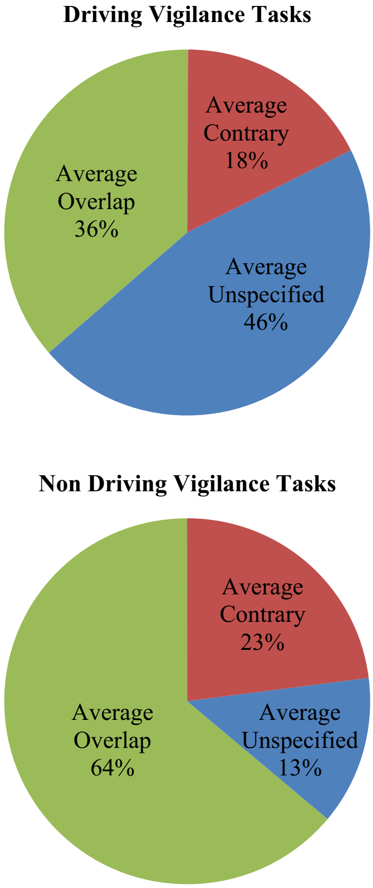

Fig. 4. Averages of classic consensus feature overlapping presence, contrary absence, and unspecified presence/absence for driving vigilance tasks ($n = 39$) versus non-driving vigilance tasks ($n = 30$).

Table 7
Counts of classic vigilance features (Table 1) for driving and non-driving vigilance experimental tasks.

Feature code	"1" Driving (39 tasks)	"1" Non-driving (30 tasks)	"0" Driving (39 tasks)	"0" Non-driving (30 tasks)	"?" Driving (39 tasks)	"?" Non-driving (30 tasks)
1	**25**	**27**	0	3	14	0
1a	14	10	14	9	11	11
2	**23**	***30***	0	0	16	0
2a	5	7	3	***17***	**31**	6
2b	14	**29**	9	0	16	1
2c	0	6	18	15	**21**	9
2d	15	**26**	3	1	**21**	3
2e	8	**21**	13	0	18	9
2f	3	10	16	***17***	**20**	3
3	17	**18**	4	11	18	1
3a	17	**18**	4	11	18	1
3b	14	**17**	6	11	19	2
4	**25**	**29**	1	0	13	1
4a	***28***	**17**	8	13	3	0
4b	2	8	2	2	***35***	***20***
4c	**25**	**27**	2	0	12	3
4d	1	15	***20***	14	18	1
4e	**20**	***30***	0	0	19	0

Note: Column header indications: "1" = feature presence; "0" = feature absence; "?" = not reported feature presence/absence. Feature counts exceeding half of the full set of tasks are in bold as "common" and the highest count is in bold and in italics as "most common".

respond to with a driving action were not found in over a third of what were coded as driving vigilance tasks. This shared difficulty alone suggests a decomposition of driving and assessment of driving vigilance to be potentially problematic. Potential solutions may include direct manipulations of instructions and/or stricter documentation of the specific instructions given to participants of driving vigilance experiments along with the avoidance of instructions which may be susceptible to generalities/assumptions such as to drive "safely", "as you normally would", "according to the law", etc. Furthermore, clear consensus was not found between driving vigilance signal operationalizations, with a relatively even split between obstacles and speed/lane deviations and with only a few light signal sources. Unfortunately, as discussed earlier, deviations from prescribed speed or lateral positions might not be as realistic a concern of driving vigilance as the perception and avoidance of obstacles (i.e., especially other traffic). Additionally, a relative scarcity of light source signals (i.e., 2 of 23 driving vigilance signals) seems problematically disproportionate, given a large prevalence of visual light signals in real-world driving (e.g., intersection lights, caution lamps, turn signals, headlights, etc.) as well as in automated warnings/indicators (e.g., dashboard, heads up displays, etc.). Considering the possible modalities all of these driving vigilance signals might manifest through (as in the non-driving vigilance signals), additionally suggests a potential mismatch of focus. At present, a gap can be seen surrounding the use of real-life and multi-modal types of signals for experimental driving vigilance assessment and investigation.

4.3. Rates of signals

More problems for an informed identification and alleviation of vigilance decrements were found in the lack of reported signal rate/frequencies when describing the driving task specific signals and responses. This same level of unspecified signal rates (79%) was not evidenced in non-driving vigilance tasks (20%) and suggests in the least difficulty in reporting, and possibly even a gap in knowledge or approach regarding frequencies of driving vigilance signals. While more than half of specified signal rates in the driving vigilance tasks were indeed within the range of a "true vigilance situation" (Stroh, 1971, p. 8) these are at a minority against the disproportionate unspecified of the majority. Thus for the accurate prediction and alleviation of vigilance decrements, the present review reveals an unfortunate lack of articulation of a presumably prudent direct consideration/exploration of exactly how rare and/or how much influence drivers might have on the signals they must respond to while driving. Generally, whenever signal-response approaches are used, it is recommended to include precise documentation of the rate of signal presentation and especially for investigations of vigilance to also include stipulations surrounding any influences a participant might have on that rate or on its being predictable for the participant.

4.4. Percentages of overlap with classic/general vigilance tasks

All the vigilance tasks of the analysis averaged together showed a weak overlap with the multi-decade consensus vigilance theory situational features (less than half on average), thus suggesting some misalignment of operationalization between theory and practice. Splitting this overlap comparison revealed less theoretical overlap for driving vigilance tasks (36%) versus non-driving vigilance tasks (64%). Additionally, the unspecified consensus aspect/qualifier presence or absence was higher for the driving vigilance tasks (46%) and lower for the non-driving vigilance tasks (13%). In the least, it is evident then and convergent with the prior results of the present analysis, that describing *driving* as a *vigilance* task and tackling its potential for detrimental vigilance performance is not straightforward and the lessons learned thus far from vigilance theory therefore might not be readily applied. Extensions of classical definitions of vigilance to situated definitions of driving vigilance, especially pertaining to anticipated or requisite characteristics (e.g., features) may provide a way forward. Moreover, such definitions might attempt to identify features that are essential throughout all driving vs. specific to particular driving contexts or scenarios.

4.5. Most common features of overlap, contrary, and unspecified

The present analysis extended beyond the identification of a lack of consensus overlap (i.e., between shared features of classic vigilance circumstances and experimental driving vigilance operationalization), to help reveal why this might be the case. Perhaps unsurprisingly, driving vigilance tasks and non-driving vigilance tasks had similar overlap with consensus vigilance features regarding the presence of a perceiver tasked to respond to signals over a prolonged period in a consistent/unchanging standard of performance. More informatively, however, the current analysis showed features that are *not* commonly reported for driving vigilance tasks but which *are* commonly reported in non-driving vigilance tasks. These features of large quantities of non-meaningful noise events which are highly similar to target signals where the target signals themselves are not predictable and not subject to any driver influence on the probability or duration of occurrence are lacking specification in driving vigilance operationalization. Such a lacking presents direct challenges of practically matching driving vigilance problems to general classic vigilance theory. Furthermore, the successive and memory burdening presentation of signals separate from noise was found to be absent in more than half of the driving vigilance tasks where instead signals emerged from or simultaneously overlapped with their noise (e.g., a pedestrian stepping away from a curb, or lateral heading drifting away from lane center, etc.).

4.5.1. Task summaries of the highest amount of overlap

Those few tasks with the highest amount of consensus feature overlap may shed light on circumstances research could focus on for safeguarding against classic vigilance decrements. In summary of the cases with an approximate two-thirds overlap with consensus classic vigilance circumstances, decrements of vigilance might be predicted for drivers alone at night attempting to follow precise lateral positions at constant speeds, in performing correct braking responses to red traffic signal lights and errant pedestrians, or in other conceivability similar circumstances. As an example of applied vigilance solutions then, deviations from a prescribed lane canter could be made more salient by auditory and visual alerting with Lane Departure Warnings. In addition to increasing the predictable/regular occurrence of encounter of pedestrians and/or traffic lights (e.g., crosswalks, intersections, etc.) such signals might be highlighted or emphasized by advanced recognition software such as with heads-up displays. However, two-thirds (while the highest found) is by definition only *partial* overlap and those elements missing might also be the ones crucial to or interactive with other aspects for performance in that specific situation. Until these are better understood from additional research and investigation, the driver vigilance support solutions may prove inadequate at best and inappropriately applied at worst.

4.5.2. Highest amount of overlap in highly automated driving?

Decrements and problems of vigilance may be expected to arise in future driver assistance and automated driving systems to the extent that circumstances of their use cases might resemble the classic vigilance situational feature set. While the driving tasks of the present analysis did not often explicitly identify themselves as operating within an automated driving paradigm, some task conditions did automate lateral and/or longitudinal control in their experimental methods and so could be seen as reflecting a NHTSA Level of Vehicle Automation 1 and/or 2. Moreover, a body of driving vigilance concerns are emerging from BASt- and NHTSA-like definitions of automated driving where a driver is required to respond to an automated system take-over request provided no/short notice and/or a pre-established length of time (Gasser & Westhoff, 2012; NHTSA, 2013). While initially out of the scope of the present analysis because the title did not use the terminology of "vigilance" or "sustained attention" in its title, the take-over request (TOR) automated driving simulator experiment of Gold, Dambock, Lorenz, and Bengler (2013) maintains relevance to the present discussion as many of its theoretical and experimental task features could be considered in overlap with the classic vigilance feature set.

In Gold et al. (2013), subjects were tasked with a pre-occupying secondary task while the car drove itself until an auditory and visual alert prompted them to take-over to avoid an accident ahead of them either through braking or swerving to another lane. In their methods, 50% of the set of features of classic vigilance tasks are present with a subject watching/listening for an infrequent, temporally uncertain, unambiguous, time-critical signal that they must perform a required response to in a consistent/routine manner. However, a much higher overlap around 83% (and highest yet of any of the tasks of the present analysis) is conceivable for TORs when adding to the specific reported methods of Gold et al. (2013) features likely within TOR in general. These additional features might include an isolated driver required to respond during prolonged periods of inactivity to imperfect automation through which the driver must make asynchronous discriminations between noise (i.e., false alarm/missed events) that is highly similar to valid signals. The classic vigilance decrement features of time criticality (i.e., short lasting signals) and lack of feedback on driving response in TOR, while respectively present and unspecified present/absent in Gold et al. (2013), however should not and does not necessarily hold true in all future real-world TOR implementations. Further research and investigation is thus seen as especially needed in regards to the specific potential for decrements of vigilance provided higher levels of driving automation surrounding the situational features entailed by design, implementation and actual driver use.

5. Summary and limitations

From reviewing experimental driving vigilance task operationalizations, the results of the present analysis have shown the topic to be of great concern but a challenge for specific consensus definition and treatment. The results are by strict definition limited to the narrow selection of literature from specific inclusion/exclusion criteria, yet may generalize beyond the use of "vigilance"/"sustained attention" and "driving" in the title. The general results of uncertainty surrounding driving vigilance operationalization might also be considered an artifact of the feature set and coding schemes undertaken. However, the marked differences observable from the non-driving vigilance tasks using these same methods serve to provide relative confirmation. Moreover subjectively, the same difficulty of complexity and articulation in driving vigilance can be appreciated merely from asking oneself which and to what extent any of the circumstances described above may or not be present when people actually drive in normal day-to-day situations.

6. Directions for future research

Concerns in the literature over the real-world applicability of findings from laboratory/simulator vigilance experimental tasks span multiple decades of criticism and review (Kibler, 1965; Craig, 1984; Mackie, 1984; Wiener, 1987) to the near present day (Hancock, 2013a) and are equally shared by driving safety researchers seeking theoretical transfer (Rosenbloom & Wolf, 2001).

Raising such discussion and concern in the transportation research literature can help protect against prohibitions regarding driving task requirements (i.e. perceptual targets and response actions) while these requirements are still uncertain and supports the introduction of new theoretical accounts. In concert with the accelerating development and applications of microprocessors that "have demanded not less but more of the human monitor" and "those who believe that just one more chip needs to be invented to automate the human out of the system" (Wiener, 1987, p. 735), a volume of tools are also growing for observation and data collection in instrumented vehicles, field operational studies, and naturalistic driving (Dingus et al., 2006; Eenink, Barnard, Baumann, Augros, & Utesch, 2014; McGehee, Carney, Raby, Lee, & Reyes, 2007; Regan, Williamson, Grzebieta, & Tao, 2012; Stutts et al., 2005; Tivesten & Dozza, 2014; Victor et al., 2010). Collectively, such studies could begin to provide exactly the wealth of real-world operational knowledge needed to bridge theory and practice (e.g., Wiener, 1987). Furthermore, they typify and support emerging theoretical perspectives, that is, *situated cognition*, that posit knowledge as inseparable from doing by being situated in activity bound to social, cultural, and physical contexts (Robbins & Aydede, 2008).

Interestingly, with accelerating advances in computation (Moore, 1965), telecommunication, and Internet connectivity technology, nothing should inherently prohibit such real-world data from entering into laboratories and like areas of greater control and manipulation. For example, augmented reality and other blended designs might be an appealing approach (Hancock & Sheridan, 2011, chap. 4) as well as widely publically available and diverse driving video data sets (e.g., YouTube DashCam videos). Overall, in parallel with a growing popularity of debunking myths of "good" and "bad" drivers (Arnstein & Arnstein, 2005), future driving vigilance research efforts might benefit from following lines of cognitive and work domain analyses well used by many other domains (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999), along with critical re-consideration of fundamental driving attention and distraction paradigms (Hancock, 2013b, chap. 2; Kircher & Ahlstrom, 2015) and direct consideration of real-world conditions and constraints typically under-represented in simulator studies, including the allowance of terminating/modulating vigilance task performance at one's own intrinsic will rather than external compulsion that fixes down attention otherwise left free to vary (Hancock, 2013a; Scerbo, 2001).

From naturalistic driving studies, evidence is only recently emerging that safety risks associated with cell-phone use are considerably smaller than previously believed (Fisher, Caird, Rizzo, & Lee, 2011, chap. 1) by distinguishing between talking/listening vs. reaching/dialing cell-phone aspects and by comparing relative to other higher risk factors like drowsiness and specific environmental situations like intersections and increased traffic densities (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Future studies may even begin to address the possibility of cell-phone use as a benefit, for example, as voluntary countermeasure to reduced alertness (Victor et al., 2015). The constant maintenance of some prescribed and predetermined level of driving vigilance may itself also be worth challenging or in the least worth re-visiting provided more specific detailing of the situational features included in actual driving activity. Indeed, the lack of consensus from the present analysis of driver vigilance operationalization may be viewed as support for reversals or at least re-examinations regarding assumptions or requirements of how drivers should, and/or how they actually do perceive and respond while driving.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trf.2016.04.001.

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Note: References marked with an asterisk indicate publications included in the present analysis.

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