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Dangerous intersections? A review of studies of fatigue and distraction in the automated vehicle

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ABSTRACT

The impacts of fatigue on the vehicle driver may change with technological advancements including automation and the increasing prevalence of potentially distracting in-car systems. This article reviews the authors' simulation studies of how fatigue, automation, and distraction may intersect as threats to safety. Distinguishing between states of active and passive fatigue supports understanding of fatigue and the development of countermeasures. Active fatigue is a stress-like state driven by overload of cognitive capabilities. Passive fatigue is produced by underload and monotony, and is associated with loss of task engagement and alertness. Our studies show that automated driving reliably elicits subjective symptoms of passive fatigue and also loss of alertness that persists following manual takeover. Passive fatigue also impairs attention and automation use in operators of Remotely Piloted Vehicles (RPVs). Use of in-vehicle media has been proposed as a countermeasure to fatigue, but such media may also be distracting. Studies tested whether various forms of phone-based media interacted with automation-induced fatigue, but effects were complex and dependent on task configuration. Selection of fatigue countermeasures should be guided by an understanding of the form of fatigue confronting the operator. System design, regulation of level of automation, managing distraction, and selection of fatigue-resilient personnel are all possible interventions for passive fatigue, but careful evaluation of interventions is necessary prior to deployment.

1. Introduction

Threats to safety often arise when multiple vulnerabilities converge (Reason, 2000). Fatigue, distraction, and system automation, may all elevate risk to vehicle operators, at least in certain contexts. Williamson et al. (2011) identified three safety-relevant factors associated with fatigue: sleep homeostasis factors, circadian influences and task effects. Their review concluded that sleep loss has the strongest effects on crash risk, but more research is needed on task-induced fatigue. The dangers of distraction have become more salient with increasing use by drivers of in-car systems, including informational systems such as GPS, entertainment systems, and cell phones, which allow the driver to engage in extraneous activities (Strayer, 2015). Fatigue and distraction factors have been extensively studied in conventional vehicles, but there is only limited research on how they may interact in their effects on safety.

Both full and partial vehicle automation can bring a range of safety benefits. Automation refers to multiple systems (Banks et al., 2014). Allocation of basic tasks such as control of speed to automation may mitigate driver workload, whereas collision warning or avoidance systems can prevent specific driver errors. Safety concerns about system automation derive from the loss of situation awareness (SA) that may occur in some circumstances (Strand et al., 2014; Young and Stanton, 2007). SA refers here to the driver's internal model of the traffic environment and its safety implications. In addition, future systems may increasingly require active collaboration between the driver and the automated systems, mediated by driver initiation of automated functions (Banks and Stanton, 2016). Optimization of trust in the automation is critical: under- or over-dependence on the automation may impair performance (Lee and See, 2004; Parasuraman and Riley, 1997).

Research is lacking on whether the safety impacts of fatigue and distraction in the automated vehicle are similar to those observed in conventional vehicles. We cannot necessarily summate risk factors to predict that, crudely, risk = fatigue + distraction + automation-induced SA loss. For example, distraction in the form of conversation may actually help to maintain alertness in the fatigued driver (Atchley and

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Table 1
A summary of studies reviewed.

	N	Sim.	Independent Variables	Key Issues
1. Saxby et al. (2013)	108 (Study 1); 168 (Study 2)	Car	1 Fatigue manipulation (wind gusts, automation, control) 2 Drive duration (10, 30, 50 min)	Effects of automation on subjective fatigue and behavioral alertness
2. Neubauer et al. (2012a)	184	Car	1 Automation (Yes/no) 2 Driver initiation of automation (Yes/no)	Comparison of externally imposed and driver-initiated automation effects
3. Wohleber et al. (2016)	143	Multi-UAV control	1 Time on task (2 hours: 15 min blocks) 2 Automation reliability (High/low)	Temporal changes in alertness and automation-reliance as fatigue develops
4. Saxby et al. (2017)	160	Car	1 Automation (Yes/no) 2 Conversation (Yes/no)	Moderation of automation-fatigue effects by concurrent phone conversation
5. Neubauer et al. (2012b)	240	Car	1 Automation (Yes/no) 2 Modality of response to texts (speech, text, free choice, control)	Moderation of automation-fatigue effects by prior phone responses to texts
6. Neubauer et al. (2014)	180	Car	1 Automation (Yes/no) 2 Input materials (conversation, trivia game, control)	Moderation of automation-fatigue effects of prior phone responses to speech

Note. Sim = Simulation. All independent variables except time on task (Study 3) were manipulated between-subjects.

Chan, 2011), and automation impacts on SA depend on a variety of moderator factors (De Winter et al., 2014). Another complication is the bidirectional, dynamic nature of the interaction between the human operator and the vehicle (Matthews, 2001, 2002). Factors including automation and in-car media impact driver workload, fatigue, and stress states, which in turn may influence use of automation and performance. Behavioral changes might potentially be maladaptive or adaptive. Effects of driver state may include changes in both attentional efficiency and strategic control of performance. Vehicle operation typically affords the driver considerable voluntary control over task demands; for example, drivers may compensate for distraction by slowing down or increasing headway to the next vehicle. Finally, as automation becomes more complex and less transparent, appropriate calibration of trust will become an increasingly important safety factor (Payre et al., 2016). Research is lacking on how fatigue and distraction might affect trust in the automated car, although such issues are salient in studies of Remotely Piloted Vehicles (RPVs: Cummings et al., 2013).

The present article aims to review six studies by the authors, summarized in Table 1, which addressed the intersection of task-induced fatigue, distraction, and automation as potential safety threats. It is structured as follows. First, we introduce Desmond and Hancock's (2001) theory of active and passive fatigue and summarize two studies on the effects of fatigue manipulations on subjective states and behavioral alertness. We found that automation induced a passive fatigue state, i.e., a state of tiredness and lack of task motivation, as well as longer response speed following manual take-over of an automated vehicle (Study 1). Driver initiation of automation did not protect against its detrimental effects (Study 2). Second, we review impacts of passive fatigue on attention and reliance on automation in RPV operation, demonstrating damaging effects in a different task domain (Study 3). Third, we address the intersection of distraction and fatigue in the automated vehicle and evaluate the claim that secondary tasks may actually counter harmful fatigue impacts. Studies 4–6 investigated whether various additional tasks, performed using a cell phone, moderated the impact of automation on subjective fatigue and alertness, following manual take-over. The studies manipulated input and output characteristics of the cell phone task, as well as its timing during or following automated driving. These studies confirmed that the detrimental effects of automation were robust, but were moderated in complex ways by the additional, potentially distracting tasks. In concluding, we consider the implications for fatigue countermeasures.

The scope of this review reflects the aims of the empirical studies, which centered on determining impacts of the experimental factors on subjective state and driver performance, in well-rested participants. The focus on task-induced fatigue excludes sleep loss and circadian effects (Williamson et al., 2011); future work might address the interactions of these fatigue factors. A limitation of the studies is that they did not include psychophysiological fatigue measures, which provide important insights (Borghini et al., 2014). The studies aimed to contribute to the basic psychological science of driver fatigue, and so a further limitation is that generalization to real driving remains to be tested. Automation is addressed here primarily from the perspective of its potential impact on alertness and SA; we do not intend to downplay its potential for enhancing safety and operator well-being (e.g., Mitchell et al., 2009). Also, our interest was in the effects of exposure to automation on the driver's mental state. Understanding safety impacts of automation also requires differentiating between specific driver assistance systems, optimizing transitions between automated and manual driving, and evaluating automation performance under different traffic conditions (e.g., Banks et al., 2014; De Winter et al., 2014 Gold et al., 2016). These issues are beyond the present scope, but future fatigue studies might benefit from more fine-grained analysis of fatigue effects on driver utilization of specific systems.

2. Fatigue in the automated vehicle

The general concern regarding automation is that as operator shift from skilled agents to passive monitors of the technology (Sheridan and Parasuraman, 2005), they become increasingly disengaged and vulnerable to the impacts of fatigue and distraction (Cummings et al., 2013). However, "automation" refers to a variety of vehicle systems with differing effects on driver behavior. First, the degree of control allocated to the automation varies. Several taxonomies specify multiple levels of automation (LOAs) ranging from full manual control to full automation (Vagia et al., 2016). It remains unclear how functions should ideally be allocated between driver and vehicle within dynamic traffic environments (Merat et al., 2014). Second, LOA can change during a drive at the initiation of either the driver or the automation, depending on circumstances. For example, at level 3 in the SAE International (2014) taxonomy, the automation may request the driver to take over control when it recognizes that driving demands exceed its capabilities. In the present research (e.g., Saxby et al., 2013), we focused especially on the challenge posed by Level 3, i.e., that the driver must switch from a possibly inattentive state during full automation to maintaining alertness following manual takeover. Externally-triggered changes in task demands appear to be generally difficult for people to manage (Helton et al., 2008), and warning signals produced by automated detection of events such as lane departures and impending collisions may be distracting (Banks et al., 2014). Third, future systems may replace the driver with a remote controller. Corporations including Amazon, Google and UPS are developing delivery systems in which fleets of unmanned ground or aerial vehicles are directed and

Table 2
Influences on active and passive fatigue in vehicle operation.

Fatigue Type	Influences
Active	High task load High density traffic Poor visibility Multi-tasking
Passive	Underload conditions Monotonous drive Extended driving periods Automated systems

monitored from a central control station (Bamburry, 2015). Even if drivers remain physically in the vehicle they may take on a command and control role, similar to a co-pilot or air traffic controller (Banks and Stanton, 2016). A system management role of this kind might counter tendencies to withdraw attention from the task produced by automation.

Automation of various types has complex effects on subjective states, attention and performance, and the operator's strategy for working with automation (Cottrell and Barton, 2013; Sauer et al., 2013). Next, we outline theoretical perspectives that help to clarify the nature of fatigue induced by automation. We address two key, interlocking research questions. First, how does automated vehicle operation influence fatigue states? Second, how does fatigue that is induced by automation influence driver performance and safety?

2.1. Theoretical perspectives on driver fatigue

The safety impacts of sleep loss and circadian rhythms are increasingly understood in terms of neuroscience models (Williamson et al., 2011). However, task fatigue, the focus of this article, may be better explained by psychological rather than neuroscience theory, specifically, the transactional theory of stress and emotion (Lazarus, 1999; Matthews, 2001; Szalma, 2012). This theory sees stress as an expression of the dynamic relationship between the operator and external pressures and challenges. Like other forms of stress, fatigue is a signal that the operator is taxed by task demands. Specifically, task-directed effort is appraised as having limited benefits for performance but substantial costs associated with discomfort and potential exhaustion (Desmond and Matthews, 2009; Noakes, 2012). Coping with fatigue takes the form of lowering performance standards and reducing effort (Hockey, 2012; Matthews and Campbell, 2009), although needs to maintain safety may elicit conflicting goals. Tired drivers may experience stress if they are aware that their fatigue is becoming dangerous (although sleep-deprived drivers may lack this insight). Thus, automation that eases the operator's workload burden, or encourages constructive self-appraisals and coping, may mitigate stress response (Cottrell and Barton, 2013). Conversely, poorly designed automation that confuses the operator or fails to highlight critical information (e.g., Endsley, 1996; Parasuraman and Riley, 1997) may exacerbate stress and fatigue (Parasuraman and Hancock, 2007).

Desmond and Hancock (2001) distinguished *active* and *passive* fatigue. Their theory is relevant to multiple domains of transportation including car and truck driving, conventional aviation, and unmanned vehicle operation. Active fatigue is associated with overload (and hence stress), especially when the person must make many frequent control movements, as when driving on a busy freeway. For example, a factor contributing to the 1990 crash of Avianca flight 52 was autopilot failure. According to Helmreich (1994), "On the day of the accident, this necessitated hand-flying, with an associated increase in workload, fatigue, and stress" (p. 271). Desmond and Hancock et al. (2001) saw active driver fatigue as a relatively common experience in surface vehicle driving, given the psychomotor control demands of the task. Prolonged active fatigue may lead to depletion of attentional resources, as shown in laboratory vigilance studies (Warm et al., 2008). Stress and anxiety may also disrupt attention (Eysenck and Derakshan, 2011).

By contrast, passive fatigue is a product of underload and sustained monotony (Desmond and Hancock, 2001), e.g., when driving on straight roads in featureless terrain with little or no traffic. In aviation, pilots may be especially vulnerable to fatigue during the monotonous cruise part of the flight (Speyer et al., 2003). Higher levels of automation that assign to the operator a primary role of system monitoring role may encourage passive fatigue. Like active fatigue, passive fatigue may impair attention. Reinerman et al. (2008) investigated fatigue effects on cerebral bloodflow velocity (CBFV) in the middle cerebral arteries, a psychophysiological marker for loss of vigilance (Warm et al., 2012). CBFV declined rapidly during a monotonous simulated drive. Passive fatigue may also provoke strategic management of fatigue by reducing performance goals. From a transactional perspective (Lazarus, 1999) the operator-vehicle interaction potentially enters a vicious cycle of progressive impairment; the fatigued driver's mental disengagement leads to increasing boredom with the task, exacerbation of fatigue, and impairments in SA and alertness (Matthews, 2001).

The active – passive fatigue distinction also informs development of countermeasures. May and Baldwin (2009) listed different influences that induce the two types of fatigue in driving, suggesting appropriate design solutions (see Table 2). May and Baldwin (2009) recommended countering passive fatigue by increasing demands, e.g., by use of interactive games. Active fatigue may be mitigated by reducing driver workload through allocating some functions to automation and using warning systems to reduce attentional demands.

Despite increasing interest in active and passive fatigue (May and Baldwin, 2009), there has been rather little empirical research on the distinction. In the next section, we describe our own research on simulated driving, which aimed to develop and validate methodologies for inducing the two forms of fatigue, to map the subjective states and cognitive stress processes associated with each one, and to explore their impact on performance and safety.

2.2. Fatigue and safety in surface vehicles

Understanding the safety impacts of fatigue requires systematic investigation of its two forms. Saxby et al. (2013) conducted two simulator studies that aimed to distinguish active and passive fatigue empirically. The two primary outcome measures were subjective fatigue – i.e., loss of task engagement – and objective alertness, defined as speed of response to an emergency event. Desmond and Hancock's (2001) definitions inspired contrasting techniques for fatigue induction. Active fatigue was elicited by simulating frequent wind gusts, so that the car driver was obliged to struggle with the controls throughout the drive. Passive fatigue was produced by full automation; the driver's only task was to monitor a display for a symbol indicating automation failure. In fact, no failure occurred. In this condition, drivers were asked to keep their hands on the wheel and their feet close to the pedals in readiness for manual take-over.

In the first study, drive duration was varied from 10 to 50 min, to examine the build-up of fatigue over time. Subjective measures included the Dundee Stress State Questionnaire (DSSQ: Matthews, 2016; Matthews et al., 2002, 2013), a multidimensional assessment of the subjective states experienced during task performance. It has been validated in various contexts including driving and simulated RPV operation (Matthews, 2016; Matthews et al., 2011). It can be scored for three broad factors of task engagement (energy, concentration, task motivation), distress (tension, negative mood, lack of confidence) and worry (self-focus, low self-esteem, intrusive thoughts about task and personal concerns). Low task engagement – that is tiredness, distractibility, and loss of motivation – indexes task fatigue (Matthews et al., 2010, 2013). Saxby et al. (2013) also administered scales for the key cognitive processes that underpin stress, appraisal and coping, in the Lazarus (1999) transactional model. The NASA Task Load Index (TLX:

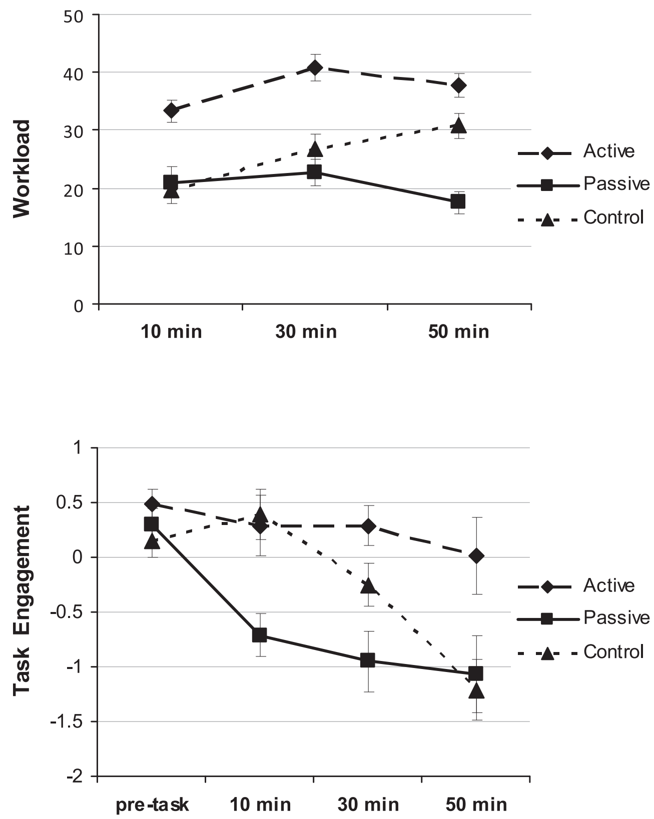

Fig. 1. Effects of three fatigue conditions and drive duration on mean workload (upper panel) and mean task engagement (lower panel). Task engagement is measured in standardized units. There were 36 participants in each of the three conditions. Error bars are standard errors (standard deviation/√N).

Hart and Staveland, 1998) was used to measure workload.

Saxby et al. (2013; Study 1) found that the two fatigue manipulations produced qualitatively different patterns of response, relative to a control condition (normal driving). Active fatigue was associated with high workload as expected. It also produced a combination of distress and moderate-magnitude loss of task engagement, together with appraisals of the task as threatening and uncontrollable, and heightened coping efforts of various kinds. By contrast, passive fatigue was characterized by especially rapid and large-magnitude declines in task engagement, together with low workload and appraisals of the task as unchallenging. Fig. 1 (upper panel) shows how active fatigue produced higher workload than passive fatigue on the TLX in this study. However, engagement was substantially lower in passive than in active fatigue conditions, even at the shortest duration (lower panel). The control condition also elicited reductions in task engagement over time, especially at the 50 min duration, but the passive fatigue manipulation produced large-magnitude loss of engagement much more quickly.

In a second study, Saxby et al. (2013) introduced a behavioral test of alertness at the end of the drive. In all conditions, the fatigue induction was followed by a short interval of normal driving under manual control. During this interval, a slow-moving van pulled out in front of the driver, requiring an evasive maneuver to avoid a crash. In the automation condition, this event took place 2.5 min after automation was terminated, a duration found to be ample for the driver to take over control of the vehicle: automation effects were attributed to persistence of the fatigue state produced by automated driving. The passive fatigue induction produced the highest level of crashes, as well as slowing braking and steering responses. Active fatigue tended to speed response and reduce crash frequency, relative to the other two conditions. Thus, although active fatigue may be associated with higher levels of workload, distress and stress-related cognitions, it is actually less of a threat to safety than passive fatigue. Maximum drive duration was 50 min, but longer-duration episodes of active fatigue may prove to be more dangerous. It was difficult for drivers to transition back to normal alertness once they had developed passive fatigue. From a safety perspective, it was especially concerning that fairly short periods of system automation produced objectively dangerous levels of fatigue. This finding is consistent with existing concerns that automation and cognitive underload may lead to loss of SA: Young and Stanton (2007) also found that use of automation led to increased braking response times.

In Saxby et al.'s (2013) study participants were assigned to experimental conditions at random. Mandatory automation may occur in future systems in which vehicles are allocated to fast-moving platoons in order to maintain freeway traffic flows (Heikoop et al., 2017). In other circumstances, the driver controls initiation of automation. Neubauer et al. (2012a) investigated the role of volitional choice in automated driving. The study included a condition in which drivers had the option of switching on full automation for a five minute period. Drivers might use this facility adaptively, in order to take a break from the cognitive demands of the task. In fact, allowing drivers to initiate automation failed to mitigate either subjective fatigue, i.e. low task engagement, or alertness, measured by speed of response to the van pulling out. These findings suggest that automation-induced fatigue is a potential threat to safety irrespective of whether or not it is under the driver's control.

The Neubauer et al. (2012a) study also revealed dynamic processes that may contribute to performance deficit. When drivers were allowed to choose to use automation, those who were low in task engagement prior to the drive were more likely to initiate automation. These are the individuals who may be most vulnerable to loss of alertness and yet they chose to put themselves at additional risk of passive fatigue. In addition, drivers who used automation showed a heightened distress response to the drive. Neubauer et al. (2012a) suggested that automation encourages drivers to focus attention on their own personal discomfort rather than on task stimuli. Thus, full vehicle automation may encourage vicious cycles in which the fatigued driver becomes progressively more disengaged and stressed, so that the workload reduction produced by automation does not actually benefit the driver.

3. Automation and fatigue in remotely piloted vehicles

As with ground transportation, advancements in technology provide increasing scope for automation of aviation operations, including RPVs. One of the present studies (Wohleber et al., 2016) tested whether passive fatigue effects observed in simulated car driving generalized to the RPV context. A simulation of multi-RPV operation was used, which also supported investigation of the effects of fatigue on reliance on automation. The simulation also provides a platform for investigating fatigue in remote controllers of vehicles.

Although best known from the military context, RPVs will see increasing civilian applications, including package delivery, monitoring crops and forests, and search-and-rescue missions (Skrzypietz, 2012). As with surface vehicles, the workload of RPV operation may be highly variable, depending on operational circumstances (Mouloua et al., 2003). Intelligence, Surveillance and Reconnaissance (ISR) operations, in particular, may be associated with monotony and the potential for passive fatigue. According to Chappelle et al., (2010, pp. 2-3), "The "dull" missions are the ones that require long loiter time and constant surveillance of a target (e.g., days to weeks) too tedious for a crew in a manned aircraft to execute without significant degradations in performance." Conversely, workload demands spike when pilots must handle high volumes of communication from multiple sources, and support combat missions involving intense, unpredictable activity (Chappelle et al., 2010). The vulnerability of operators to fatigue may be exacerbated by occupational factors such as long operational hours and shift work, combined with various stressors (Ouma et al., 2011; Tvaryanas and MacPherson, 2009).

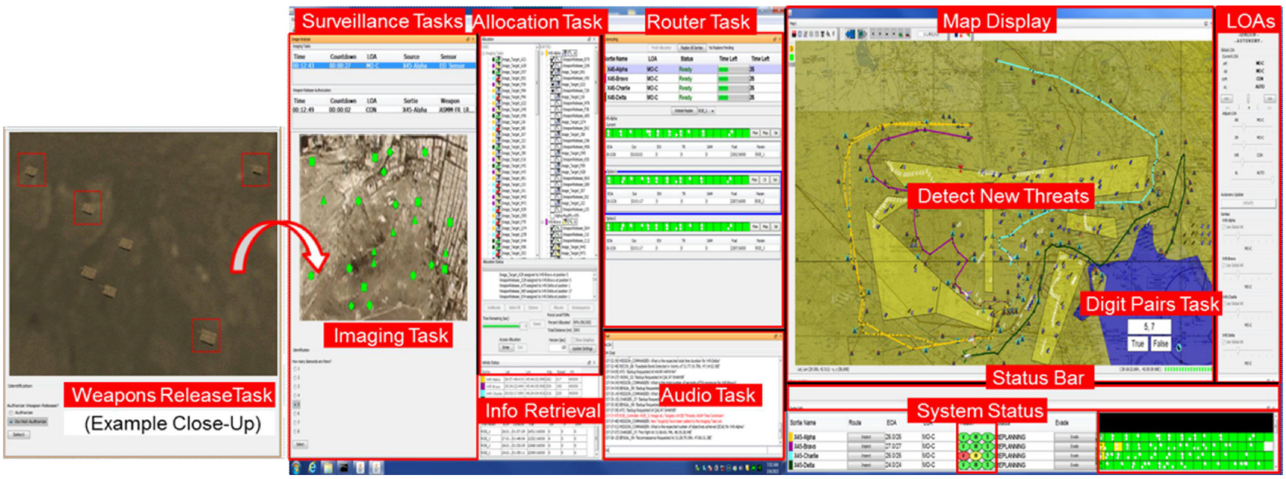

Fig. 2. ALOA multi-RPV simulation display (two screens).

Current RPVs typically require a small team of operators, including a pilot and sensor operator. In the future, single operators may control multiple vehicles, which requires many of the functions of the RPV to be automated (Calhoun et al., 2011), e.g., assigning a ground target for surveillance or determining the optimal route to follow to a target. A key question is what LOA should be applied to RPV operation. Higher LOAs (more machine control) are likely to introduce human factors issues similar to those associated with full automation. The operator may become passive and reactive, over-reliant on the machine, and prone to loss of SA (Calhoun et al., 2011). Conversely, if LOA is too low, the extra workload needed to process inputs from the machine may outweigh the workload mitigation provided by the system. It may be easier for operators to rely on their own skills rather than expending mental effort figuring out what to do with the additional information provided by the automation.

Wohleber et al. (2016) addressed the issue of passive fatigue in RPV operation using the Adaptive Levels of Autonomy (ALOA) multi-RPV simulation (see Calhoun et al., 2011). ALOA includes multiple sub-tasks designed to impose the cognitive demands experienced by an operator managing multiple RPVs (see Fig. 2). These include routing the vehicles, monitoring the "health" of the vehicle, and monitoring events on a map display. The study focused on the sensor operator task of processing camera images of sites of interest on the ground. For example, the Weapons Release subtask required the operator to distinguish confusable images of friendly and hostile tanks; identifying a hostile tank was assumed to call in an air strike. ALOA supports an automated decision aid to assist operators with surveillance tasks, which can be set to different LOAs. An earlier study confirmed that a higher LOA tended to induce higher reliance on the automation, and greater neglect of images (Lin et al., 2015).

In the Wohleber et al. (2016) study, the LOA used was "management-by-consent", in which the automation makes a recommendation, which the operator must explicitly endorse or reject. The simulated mission lasted two hours. Events were infrequent, and interspersed with intervals of "dead time", conditions thought to be conducive to passive fatigue. Reliability of the automation was manipulated (60% vs. 86.7% correct). The primary performance measures for surveillance were accuracy and reliance. Accuracy refers to the overall percentage of correct decisions made in analyzing camera images, i.e., discriminating hostile and friendly tanks. Reliance refers to the percentage of decisions for which the operator followed the recommendation made by the automation.

Here, we focus on the attentionally-demanding Weapons Release surveillance task. The simulation configuration induced passive fatigue. DSSQ data showed that task engagement decreased substantially from pre- to post-task, with no increase in distress: the magnitude of the effect was comparable to that for automation effects in Saxby et al.'s (2013) data. As expected, lower automation reliability was associated with lower accuracy and less reliance on the automation. As fatigue developed over the two-hour session, accuracy declined over time, especially when automation reliability was low, but accuracy returned to initial levels towards in the last task period. This "end effect" suggested that the impact of fatigue may have been moderated by effort-regulation, similar to driver fatigue (Matthews and Desmond, 2002). Participants may have increased effort when they saw on the map display that vehicles were approaching the end of their routes. Reliance on the automation fell over time, as shown in Fig. 3. In both conditions, reliance dropped to sub-optimal levels, i.e., less than the actual reliability of the system. This finding seems counter-intuitive: if passive fatigue is associated with relinquishing personal agency and control (Desmond and Hancock, 2001), the fatigued operator should rely increasingly on the automation, especially with reliable automation. However, decreasing reliance may also be a result of passive fatigue. Operators may see managing the automation as an additional sub-task. Consistent with previous demonstrations of task-shedding under fatigue, participants increasingly simplify the task by neglecting the automation in favor of their own judgment. Especially with unreliable automation, this strategy tends to lead to loss of accuracy, unless countered with increased on-task effort which appears to have been applied at the end of the task.

Fatigue impacts may be different in other contexts. For example, fatigue might be associated with complacency and overuse of

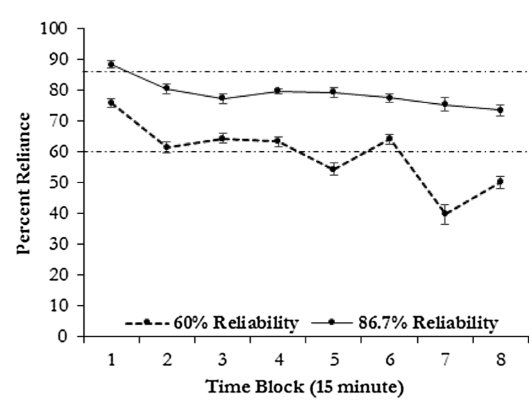

Fig. 3. Mean reliance on automation during a 2-hr RPV simulation as a function of reliability and time block. Broken lines show optimum reliance at each level of reliability. There were 67 participants in the high-reliability condition and 64 participants in the low-reliability condition. Error bars are standard errors (standard deviation/√N).

automation if LOA was higher, and automation reliability was nearer to 100%. Indeed, the prevailing view in conventional aviation is that fatigue may promote complacency and over-reliance on automation, although evidence is lacking (Funk et al., 1999). Another ALOA study in our lab (Lin et al., 2015) showed that overload can also promote disuse of automated support for surveillance tasks; participants, especially those high in conscientiousness, tended to take personal charge of task performance under a stressful high task load, although reliance on automation would have been a more effective strategy. However, in real settings, overload may motivate operators to make more use of automation (Parasuraman and Riley, 1997). As in surface vehicle driving (Neubauer et al., 2012a), operator strategies for using automation are not necessarily adaptive, and more research is needed to understand how operators appraise the value of automation in coping with taxing task conditions in different performance contexts.

4. Distraction and the fatigued driver

Another technological challenge that may intersect with fatigue and automation is the proliferation of in-car information systems, notably cellphones (Strayer, 2015). The known dangers of distraction may be compounded by systems that provide internet access to information and entertainment (Feng et al., 2017). More severe forms of distraction such as texting (Caird et al., 2014) may be harmful irrespective of the mental state of the operator. The impacts of phone conversation on driving appear to be more subtle. Recent studies showing conflicting evidence on the safety impacts of phone use on drivers (Hickman and Hanowski, 2012; Victor et al., 2015) suggest that effects of conversation may be more context-dependent.

The present issue is how driver distraction may interact with fatigue and stress. The answer is not obvious. On the one hand, if the driver is already distractible and disengaged as a consequence of fatigue, the safety impact of activities such as cellphone use may be exacerbated. Similarly, stress and anxiety may weaken the person's capacity to inhibit processing initiated by distracting stimuli (Eysenck and Derakshan, 2011). On the other hand, activities such as cellphone use might have an alerting function. Anecdotal accounts dating back to the days of truck drivers using CB radios suggest benefits to conversation. Two simulator studies (Atchley and Chan, 2011; Atchley et al., 2014) found that a phone conversation during the latter part of a fatiguing drive enhanced vehicle control. Similarly, secondary, quiz-like interactive cognitive tasks appear to enhance alertness and performance during prolonged driving (Gershon et al., 2009).

4.1. Simulation studies of media use and automation-induced fatigue

Three studies in our lab addressed possible interactions between fatigue and interaction with in-car media, using the Saxby et al. (2013) paradigm for assessment of alertness. Zeeb et al. (2015) found that distracted drivers were relatively slow to respond to a requirement for manual takeover from automated driving, but results vary across studies (Gold et al., 2017). A modeling study performed by these authors found that performing a secondary task prior to takeover can have both positive and negative effects. However, it is unknown how fatigue might interact with any distraction effect. Saxby et al. (2017) tested whether a conversation produced any immediate enhancement in alertness in drivers who were already fatigued. Similar to Saxby et al. (2013; Study 2), fully automated driving was followed by reversion to full manual control. Shortly after manual take-over, the driver was required to respond to an emergency event (van pulling out). To investigate distraction, a condition was run in which the experimenter conducted a structured conversation about a close-call event experienced by the participant, during the normal driving interval, prior to the emergency event. This form of conversation is personally involving and so may be distracting (Drews et al., 2008). Replicating Saxby et al. (2013; Study 2), automation lowered task engagement, and slowed response to the emergency event, leading to greater crash likelihood. Conversation failed to reduce these harmful impacts of passive fatigue (although it did not make them worse). Phone use also seemed to reduce drivers' concerns about performance in the automated driving condition. Since performance concerns were realistic in this condition, this finding suggests that distraction may reduce drivers' insight into how fatigue might be affecting their performance.

Saxby et al. (2017) showed the passive-fatigued driver receives no immediate benefit to alertness from conversation. Neubauer et al. (2012b) addressed a slightly different question: does repeated cellphone use during the period of automated driving lead to later benefits in alertness? Perhaps multiple episodes of phone use could serve to maintain alertness, similar to Gershon et al.'s (2009) cognitive task. Participants were sent 12 text messages during the 25-min automated phase of the drive, to which they could respond by either speech or text. A further condition allowed participants to choose what response modality to use. Again, the automated phase was followed by measurement of speed of response to a van pulling out as a test of alertness. As well as replicating previous findings that texting disrupts vehicle control, the study showed that the impact of repeated phone use on alertness depends on fatigue (see Fig. 4). In the control condition (phone used during normal driving), participants required to use the phone showed slower braking response to the emergency event, similar to previous studies showing alertness impairments (Caird et al., 2008). In the passive fatigue condition (phone used during automated driving), phone use of all types countered the slowed responses produced by the fatigue induction. That is, repeated prior phone use may help the driver to maintain alertness while transitioning from automated to normal driving. The study also confirmed Neubauer et al.'s (2012b) conclusion that drivers are prone to misuse opportunities for voluntary regulation of workload. Given the choice between responding to phone messages through speech or texting, drivers preferred to text, although texting produced higher elevations of workload and distress.

Neubauer et al. (2012b) investigated the impact of visual material delivered via phone, given that drivers of fully automated vehicles can potentially safely direct visual attention away from the traffic environment. By contrast, media-based interventions for fatigue in conventionally controlled vehicles have employed auditory stimuli such as trivia questions (Gershon et al., 2009), to limit interference with visual attention. The cognitive demands of Gershon et al.'s (2009) trivia game appeared to alleviate boredom and loss of engagement, implying that the technique might also be effective for automation-induced fatigue. Neubauer et al. (2014) tested this proposition. They also included a condition in which participants performed "close-call" phone conversations similar to those utilized by Saxby et al. (2017) to test whether the cognitive demands of speech produced benefits similar to answering trivia questions.

In fact, results were mixed. Subjective state data (DSSQ) showed that both trivia and conversation interventions were effective in reducing (though not eliminating) the loss of task engagement produced by vehicle automation, consistent with Gershon et al. (2009) findings. In addition, conversation, but not the trivia game, reduced distress. However, neither intervention mitigated the behavioral outcome of automation, i.e., slowed braking to the emergency event following manual take-over. Neubauer et al. (2014) also included a condition (SAE International, 2014, Level 1), in which speed was automatically controlled, but the driver was required to steer. Both the trivia game and the conversation improved lateral control of the vehicle during this condition, consistent with evidence that increased task demands may sometimes enhance control (Matthews et al., 1996). Thus, the study points towards some benefits for media use during fatiguing drives, but the interventions were not sufficient to consistently prevent the loss of alertness produced by automated driving.

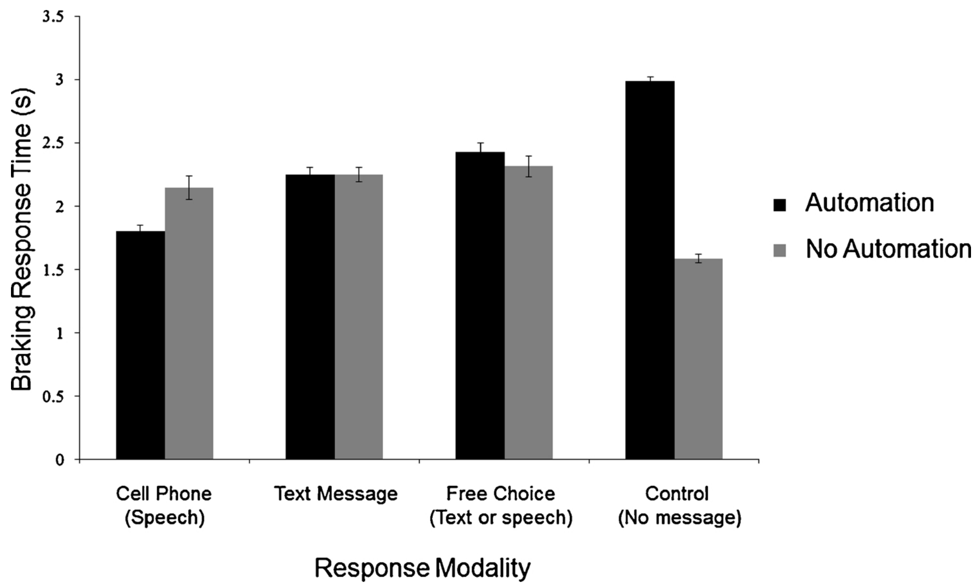

Fig. 4. Mean braking response time to emergency event as a function of vehicle automation and response modality. There were 30 participants in each of the eight conditions. Error bars are standard errors (standard deviation/√N).

4.2. Implications: "Distraction" as countermeasure?

Taken together, the findings reinforce that much remains to be learnt about interactive effects of fatigue and distraction on subjective fatigue (loss of task engagement) and alertness (speed of reaction to emergency event). The studies reviewed suggest that in-car media use may variously improve alertness but not subjective state (Neubauer et al., 2012b), improve subjective engagement but not alertness (Neubauer et al., 2014), or have no effect on alertness (Saxby et al., 2017). These contrasting findings may in part reflect the differing methodologies of the studies. Factors that may moderate secondary media effects include the modality of phone stimuli (visual vs. auditory), the time of delivery of stimuli (during automation vs. during post-automation manual control), and the personal relevance of the material (trivia vs. close call conversation). Furthermore, as previous distraction work has demonstrated (Caird et al., 2008), effects vary according to the performance variable examined (emergency response speed vs. vehicle control). Thus, further work is needed to identify the circumstances under which media use may benefit the fatigued driver. In the meantime, despite some promising findings in normal driving (Atchley et al., 2014; Gershon et al., 2009), secondary tasks cannot be recommended as countermeasures for automation fatigue, without a better understanding of the moderator effects of task demands.

Neubauer et al.'s (2012b) study suggested that speech can be helpful during periods of fully automated driving. In cases where systems impose schedules of full automation interspersed with manual control, speech communication might be used to maintain alertness. Consistent with May and Baldwin's (2009) suggestion to use games as countermeasures, speech could be incorporated into a game like task. Indeed, performance metrics might be diagnostic of the driver's current alertness and could be used to initiate countermeasures such as requiring a rest break or offering suitable automated support. A limitation of our studies is that they did not investigate the possible role of driver's familiarity and practice with in-car phone usage, although Cooper and Strayer (2008) found that neither simulator practice nor real-world experience mitigated distraction effects.

4.3. Distraction and RPVs

As with surface vehicle driving (Neubauer et al., 2012b, 2014), distraction may be potentially both beneficial and harmful to fatigued RPV operators. Cummings et al. (2013) cited survey data showing that RPV pilots frequently find the task boring. The technology is so reliable in supporting basic flight functions such as maintaining a holding pattern over a location that there is little for operators to do. Although studies have yet to assess task-induced fatigue systematically, these circumstances promote passive fatigue. Cummings et al. (2013) coded attentional behaviors during a 4-hour simulation, and found that operators spent around half the time in a distracted state. RPV operators may counter fatigue by engaging in extraneous activities during low-workload phases of the task, such as conversing with others, eating snacks and using the internet. A key difference from surface vehicle driving is that social interaction in RPV teams may mitigate against passive fatigue. Guznov et al. (2010) found that working in a team on a command-and-control (C2) simulation countered loss of task engagement seen in solo operators. Thus, the intention to move away from team operations to individuals controlling one or more RPVs (Calhoun et al., 2011) may pose new fatigue risks associated with the absence of beneficial social distraction.

5. Safety implications

The studies reviewed demonstrate that task fatigue is a multidimensional state that may impact several aspects of information-processing and task strategy. Acknowledging the complexity of fatigue suggests the following countermeasures.

5.1. Designing for fatigue

Automation that takes over some but not all driving functions may protect against some kinds of fatigue and contribute to improved attention to the traffic environment (Funke et al., 2007). Automation that reserves the more 'interesting' elements of the task to the human while taking control over more routine functions may mitigate both passive and active fatigue. Further work could explore optimal LOAs for automation. Attention is especially sensitive to fatigue, as shown in studies of both single critical events (Saxby et al., 2013) and continuous monitoring of the traffic environment (Matthews and Desmond, 2002), as well as vigilance (Warm et al., 2008). Thus, driver support for sustained attention in the fatigue state may be a beneficial form of automation. For example, displays that alert the driver to hazards such as unsafe following distances, excessive speed, and close object and vehicle proximity (Banks et al., 2014) may help to counter automation-induced fatigue. Connected-vehicle technology that alerts the driver to upcoming hazards in their path (Lerner et al., 2014) may be similarly supportive. These design solutions mitigate the safety impacts of fatigue that has already developed, and might only be effective for lower levels of fatigue.

Design may also mitigate the development of fatigue itself as a result of automation. Maintaining a sense of challenge and control over task contingencies are especially important. Effective system design can elicit operator interest and encourage constructive appraisals and task-focused coping (Cottrell and Barton, 2013). Adaptable automation which allows the operator to set their preferred LOA may be advantageous in the stress context (Sauer et al., 2013). However, the tendency for fatigued drivers to lack awareness of their own performance competency (Saxby et al., 2017) may limit its utility in this context. May and Baldwin (2009) recommended the use of interactive games to counteract passive fatigue. A system that monitored the driving habits and focus of the driver could provide feedback in the form of a safety score to encourage safe driving and to counteract fatigue. Such a score might be based on both measures of both performance (e.g., lane keeping habits) and driver neurocognitive state (e.g., as measured by eye movements and blinks). Recent research provides initial evidence that "gamification" of driving may counter boredom and disengagement (Steinberger et al., 2017). Finally, the role of social interaction in promoting task engagement (Guznov et al., 2010) suggests a role for autonomous agent technology. Future vehicles may incorporate automation that is coupled with a virtual persona that provides transparency and acts as a "wingman" to the driver, evaluating driver state and providing constructive feedback and support. Careful design of such autonomous systems is necessary to mitigate their potential for causing stress (Matthews et al., 2016).

5.2. Finding the appropriate level of automation

There has been little research on how the impacts of active and passive fatigue may interact with LOA. Tentatively, we suggest that a lower level (more human control) is appropriate when there is a risk of passive fatigue, and a higher level is preferred to counter active fatigue. Generally, we recommend evaluating systems to find the highest LOA that avoids complacency and loss of alertness in the fatigued operator. Adaptive automation may be designed to raise or lower workload as needed to maintain operator engagement (Freeman et al., 2004). However, more work is needed on configuring automation to support the person as fatigue develops. Wohleber et al. (2016) showed increasing neglect of automation in the RPV context, suggesting a need to keep the operator engaged with the automation, through interface design or training. A second issue is the extent to which the operator can regulate LOA, choosing the amount of automated support received (adaptable automation). Fatigued operators may lack insight in how best to use automation and regulate workload, so that any license afforded to the operator requires careful evaluation. On the other hand, a study of process control showed that adaptable automation may be beneficial in a stressful environment (Sauer et al., 2012). There may be scope for training operators in adaptive workload management.

5.3. Management of distraction

Stress increases distractibility (Eysenck and Derakshan, 2011), so it is straightforward to recommend minimizing distraction in environments conducive to active fatigue. The evidence on passive fatigue is equivocal, with scope for both harm and gain from distractions. Certainly, anecdotal reports of distractions enhancing alertness should be taken with a grain of salt, given the limited evidence from controlled studies for beneficial effects of distraction (Saxby et al., 2017). However, potential benefits of distraction in task environments characterized by monotony suggest that further work might develop useful countermeasures to passive fatigue (Neubauer et al., 2012b). It may be important to schedule distraction systematically rather than to rely on the fallible intuitions of the operator.

5.4. Operator selection

For safety-critical applications it is critical to select individuals with a high aptitude for maintaining attention in fatiguing environments (Cummings et al., 2013; Szalma, 2009). There are also individual differences in factors related to automation utilization such as potential for complacency (Parasuraman and Riley, 1997). In fact, predicting individual differences in performance under fatigue is more difficult than it might appear; fatigue scales do not always predict objective performance (Shaw et al., 2010). Matthews et al. (2013) advocated using short work-sample tasks to evaluate the operator's ability to maintain engagement under fatigue and stress. The rapidity with which passive fatigue can be induced during automated system operation supports this suggestion (Saxby et al., 2013). Similarly, simulation of extreme workloads over relatively short time durations may be used to identify operators resilient under active fatigue (Matthews and Campbell, 2009). Such techniques could be incorporated into future selection batteries for professional drivers and RPV operators (e.g., Carretta, 2013).

6. Conclusion

As vehicle technology advances, the dangers of fatigue will increasingly intersect with those of distraction and loss of SA resulting from automation. However, tiring driving conditions elicit a range of responses, which may include changes in stress, subjective workload, and trust, as well as subjective loss of engagement. A multivariate perspective on fatigue and stress informed by cognitive theory is essential (Matthews et al., 2012). The distinction between active and passive fatigue (Desmond and Hancock, 2001; May and Baldwin, 2009) is especially important for safety. The trend towards increasing automation in transportation is likely to bring the risks of passive fatigue towards the forefront of safety concerns. The effects of driver stress associated with overload may also be complex. Consistent with the transactional theory of stress (Lazarus, 1999; Matthews, 2001), fatigue and other stress responses may be dependent on the driver's appraisal and coping strategies (Cottrell and Barton, 2013; Matthews, 2002). It is also important to build on existing studies of different LOAs for vehicle automation (Trimble et al., 2014) to investigate how fatigue effects might be moderated by the design of the various systems concerned. The challenges posed by automation highlight the urgency of introducing higher levels of automation (i.e., SAE Level 4) that transition to minimal risk operation immediately when risks to safety including compromised driver performance are identified (Happee et al., 2017). Countermeasures for task fatigue should acknowledge its complexity.

Findings from simulator studies require verification from real vehicle operation. With this caveat, the empirical studies reviewed demonstrate that full vehicle automation consistently induces a dangerous state of passive fatigue quite rapidly, threatening safe reversion to manual control (Saxby et al., 2013). Wohleber et al. (2016) also found loss of task engagement and attentional impairment in an RPV simulation designed to induce passive fatigue. In the RPV task domain, operators also use automation suboptimally in conditions of both underload (Wohleber et al., 2016) and overload (Lin et al., 2015). The effects of distraction on the fatigued driver varied with the configuration of the task. Distractions such as conversation are on balance more likely to do harm than good to the fatigued operator, but there may sometimes be safety benefits Atchley et al. (2014), especially during episodes of fully automated driving (Neubauer et al., 2012b). However, improvements in alertness following automated driving do not seem robust (Neubauer et al., 2014; Saxby et al., 2017), It may also be unwise to rely on the operator's discretion in managing distraction and workload; when given freedom of choice, drivers may use both automation (Neubauer et al., 2012a) and phones (Neubauer et al., 2012b) maladaptively.

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