Fatigue and Voluntary Utilization of Automation in Simulated Driving

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**Objective:** A driving simulator was used to assess the impact on fatigue, stress, and workload of full vehicle automation that was initiated by the driver.

**Background:** Previous studies have shown that mandatory use of full automation induces a state of “passive fatigue” associated with loss of alertness. By contrast, voluntary use of automation may enhance the driver’s perceptions of control and ability to manage fatigue.

**Method:** Participants were assigned to one of two experimental conditions, automation optional (AO) and nonautomation (NA), and then performed a 35-min, monotonous simulated drive. In the last 5 min, automation was unavailable and drivers were required to respond to an emergency event. Subjective state and workload were evaluated before and after the drive.

**Results:** Making automation available to the driver failed to alleviate fatigue and stress states induced by driving in monotonous conditions. Drivers who were fatigued prior to the drive were more likely to choose to use automation, but automation use increased distress, especially in fatigue-prone drivers. Drivers in the AO condition were slower to initiate steering responses to the emergency event, suggesting optional automation may be distracting.

**Conclusion:** Optional, driver-controlled automation appears to pose the same dangers to task engagement and alertness as externally initiated automation.

**Application:** Drivers of automated vehicles may be vulnerable to fatigue that persists when normal vehicle control is restored. It is important to evaluate automated systems’ impact on driver fatigue, to seek design solutions to the issue of maintaining driver engagement, and to address the vulnerabilities of fatigue-prone drivers.

**Keywords:** automation choice, driver behavior, fatigue, individual differences, workload

INTRODUCTION

Numerous advancements have been made in automated vehicle systems that reduce driver workload and may thus improve safety (Lee, 2006; Matthews, Saxby, Funke, Emo, & Desmond, 2011). Systems include those under driver control, such as adaptive cruise control (ACC). By contrast, future intelligent highways will deploy a range of technologies that may eventually support full vehicle automation on some roadways (Stanton & Salmon, 2009). These automated highway systems consist of “smart” roads, with driving tasks such as steering, braking, and speed controlled. Use of such systems will be mandatory, not optional.

Innovations in vehicle automation potentially mitigate harmful fatigue effects on safety because they reduce the prolonged workload placed on drivers (Neubauer, Matthews, & Saxby, in press). Nevertheless, simulator studies show that automation may exacerbate fatigue (Saxby et al., 2008; Saxby, Matthews, Hitchcock, & Warm, 2007), and impair situation awareness, as evidenced by slowing of braking responses (Young & Stanton, 2007). However, in such experimental studies, participants are randomly allocated to different automation conditions. In actuality, drivers often have voluntary control over using automated devices, such as ACC.

The general aim of the present study was to evaluate the effects of voluntarily initiated automation on fatigue and stress. In the remainder of this introduction, we discuss the possible role of driver choice and control in moderating automation effects, safety consequences, and the impact of individual differences in fatigue vulnerability.

**Fatigue and Vehicle Automation: The Role of Choice and Control**

It is uncertain whether vehicle automation might counter fatigue. Field studies implicate
workload in driver fatigue (Friswell & Williamson, 2008), suggesting that a reduction of driver workload might be beneficial. Hancock and Verwey (1997) described automation technologies capable of monitoring driver workload and performance and providing driver support on an adaptive basis. Automation may counter fatigue in other contexts also, such as military command and control (Breton & Bosse, 2002). Automation may thus aid the driver who is fatigued or indeed compromised for other reasons.

However, other research suggests that automation may induce fatigue, and fatigue may affect operation of automated systems. Persson, Garde, Hansen, Ørbæk, and Ohlsson (2003) showed that increased automation of an industrial production system elevated subjective fatigue. Even short-duration automation duty cycles may affect fatigue (Scallen, Hancock, & Duley, 1995). Fatigue may also be a concern when operators interact with complex interfaces supporting automated functions, such as the automated flight deck of commercial aircraft (Caldwell et al., 2009) and interfaces for operating unmanned vehicles (Tvaryanas & MacPherson, 2009). Stanton and Young (2005) discuss how automation may produce passivity and loss of situation awareness in the vehicle driver, potentially increasing the vulnerability of performance to fatigue. Several authors (e.g., Hancock & Szalma, 2003; Scerbo, Freeman, & Mikulka, 2003) have pointed out that active engagement with the task is important both for system performance and for operator well-being.

Desmond and Hancock (2001) distinguished passive fatigue, associated with low workload and lack of direct control over the task, from active fatigue, associated with overload. Automated systems may be beneficial for high workload conditions that induce active fatigue states but may actually worsen passive fatigue effects, which can result from monotonous roadways (May & Baldwin, 2009). Both simulator studies (Gershon, Shinar, & Ronen, 2009; Thiffault & Bergeron, 2003) and on-road investigations (DeWaard & Brookhuis, 1991; Schmidt et al., 2009) confirm that environmental monotony provokes driver fatigue. Poorly designed vehicle automation may add to monotony, increasing vulnerability to passive fatigue.

Fatigue states are multifaceted and overlap with stress (Matthews, Desmond, & Hitchcock, in press; Oron-Gilad, Ronen, & Shinar, 2008), so states should be assessed on a multidimensional basis. Our research uses a subjective state model (Matthews et al., 2002) that differentiates broad dimensions of task engagement, distress, and worry. Declining task engagement is a hallmark of fatigue, expressed as tiredness, loss of motivation, and impaired concentration. Driver fatigue responses often combine loss of engagement with increased distress in both simulator studies (Matthews & Desmond, 2002) and real driving (Desmond & Matthews, 2009).

Thus, we use stress and fatigue as broad descriptors of state changes that may be specified more precisely using the multidimensional model.

In previous simulator studies (Saxby et al., 2007, 2008), subjective fatigue (loss of task engagement) developed more rapidly in the automated condition than during normal driving, consistent with Desmond and Hancock’s (2001) analysis of fatigue. The monotony of operating an automated vehicle (passive fatigue) may be especially detrimental to subjective alertness and task motivation (Hancock & Verwey, 1997). By contrast, the active fatigue manipulation (induced through frequent wind gusts) provoked smaller magnitude decreases in task engagement but had larger effects on workload and distress than passive fatigue did.

Damaging effects of automation on driver mental state may be associated with lack of perceived control. In the Saxby et al. (2008) studies, drivers were randomly assigned to the automation condition and were unable to switch it on or off. Workplace studies show that perceived control mitigates against stress and exhaustion (Michinov, 2005). Parsons, Warm, Nelson, Riley, and Matthews (2007) found in a vigilance study that observers allowed to attack enemy vehicles showed less fatigue and better detection performance than did those who merely detected the target stimuli passively. Indeed, even illusory perceived control may help to support sustained attention (Dember, Galinsky, & Warm, 1992) and promote positive mood, motivation, persistence, and performance (Taylor & Brown, 1988). Supporting the driver’s sense of perceived control may be important in
the design of vehicle automation (Stanton & Young, 2000). Funke, Matthews, Warm, and Emo (2007) found benefits for partial automation that controlled speed (e.g., cruise control) but required the driver to maintain steering control of the vehicle. Automation reduced distress, without elevating fatigue.

Given the choice, drivers may prefer to use automation sparingly. A need to “take control” may influence operator decisions to avoid full automation when automation is optional (Beck, Dzindolet, & Pierce, 2007). In a study of multitasking, Harris, Hancock, Arthur, and Caird (1995) found that performance was better when participants were given the option of using automation, relative to conditions in which only manual or only automated control was available. Both manual and automated control modes were associated with task-induced fatigue, but the study did not test for effects of optional control on fatigue. However, the performance benefits of choice suggest that it may improve operator well-being. In addition, given that even short rest breaks may provide some relief from fatigue (Caldwell et al., 2009; Tucker, 2003), optional automation may allow the driver to manage fatigue adaptively.

**Behavioral Consequences of Fatigue**

Thus far, we have discussed effects of automation on the mental state of the driver. A further question is how fatigue states influence behavior. Potentially, fatigue influences the decision to use automation, so that use of automation is dynamically related to states of fatigue and stress. Driver fatigue leads to reluctance to exert effort (Brown, 1994). Thus, fatigued drivers may especially utilize the opportunity to reduce workload by engaging automation, even if workload is already low. If driver-controlled automation does indeed reduce fatigue and stress, using automation may be an effective strategy for alleviation of fatigue.

Fatigue also impairs driver performance (Neubauer et al., in press). Simulator studies have identified various behavioral indices of fatigue, including deterioration in steering of the vehicle and loss of attention to the traffic environment (Liu & Wu, 2009; Matthews et al., 2011; Philip et al., 2003). Passive fatigue effects are explained by the Hancock and Warm (1989) effort-regulation model. Operators adapt to varying degrees of task demands, but their abilities to adapt become increasingly impaired in both underload and overload conditions. Underload disrupts appropriate matching of effort to task demands, leading to performance deficits resulting from withdrawal of effort (Matthews & Desmond, 2002; Young & Stanton, 2007). Similarly, automation disrupts effort regulation because of underload. Saxby et al. (2008) tested the fatigued driver’s response to an emergency event, a van pulling out in front of the driver unexpectedly. Passive, but not active, fatigue was associated with slowed response times (RTs) for braking and steering and a higher likelihood of crashing.

**Individual Differences in Fatigue Vulnerability**

The effects of automation may also depend on the driver’s susceptibility to fatigue. Multiple personality characteristics govern stress vulnerability, including a fatigue proneness dimension measured by the Driver Stress Inventory (DSI; Matthews, 2002). Fatigue proneness correlates with subjective fatigue response in both real driving (Desmond & Matthews, 2009) and simulator studies (Matthews & Desmond, 1998). Fatigue-prone drivers experience higher state fatigue even prior to driving, but fatigue proneness also predicts increases in subjective fatigue over predrive baseline (Desmond & Matthews, 2009). Other DSI scales are associated with different stress responses; for example, Dislike of Driving predicts emotional distress, and Aggression is associated with anger (Matthews, 2002).

Greater fatigue vulnerability may encourage the driver to use automation, if automation is perceived as an effective fatigue-management strategy. Similarly, if voluntary use of automation is effective, fatigue-prone drivers might experience more benefits from automation than fatigue-resistant individuals.

**Aims and Objectives**

This study aimed to test the effects of full automation on fatigue and stress when drivers were able to choose whether and when to initiate automation. The 35-min simulated drive was
configured to be monotonous and fatiguing. In previous studies, similar durations induced large-magnitude fatigue and stress responses to automated driving (Matthews & Desmond, 1998, 2002; Saxby et al., 2007, 2008), comparable to those seen in studies of real driving (Desmond & Matthews, 2009). The drive duration also produces declines in cerebral bloodflow velocity, a psychophysiological index of fatigue (Reinerman, Warm, Matthews, & Langheim, 2008) as well as performance impairments (Matthews & Desmond, 2002; Saxby et al., 2008).

Drivers were randomly assigned to an automation optional (AO) condition, affording choice, or a nonautomation (NA) condition representing normal driving. There are two ways in which personal control of automation might benefit the driver. First, knowing that automation is available if desired may increase perceived control, which has various benefits on performance and subjective state (Dember et al., 1992; Taylor & Brown, 1988). The role of automation availability was investigated by testing whether drivers assigned to the AO condition showed higher task engagement than those in the NA condition (irrespective of whether they actually used automation). Second, use of automation at a time of the driver’s own choosing might act as a rest break and relieve fatigue. Within the AO condition, we tested whether choosing to use automation was related to subjective state. Normal control was restored to all drivers for the final 5 min of the drive. At this time, we tested whether participant groups differed in speed of response to an emergency situation.

Hypotheses were generated on the basis of a “benign” model of automation, which assumes drivers can employ automation strategically to alleviate fatigue (see Figure 1).

Specific hypotheses were as follows:

**Hypothesis 1 (H1):** Perceived control typically enhances subjective state (Taylor & Brown, 1988). Drivers in the AO condition should experience higher task engagement and lower distress than those in the NA condition, regardless of whether or not automation is actually used.

**Hypothesis 2 (H2):** Fatigued drivers are motivated to avoid effort (Brown, 1994). They will be more likely to use automation to reduce workload when given the opportunity, in the AO condition.

**Hypothesis 3 (H3):** Automation may mitigate fatigue through workload reduction (Harris et al., 1995). Drivers who choose to use automation will experience reduced levels of fatigue (higher task engagement) relative to those who do not use automation.

**Hypothesis 4 (H4):** Drivers high in the fatigue proneness trait are more vulnerable to fatigue states. Fatigue proneness will generally relate to lower task engagement (H4a), and the fatigue-prone driver will especially benefit from the alleviation of fatigue provided by voluntary use of automation (H4b).

**Hypothesis 5 (H5):** Beneficial effects of automation on subjective state will also

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*Figure 1. A schematic model of benign effects of voluntary automation used to formulate study hypotheses.*
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enhance driving performance, especially faster response to an unexpected, hazardous event at the end of the drive. Testing this hypothesis was a subsidiary aim, given that short intervals of automation may produce only a transient impact on performance after reversion to manual control.

METHOD

Participants

A total of 190 fully licensed drivers were recruited from the University of Cincinnati Introductory Psychology research pool. Of these, 6 participants were excluded because of missing data or failure to comply with instructions, leaving a total of 184 (73 males, 111 females), 93 in the AO condition and 91 in the NA condition. The age range was 18 to 30 (M = 20.16, SD = 3.13). All participants were required to have a valid driver’s license and wear corrective lenses if appropriate.

Materials and Apparatus

All groups participated in a 35-min simulated drive, on a Systems Technology, Inc. STISIM Model 400 simulator, which is programmable to create a variety of driving scenarios. It is equipped with a car seat and full-size steering wheel and pedals. Speed-sensitive “steering feel” is provided by a torque motor. A 42-in. HD LCD video monitor displayed the roadway and other task elements.

Questionnaire Measures

Subjective stress states were assessed, before and after the drive, using the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 2002). The DSSQ assesses 11 scales for mood, motivation, and cognition in performance settings, grouped into three higher order factors associated with task engagement (energy, task motivation, concentration), distress (tension, unpleasant mood, low confidence), and worry (self-focus, low self-esteem, task-related thoughts, task-unrelated thoughts) factors. These three factors were estimated from the 11 primary scales using regression weights derived from a large normative sample (Matthews et al., 2002), scaled as standard scores. The posttask DSSQ also includes the NASA Task Load Index (Hart & Staveland, 1998), a standard workload measure based on ratings of task demands and subjective reactions to the task. The DSI (Matthews, 2002) assessed stress vulnerability traits including fatigue proneness, dislike of driving, aggression, hazard monitoring, and thrill seeking.

Procedure

Participants were individually tested and randomly assigned to one of two experimental drives: AO and NA. The two groups were matched for gender. They did not differ significantly in age, years since obtaining driving license, estimated annual mileage, and means on the five DSI scales and three pretask DSSQ factors. By engaging the turn signal, participants in the AO condition had the option of initiating automation at their discretion for periods of 5-min blocks throughout the drive, a duration sufficient to provide a rest break from the task but not so long to itself provoke passive fatigue, whereas the NA group did not. When participants signaled that they wished to use automation, the experimenter switched automation on for 5 min, before terminating it. The vehicle was fully automated during these 5-min intervals; participants were not required to keep their hands and feet on the controls. Participants were told that after 5 min they would need to regain control when they noticed that the vehicle slowed or started to veer slightly.

Initially, participants completed the DSI, followed by the DSSQ, to attain baseline measurements of fatigue and stress states. Participants then performed a 3-min practice drive, followed by their assigned 35-min drive. After the drive, participants completed the posttask DSSQ to assess changes in subjective state induced by the drive. The roadway followed resembled that of Saxby et al. (2007), which was found to be monotonous. The scenario included sections of “rural” driving (speed limit of 60 MPH) where the scenery was trees and “city” driving (speed limit of 40 MPH) in which the scenery was buildings. The roadway included both straight and curved sections and some hills. There was no traffic in the driver’s lane and occasional
oncoming vehicles. Performance was assessed during the final 5 min of the drive. After 30 min, an alarm indicated that automation would no longer be available to drivers in the AO group, so that all participants drove normally in the final 5 min. The standard deviation of the driver’s lateral position was calculated for successive 30 s intervals during this time. After approximately 2 min, RTs to an emergency event were measured: A van initially parked on the side of the road suddenly pulled out in front of the driver. This event occurred once during the drive, so that drivers were not able to anticipate it. RTs were obtained from the time of the first movement of the van to the times of the first steering and braking responses that followed, as participants tried to avoid collision. The total experimental protocol lasted 1.5 to 2 hr, of which approximately 40 min were dedicated to the practice and main drives and the rest for completing questionnaires.

RESULTS

Four sets of analyses are summarized here. First, we tested for effects of the drive on subjective state. Second, we tested whether the choice to use automation was associated with subjective state, within the AO group. Third, we performed correlational and regression analyses to investigate the role of stress vulnerability factors in state response. Fourth, we tested for effects of prior use of automation on driver performance and alertness in an emergency situation.

Effects of Driving on Subjective State

State was assessed using the three DSSQ factors of task engagement, distress and worry.

For each state factor, we ran a 2 (pre-post) × 2 (condition) ANOVA. Pre-post was a within-subjects factor contrasting pre- and postdrive state. Condition was a between-subjects factor contrasting the AO and NA groups. Main effects of pre-post were found for task engagement, \( F(1, 185) = 88.86, p < .01 \), partial \( \eta^2 = .33 \), and distress, \( F(1, 185) = 160.70, p < .01 \), partial \( \eta^2 = .47 \), but not for worry. There were no effects of condition. For the whole sample, engagement decreased by \( -0.52 \ SD \) and distress increased by \( 0.69 \ SD \). Thus, the drives were generally fatiguing and stressful, irrespective of the availability of automation. (For space reasons, we report only analyses of the three higher order factors here. However, additional analyses of the 11 first-order scales of the Dundee Stress State Questionnaire showed that the intrinsic interest motivation scale declined by \( 0.91 \ SD \) from pre- to posttask, confirming that the drives were generally experienced as monotonous.) There was no significant difference in mean workload across the two groups. Mean workload for the whole sample, expressed on a 0–10 scale, was 4.73 (SD = 1.43).

Effects of Automation Use on State

Of the 93 participants allocated to the AO condition, 44 chose to use automation at least once and 49 did not. (Frequency of use of automation was unrelated to the fatigue and stress measures.) In the 44 automation users, the mean frequency of use was 2.16 (SD = 1.67). Use of automation was fairly evenly distributed across the 30-min period during which automation was available. Across all AO participants, 31 instances of automation use were logged during Minutes 1 to 10, 34 instances in Minutes 11 to 20, and 31 in Minutes 21 to 30. Among users of automation, the mean time of first initiation of automation was 10.5 min (SD = 9.4).

We analyzed differences in pre- and post-drive subjective states between users and non-users of automation within the AO group. Separate 2 (pre-post) × 2 (automation use) ANOVAs were run for each DSSQ factor, including pre-post as a within-subjects factor. The two critical tests here are for the main effect of automation use, suggesting an overall difference in state, and for the automation use × pre-post interaction, suggesting a time-dependent effect of automation. The main effect of automation use on task engagement was significant, \( F(1, 91) = 6.85, p < .01 \), partial \( \eta^2 = .07 \), but the interaction was not. For distress, the main effect of automation use was also significant \( F(1, 91) = 4.09, p < .05 \), partial \( \eta^2 = .04 \), as well as the automation use × pre-post interaction \( F(1, 91) = 5.07, p < .05 \), partial \( \eta^2 = .05 \). Automation use did not affect worry.
Figure 2. Pre- versus posttask engagement for users and nonusers of automation in automation optional condition. Error bars are standard errors.

Figure 3. Pre- versus posttask distress for users and nonusers of automation in the automation optional condition. Error bars are standard errors.
Mean levels of engagement and distress in users and nonusers of automation are shown in Figures 2 and 3. Engagement was higher in nonusers prior to the drive and remained relatively high postdrive. Follow-up $t$ tests confirmed significant differences between groups both predrive, $t(92) = 2.05$, $p < .05$, and postdrive, $t(92) = 2.72$, $p < .01$. Lower task engagement preceded the choice to use automation. The group difference in distress was apparent only in the postdrive data. There was no significant difference in predrive distress, but there was a significant postdrive difference, $t(92) = 2.76$, $p < .01$, suggesting that using automation increased distress.

**Stress Vulnerability as a Correlate of Subjective State**

Mean DSI fatigue proneness was 43.3 ($SD = 15.3$), a distribution similar to those in previous studies (e.g., Saxby et al., 2007, 2008). Fatigue proneness was significantly correlated with lower task engagement both predrive ($r = -.44$, $p < .01$) and postdrive ($r = -.48$, $p < .01$) and with higher distress predrive ($r = .29$, $p < .01$) and postdrive ($r = .44$, $p < .01$). Correlation magnitudes were similar in AO and NA conditions. Regression analyses tested whether (a) fatigue proneness moderated the task-induced increases in fatigue and stress in the two experimental conditions and (b) whether fatigue proneness moderated effects of automation use on state within the AO condition.

For the first regression, postdrive task engagement was the criterion. Four predictors were entered into the equation in successive steps: predrive engagement, AO or NA condition (effect-coded), fatigue proneness (centered), and condition × fatigue proneness. The product term tests for the interaction between fatigue proneness and experimental condition. A similar regression was run using distress in place of engagement. Table 1 shows summary statistics from the regressions. Fatigue proneness predicted decreased engagement and increased distress, with predrive states controlled, but there was no interactive effect of fatigue proneness and automation condition.

**TABLE 1: Summary Statistics for Regression Models of Postdrive Engagement and Distress, Regressed Onto Predrive State, Experimental Factors, and Fatigue Proneness**

<table>
<thead>
<tr>
<th>Analysis of Whole Sample</th>
<th></th>
<th>Engagement ($R^2 = .47$)</th>
<th></th>
<th>Distress ($R^2 = .42$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step</td>
<td>Predictors</td>
<td>$\Delta R^2$</td>
<td>Final $\beta$</td>
<td>$\Delta R^2$</td>
</tr>
<tr>
<td>1</td>
<td>Predrive state</td>
<td>.42**</td>
<td>.55**</td>
<td>.34**</td>
</tr>
<tr>
<td>2</td>
<td>Condition</td>
<td>.03</td>
<td>-.06</td>
<td>.00</td>
</tr>
<tr>
<td>3</td>
<td>FP</td>
<td>.05**</td>
<td>-.24**</td>
<td>.08**</td>
</tr>
<tr>
<td>4</td>
<td>Condition × FP</td>
<td>.00</td>
<td>-.03</td>
<td>.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis of Automation Optional Group Only</th>
<th></th>
<th>Engagement ($R^2 = .51$)</th>
<th></th>
<th>Distress ($R^2 = .46$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step</td>
<td>Predictors</td>
<td>$\Delta R^2$</td>
<td>Final $\beta$</td>
<td>$\Delta R^2$</td>
</tr>
<tr>
<td>1</td>
<td>Predrive state</td>
<td>.47**</td>
<td>.56**</td>
<td>.29**</td>
</tr>
<tr>
<td>2</td>
<td>Automation use</td>
<td>.02</td>
<td>.11</td>
<td>.06**</td>
</tr>
<tr>
<td>3</td>
<td>FP</td>
<td>.04**</td>
<td>.25**</td>
<td>.08**</td>
</tr>
<tr>
<td>4</td>
<td>Automation use × FP</td>
<td>.00</td>
<td>-.09</td>
<td>.03*</td>
</tr>
</tbody>
</table>

**Note.** FP = fatigue proneness.

*R^2 value is for final equation (after Step 4).

$^{b}\beta$ is standardized regression coefficient in the final equation (after Step 4).

*p < .05. **p < .01.
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(Additional Driver Stress Inventory factors also predicted state response, similar to previous studies [e.g., Desmond & Matthews, 2009], giving some confidence that the simulator reproduces the pressures of real driving. Further details are available from the authors.)

Further regressions were run within the AO condition, again with postdrive task engagement and distress as the criteria. Four predictors were entered sequentially: predrive state, use or nonuse of automation (effect coded), fatigue proneness (centered), and automation use × fatigue proneness. Table 1 shows that, in addition to linear effects of fatigue proneness, the interaction term was significant for distress ($\Delta R^2 = .027, p < .05$). The effect of fatigue proneness on distress was accentuated in automation users. Additional regression analyses showed that fatigue proneness predicted postdrive distress, with predrive distress controlled, in automation users ($\Delta R^2 = .096, p < .05$), but not in nonusers of automation ($\Delta R^2 = .010$).

**Performance**

Initially, we looked at whether the experimental manipulations influenced gross features of driver performance. We calculated mean speed in NA and AO conditions for the first 30 min of the drive (excluding intervals where driving was automated). Means for NA (53.2, $SD = 3.6$) and AO (52.8, $SD = 4.0$) did not differ significantly on a $t$ test. Within the AO condition, means for automation users (52.2, $SD = 3.8$) and nonusers (53.4, $SD = 4.2$) also did not differ.

We also tested whether the automation availability manipulation influenced mean speed and $SD$ of lateral position (SDLP) in the final 5 min of driving. We analyzed effects of automation condition across four successive 30-s intervals following the termination of automation availability in the AO group as well as the final 30-s period after the driver had recovered from response to the emergency, using 2 × 5 (condition × period) mixed model ANOVAs. We excluded 13 participants from the AO condition who were actually in automated mode at the cessation of automation, requiring a sudden transition to manual control, because the transition itself might influence subsequent vehicle control. Automation condition had no effects on speed. For SDLP, the main effect of condition was close to significance, $F(1, 149) = 3.67, p = .057$, partial $\eta^2 = .02$, reflecting a trend toward poorer vehicle control in the AO condition (see Figure 4). We also tested for effects of automation use on performance within the AO group, again excluding the 13 drivers interrupted during automated driving; no significant effects on speed or SDLP were found.

![Figure 4](image1.png)

*Figure 4.* Standard deviation of five lateral positions (LPs) for both experimental groups. Error bars are standard errors.

![Figure 5](image2.png)

*Figure 5.* Response times (RTs) for steering and braking in the automation optional and nonautomation conditions. Error bars are standard errors.
In the analysis of response to the emergency event (van pulling out), the two principal performance measures were RTs for steering and braking responses. We analyzed (a) effects of NA versus AO condition and (b) effects of automation use within the AO condition. Independent samples t tests revealed a significant difference between groups for the RTs for steering, *t*(150) = 2.06, *p* < .05, but not for braking, *t*(152) = 0.102, *p* > .05. (The dfs for these analyses differ because some drivers steered but did not brake, and vice versa.) The NA group showed faster RTs for steering, compared to the AO group (see Figure 5). There were no significant differences in RTs between automation users and nonusers in the AO group. Last, 27.9% of drivers crashed into the van, but the frequency of crashes was similar in the AO (26) and NA (27) groups.

**DISCUSSION**

This study explored the effects of automation use in simulated driving on subjective fatigue and stress states and performance when drivers were given the option of using automation. Data extended previous findings (Saxby et al., 2007, 2008) showing that high levels of fatigue (task disengagement) and distress are observed following automated driving. The control (non-automated) drive also elicited a pronounced fatigue response, reflecting the monotony of the driving task. Thus, the data are generally incompatible with a “benign” view of driver-controlled automation as a potential fatigue countermeasure, expressed in Figure 1.

The hypothesis that providing optional automation would protect against adverse state changes (H1) was not confirmed. Similar, large magnitude changes in distress and task engagement were seen in both AO and NA conditions and in the automation users in the AO condition, Although benefits of perceived and actual control are well documented (e.g., Michinov, 2005), drivers do not seem to be able to use automation as an effective countermeasure to fatigue and stress experienced in monotonous driving conditions.

The comparison of state changes in users and nonusers of automation within the AO group suggested more subtle interrelationships among automation use, stress, and fatigue. In support of H2, drivers who chose to use automation were, on average, initially relatively low in task engagement prior to the drive. Fatigue states may encourage the driver to use automation, consistent with a report that fatigue encourages commercial transport pilots to use automation (Riley, 1996). However, contrary to H3, automation use did not relieve fatigue. If anything, engagement dropped more rapidly in automation users than in nonusers, although the automation use × time interaction was not significant. Thus, low task engagement spurs the driver to use automation, but, even under voluntary control, automation does not alleviate distress. A different dynamic was evident for distress. This stress state factor did not predict use of automation, but distress was elevated in those who chose this option (depending on fatigue proneness, as discussed below). Possibly, automation increases awareness of the discomfort of fatigue, which in turn increases distress. Conversely, the need to direct attention externally during normal driving may protect against awareness of discomfort.

As expected, drivers high in DSI fatigue proneness were lower in task engagement prior to the drive and also showed greater task-induced declines in engagement (supporting H4a). Fatigue proneness also predicted distress in response to the drive, supporting a link between stress and fatigue (Matthews & Desmond, 2002). The fatigue proneness trait appears to be associated with a broad vulnerability to fatigue and stress states. Contrary to H4b, fatigue-prone drivers obtained no benefit from using automation in the AO condition. Indeed, the regression analysis revealed an interesting interaction such that fatigue-prone drivers who use automation were especially vulnerable to distress. One element of fatigue proneness may be heightened awareness of the mental and somatic discomforts of fatigue, which become more salient when the driver need not direct much attention to the driving task, during automation.

Performance effects in this study were minor, and H5 was not supported. Drivers in the AO condition showed slower steering RTs to the emergency event than did drivers in the NA
condition, suggesting a loss of alertness. They also showed a trend toward poorer vehicle control during the final part of the drive. Parasuraman and Riley (1997) suggested that deliberations over when to employ an automated system might add to workload. Although participants were aware that automation was no longer available at this stage of the drive, its earlier provision may have had a distracting effect.

Automation use did not affect performance within the AO group, perhaps reflecting drivers’ limited usage of automation. Even those who chose to use automation typically interwove the 5-min periods of automation with periods of normal driving. Longer periods of uninterrupted automation use may be necessary to produce the loss of alertness to hazardous events observed by Saxby et al. (2008).

The findings of this study have several practical implications, assuming findings generalize from simulated to real driving. First, they further highlight possible dangers as well as benefits of vehicle automation (e.g., Young & Stanton, 2007). Reduction of overt task demands may interfere with the driver’s active engagement with the task. Full vehicle automation fails to protect against fatigue irrespective of whether automation is externally imposed, as might be the case in an intelligent highway, or whether the driver initiates automation (e.g., ACC). Automated systems should be evaluated for their impact on fatigue prior to introduction into vehicles and roadways.

Second, data emphasize the importance of countermeasures for fatigue in the disengaged but wakeful driver (May & Baldwin, 2009; Neubauer et al., in press). Even short-duration, monotonous drives may provoke substantial changes in fatigue and stress, states that represent precursors to performance breakdown (Hancock & Warm, 1989). Furthermore, the cyclic process whereby fatigue elicits use of automation, which, in turn, elevates distress in drivers who are already fatigue prone, confirms that drivers are sometimes poor at self-management of fatigue (Hanks, Driggs, Lindsay, & Merrill, 1999), supporting the use of external technology in countermeasures (Desmond & Matthews, 1997; Stanton & Salmon, 2009).

Third, questionnaire measures may be used to identify and select professional drivers who are especially resistant to fatigue (Desmond & Matthews, 2009). The present findings add to existing results by showing that automation provides no support to fatigue-prone drivers and may even exacerbate fatigue symptoms in this group. It may be tempting to recommend automation for drivers with sleep disorders, neurological disorders, or conditions such as attention-deficit/hyperactivity disorder that promote fatigue (e.g., Biederman et al., 2007). In fact, findings suggest that such individuals should avoid reliance on automation as a fatigue countermeasure. Design solutions that encourage active involvement in system control, and accommodate individual differences, may be a more effective path toward developing fatigue countermeasures in the automated vehicle (Hancock, 1997; Szalma, 2009).

Finally, study limitations should be noted. First, there may be some uncertainty over the level of monotony of the drive, given that the drive included some urban scenery (cf. Thiffault & Bergeron, 2003), although participants typically reported finding the drive monotonous at debriefing. Second, given that, even in the AO condition, driving was primarily under manual rather than automated control, both passive and active fatigue states may have been elicited. However, the pattern of state change on the DSSQ was closer to that seen in passive fatigue, suggesting that fatigue was predominantly passive in nature. Third, the data suggest some dissociation between subjective response and performance data. Participants in the AO condition showed trends toward performance deficit that were not evident in the subjective data. Further work is needed to test whether automation availability produces changes in style of attention that are not accessible to conscious awareness.

**KEY POINTS**

- Several existing studies have shown the required or mandatory automation use elicits a state of “passive fatigue” that is associated with subjective feelings of decreased task engagement and loss of alertness.
• Alternatively, voluntary use of automated systems may enhance the driver’s perceptions of control and capacity for fatigue management.
• Results of this study suggest that even voluntary use of automation failed to alleviate subjective ratings of stress and fatigue states as well as failing to improve driver performance.
• Similar to required automation use, voluntary automation use appears to pose similar dangers to driver alertness, task engagement, and fatigue.

NOTES
1. For space reasons, we report only analyses of the three higher order factors here. However, additional analyses of the 11 first-order scales of the Dundee Stress State Questionnaire showed that the intrinsic interest motivation scale declined by 0.91 SD from pre- to posttask, confirming that the drives were generally experienced as monotonous.

REFERENCES


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*Date received: July 11, 2010*

*Date accepted: July 19, 2011*