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Fatigue and Automation-Induced Impairments in Simulated Driving Performance

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A driving simulator study investigated the effect of automation of the driving task on performance under fatiguing driving conditions. In the study, drivers performed both a manual drive, in which they had full control over the driving task, and an automated drive, in which the vehicle was controlled by an automated driving system. During both drives, three perturbing events occurred at early, intermediate, and late phases in the drives: in the automated drive, a failure in automation caused the vehicle to drift toward the edge of the road; in the manual drive, wind gusts resulted in the vehicle drifting in the same direction and magnitude as the "drifts" in the automated drive. Following automation failure, drivers were forced to control the vehicle manually until the system became operational again. Drivers' lateral control of the vehicle was assessed during three phases of manual control in both drives. The results indicate that performance recovery was better when drivers had full manual control of the vehicle throughout the drive, rather than when drivers were forced to drive manually following automation failure. Drivers also experienced increased tiredness, and physical and perceptual fatigue symptoms following both drives. The findings have important implications for the design of intelligent transportation systems. Systems that reduce the driver's perceptions of task demands of driving are likely to undermobilize effort in fatigued drivers. Thus, the results strongly support the contention that human-centered transportation strategies, in which the driver is involved in the driving task, are superior to total automation.

Automation-induced impairments are of particular concern in driving in the light of future transportation developments such as intelligent transportation systems (ITS) (*1*). In such systems, in-vehicle navigation and collision avoidance systems are integrated with the control software of the vehicle to automate many aspects of the driving task. A serious issue that needs to be addressed with the implementation of systems that reduce the driver's perceptions of the task demands of driving is the possibility of interaction between fatigue and automated highway systems (*2*).

A potentially serious consequence of automated systems in tasks such as driving is that impairments in performance may occur. Several studies have demonstrated impaired detection of system failures in automated environments (*3,4*). Moreover, it appears that when operators are forced to operate a system manually following a failure in automation, their performance is impaired compared with operators who perform the same task without automation (*5*). Several explanations have been postulated to account for performance-related impairments in automated environments. According to Endsley and Kiris (*5*), such impairments can be largely accounted for by a loss of situation awareness (SA). *Situation awareness* is "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (*6*). Endsley and Kiris argue that operators who have lower SA are slower to detect difficulties and to focus on relevant features of the system that will allow them to identify the problem and regain manual performance. In a recent study of an automobile navigation task, Endsley and Kiris (*5*) showed that operators experienced a greater impairment in SA under full automation than under intermediate automation levels, as compared to manual control of the automobile navigation task. When the operator was involved in controlling the task, SA remained at a higher level and operators were more capable of performing the task manually when required. Operator complacency has also been proposed as a major factor that relates to degraded vigilance in monitoring performance under automation. Studies of aircraft cockpits suggest that performance may be impaired by complacency resulting from pilot's confidence in automated systems (*7*). Singh et al. (*7*) used a cockpit simulation to demonstrate that subjects reporting tiredness were more prone to performance decrements of this type.

Few studies have examined the possible interaction between fatigue and automated systems in driving. We define *fatigue* as "an individual's multidimensional physiological-cognitive state associated with stimulus repetition which results in prolonged residence beyond a zone of performance comfort" (*8*). A difficulty with fatigue-related impairments in driving performance is that such impairments appear to vary with the task demands of driving. This issue has been explored in detail in a series of studies of simulated driving conducted by Desmond and Matthews (*9*). In these studies, drivers performed a fatiguing drive, in which they were required to perform a demanding secondary task for approximately 24 min, and a control drive without a secondary task. Following the fatiguing drive, drivers experienced not only increased subjective tiredness and physical and perceptual fatigue symptoms, but also increased tension and annoyance and reduced task motivation, indicating that the drive was generally stressful. Lateral control of the vehicle was assessed on straight and curved road sections, early and late in fatigue and control drives. The findings indicated that lateral control of the vehicle was worse on straight sections than on curved sections following the fatigue drive. Thus, when the task is relatively difficult (curved road), fatigued drivers are able to cope with task demands; when it is easy (straight road), performance tends to deteriorate, implying that fatigued drivers are failing to mobilize effort effectively. The results of these studies have important implications for ITS. The implementation of systems such as intelligent cruise controls may act to reduce the fatigued driver's perceptions of the demands of the driving task. If so, the fatigued driver may fail to mobilize effort effectively when system failure occurs, and thus will showed impaired performance when he or she is required to operate the vehicle manually.

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The present study set out to test this hypothesis using the Minnesota Wrap-Around Environment Simulator (WES), a high-fidelity computer-controlled simulator. In the study, drivers performed both a manual drive, in which the vehicle was under full control of the driver, and an automated drive, in which the vehicle was under automated control. In both drives, the driver experienced three perturbing events: in the automated drive, the automated system failed and caused the vehicle to drift toward the edge of the driver's lane; in the manual drive, winds gusts caused the vehicle to drift in the same direction and magnitude. The effects of the automated system on drivers' subjective states were assessed by a selection of subjective measures. Control of the lateral position of the vehicle was indexed by *heading error,* the mean deviation between the direction of the vehicle and the direction of the road measured in degrees. Heading error was assessed during early, intermediate, and late phases of manual driving in both drives. It was predicted that lateral control of the vehicle would be poorer following automated failure than during the same periods in the manual driving condition.

METHOD

Subjects

Thirty-four drivers (17 male and 17 female) participated in the study. Drivers' mean age was 20.96 years, ranging from 18 to 27 years. Time since obtaining the driving license ranged from 2 to 8 years, with a mean of 4.9 years.

Minnesota Wrap-Around Environment Simulator

The WES is a high-fidelity driving simulator that provides the driver with a 360° degree viewing area in a virtual environment (Figure 1). The WES is a spherical steel and wooden dome structure onto which eight white fiberglass screens were fixed. Each screen extended up from the floor and was 250 cm in height. Each screen was synthesized with the adjacent screens so it appeared as if there was a single screen wrapping 360 degrees around the driver and vehicle. At the widest point, the wrap-around screen created a diameter of 549 cm, 22 cm above the floor; the diameter at floor level was 472 cm. The driving scene presented to participants was created by Coryphaeus Easy Scene computer software, generated by a Silicon Graphics Incorporated Onyx computer (Reality2 engine), and projected through three Electrohome ECP-3100 projectors to the curved wall of the WES. The three separate images projected to the curved wall were synthesized so they appeared as a single image, subtending a 165-degree field of view horizontally and a 55-degree field of view vertically. Participants sat in the driver's seat of a full-sized 1985 Acura Integra RS, which was positioned in the center of the WES. The driving scene presented to drivers was a flat, gray, straight road 10 m wide, separated by a left- and right-hand lane each 4.15 m wide. The length of the road was 53 086.7 m. A broken yellow line was placed down the center of the road. A tree appeared on alternating left and right sides of the road every 500 m. In both automated and manual drives, there were no other vehicles present on the road, and no traffic signs were presented to drivers. The screen refresh rate for the simulator was 30 times per second.

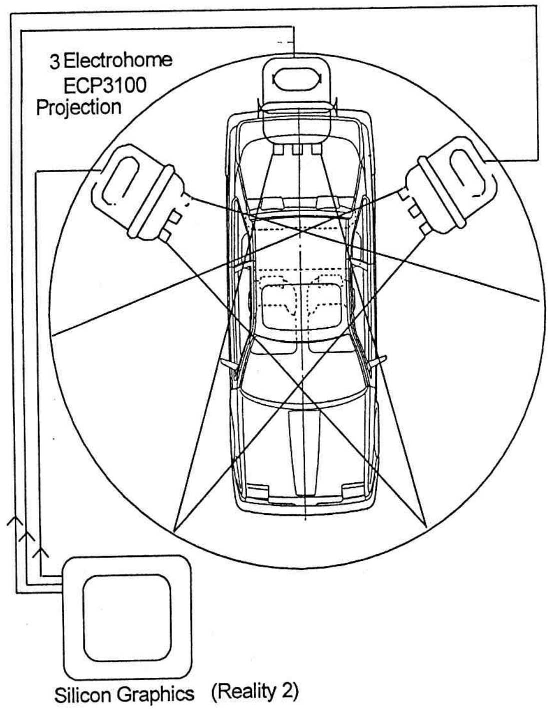

FIGURE 1 Minnesota Wrap-Around Environment Simulator.

Vehicle Dynamics of Minnesota Wrap-Around Environment Simulator

Performer software is used to design the driving scene presented to drivers, and the dynamics of the driving simulator are programmed using Clarus Drive software by Prosolvia Clarus. The car has a weight of 1 400 kg, a length of 4.79 m, a width of 1.76 m, and a height of 1.41 m. The WES is equipped with an automatic gearbox. The engine parameters are as follows: maximum power generated by the engine is 170 000 W, maximum power revolutions per minute (RPM) is 3,000, maximum torque is 300 Nm, and maximum torque revolutions is 3,000 RPM.

Subjective Measures

A variety of measures were administered to assess fatigue, mood, and other components of subjective stress states. Three fatigue scales (*10,11*) were used to measure physical fatigue, perceptual fatigue, and boredom/apathy. Each scale consisted of eight items. *Physical fatigue* refers to symptoms such as muscle stiffness, headache, and nausea; *perceptual fatigue* to eyestrain and auditory symptoms, such as ringing in the ears; and *boredom* to feelings of apathy and loss of interest in the task. Mood was assessed with the University of Wales Institute of Science & Technology Mood Adjective Checklist (UMACL) (*12*), which assesses energy, tension, and hedonic tone (pleasantness of mood). A modification of Sarason et al.'s (*13*) Cognitive Interference Questionnaire (CIQ) was used to assess intruding thoughts. Its scale comprises items relating to (1) task-relevant interference and (2) task-irrelevant personal concerns. Scales developed and validated at Dundee University were used to assess motivation, perceived control, concentration, and

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active effortful coping (*14*). All scales were internally consistent. A postdrive measure of workload, the National Aeronautics and Space Administration Task Load Index (NASA-TLX) (*15*), was also given.

Driving Performance Measures

The main performance measure examined in the study was drivers' lateral control of the vehicle. Inefficiency of control was indexed by heading error, the mean deviation between the direction of the road and the direction of the vehicle measured in degrees. Previous studies of driver fatigue (e.g., *16,7*) have shown that heading error is sensitive to fatigue-related decrements in driving performance. Specifically, Desmond and Mätthews have found that fatigued drivers' heading error increases during low-demand driving episodes.

Experimental Conditions

The study examined driving performance under two conditions: a manual driving condition and an automated driving condition. In the manual driving condition, drivers had full control over the velocity and position of the vehicle; in the automated driving condition, the velocity and position of the vehicle was controlled by an automated system. Thus, the task of drivers in the automated driving condition was simply to monitor the automated driving system when it was operational. Perturbing drifts occurred at three points during both drives: between 11.98 and 12.00 min, 22.98 and 23.00 min, and 33.98 and 34.00 min. During these time periods, the car behaved as if the steering wheel had turned $2/75\ \pi$ rad to the right. Following the wind gusts, the steering wheel was set to straight—that is, any left-turn motion by the driver turned the car left as opposed to straightening the car before heading it left.

Procedure

A repeated-measures Latin square design was used such that each subject performed an automated and manual drive on separate occasions, with order of drives counterbalanced. Each subject was tested between 9:00 a.m. and 1 p.m., and between 3:00 p.m. and 7 p.m. First, two practice runs were performed. On the first practice run, subjects were asked to drive at 80 km/h for 5 min. On the second practice run, subjects in the automated driving condition were informed that the vehicle was fitted with an automated driving system that controlled the velocity and direction of the vehicle. Subjects were instructed that when the system was operational, a message would appear on the screen directly in front of them to indicate that the system was on. Subjects were also told that the system might fail and that, should this occur, the vehicle would drift toward the edge of the right-hand lane. They were told that if the system failed, they should take over control of the vehicle as quickly as possible and continue driving until the system was operational again. However, while the system was operational, subjects were told to keep their hands off the steering wheel. Subjects performed the practice drive in which they were exposed to the automated system and experienced a system failure. Subjects in the manual driving condition were informed that, during the drive, they might experience occasional "side winds" which would cause the vehicle to drift toward the edge of the right-hand lane. Subjects performed the practice drive in which they experienced a side wind. Following the practice drives, subjects completed the UMACL, fatigue scales, task motivation scale, modified CIQ, perceived control and active coping scales, and the subjective concentration scale. Subjects then completed the main drive. They were instructed to drive at 80 km/h. Both drives lasted for 40 min. In the automated driving condition, system failure occurred at 12, 23, and 34 min. Subjects were required to control the vehicle manually for 3 min following each failure, after which the automated system became operational again. In the manual driving condition, side winds occurred at the same time intervals. The direction and magnitude of drift was the same throughout the drives. During each 3-min phase of manual driving in the drives, the trajectory and velocity of the vehicle was recorded once every second. Following the main drive, subjects completed the UMACL, fatigue scales, task motivation scale, modified CIQ, perceived control and active coping scales, subjective concentration scale, and posttask NASA-TLX.

RESULTS

Effects of Automation on Subjective Measures

Data were analyzed with repeated-measures factors of time (pretask versus posttask) and drive (automated versus manual drive). The analyses indicated no significant time-drive interactions for most of the measures, indicating that the two drives did not differ in their effects on subjective states. However, both drives produced changes in subjective measures over time, as indicated by a significant main effect of time. Figure 2 shows the standardized change scores for subjective state measures across automated and manual drives. For the UMACL, significant main effects of time ($p < .01$) were found for EA, TA, AF, and HT. The decrease in energetic arousal indicates that both drives were fatiguing. However, the increase in tension, anger, and depression indicates that both drives were also mildly stressful. The three fatigue scales also produced significant main effects of time ($p < .01$): PHY, PER, and BOR. In addition, a significant time × drive interaction ($p < .01$) was found for physical fatigue: drivers in the manual condition reported greater physical fatigue symptoms than drivers in the automated condition. This finding is not surprising, since drivers in the manual condition were driving continuously throughout the drive. A significant main effect of time ($p < .01$) was found for the task-motivation scale (MOT). This result indicates that both drives induced apathy in drivers. For the modified CIQ, a significant main effect of time ($p < .01$) was produced for both task-relevant interference (CGTR) and task-irrelevant interference (CGTIR). The increase in these stress-related measures provides further evidence to indicate that both drives were mildly stressful for drivers. A significant main effect of time ($p < .01$) was found for concentration efficiency (CON). The perceived control (PERC) and active coping (ATCOP) scales both produced significant main effects ($p < .01$) of time. For the six dimensions of the NASA-TLX, a significant main effect of drive ($p < .01$) was found for physical demand: drivers reported greater physical demand following the manual drive than the automated drive. However, there were no significant main effects of drive for the remaining workload dimensions.

Effects of Automation on Driving Performance

Mean heading error was analyzed across early, intermediate, and late phases of manual driving during both automated and manual

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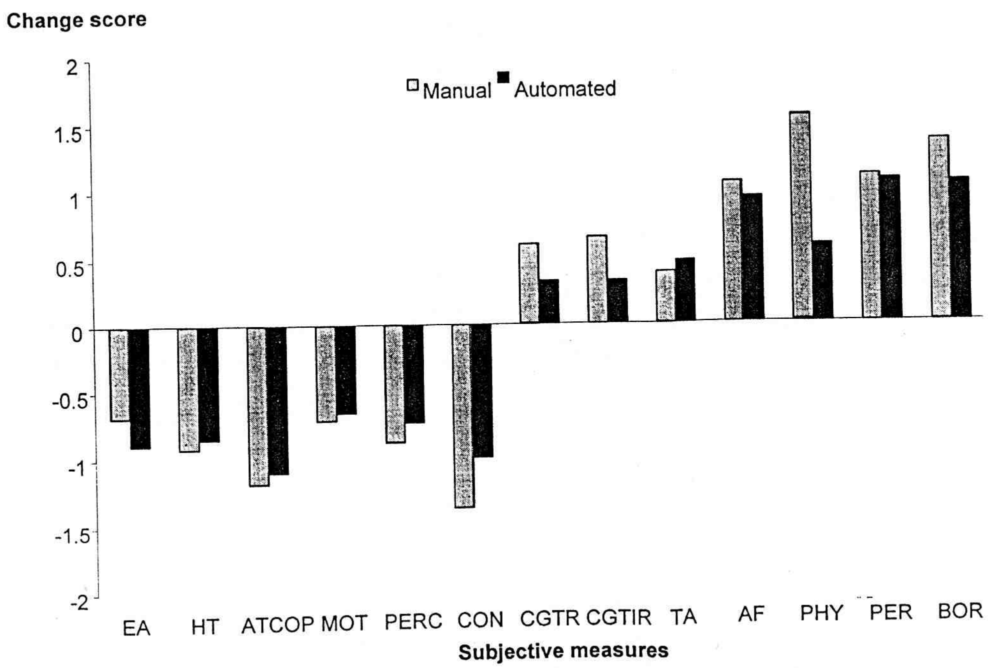

FIGURE 2 Standardized change scores for subjective measures across manual and automated drives (EA = energetic arousal; HT = hedonic tone; ATCOP = active coping; MOT = task motivation; PERC = perceived control; CON = concentration efficiency; CGTR = task-relevant interference; CGTIR = task-irrelevant interference; TA = tense arousal; AF = anger/frustration; PHY = physical fatigue; PER = perceptual fatigue; BOR = boredom/apathy).

drives. These phases represent manual control of the vehicle immediately following automation failure or, in the manual drive, after perturbing wind gusts. Each phase of manual driving lasted for 3 min. For early, intermediate, and late phases of manual driving, mean heading error was analyzed across nine 20-s periods in both drives. The nine 20-s blocks of manual driving performance were recorded at early, intermediate, and late phases of the drive immediately following automation failure or wind gusts. Previous studies of automation-induced impairments demonstrate the importance of examining performance following automation failure in terms of "critical windows" of performance (*17*). In these studies, performance immediately following automation failure is averaged across relatively short time intervals. In the present study, data were analyzed within a 2×9×3 multiple analysis of variance with repeated-measures factors of drive (automated versus manual); block (nine 20-s periods); and phase (early, intermediate, and late). The analyses indicated a significant main effect of block ($p < .01$) and a significant block × drive interaction ($p < .01$). Figure 3 shows mean heading error averaged across early, intermediate, and late phases of manual driving performance for nine 20-s periods.

Heading error is greater immediately following automation failure than following wind gusts in the manual drive during early, intermediate, and late phases of driving performance. Thus, performance recovery appears to be better in the manual driving mode than in the automated mode during the first 20-s period [$t(33) = 5.07$, $p < .001$]. However, drivers in the manual condition showed progressive poorer lateral control during the remaining periods, especially during the fifth 20-s period [$t(33) = 2.24$, $p < .05$] and the ninth 20-s period, [$t(33) = 2.75$, $p < .05$]. The initial heading error of 0.4 degrees in the automated driving condition has important safety implications. It is assumed that the vehicle is traveling at 80 km/h, and thus traveling at a velocity of 22.3 m/s. If the vehicle deviates by 0.4 degrees for 3 s, the final position of the vehicle would be 1.6 m from the centerline of the road, resulting in a lane exceedance.

Figure 4 shows mean heading error during the first 20-s block across early, intermediate, and late phases of manual driving under automated and manual driving conditions. One might argue that the results presented in Figure 3 can be accounted for simply in terms of drivers in the automated driving condition having their hands off the steering wheel prior to automation failure. However, this account appears to oversimplify the findings when the results presented in Figure 4 are examined. The figure shows that drivers in the automated condition show poorer lateral control of the vehicle—by 2 s—than drivers in the manual condition [$t(33) = 3.58$, $p < .001$]. However, by the 3rd and 4th s there are no significant differences in heading error between automated and manual driving conditions. Thus, after 3 s, recovery is equivalent in both drives. The results indicate that drivers in the automated condition show significantly poorer lateral control during the 5th [$t(33) = 2.47$, $p < .05$], 6th [$t(33) = 3.06$, $p < .01$], 7th [$t(33) = 3.90$, $p < .001$], 8th [$t(33) = 4.48$, $p < .001$], 9th [$t(33) = 3.91$, $p < .001$], 10th [$t(33) = 2.98$, $p <. 01$], 11th [$t(33) = 3.27$, $p < .01$], 12th [$t(33) = 3.45$, $p < .01$] and 13th [$t(33) = 3.49$, $p < .01$] s than drivers in the manual driving condition. Thus, a consistent pattern of impairment in lateral control is not evident until 5 s following automation failure.

DISCUSSION OF RESULTS

The findings from the subjective measures in the study demonstrate that drivers found both drives to be generally stressful. Drivers experienced not only increased subjective tiredness and physical and

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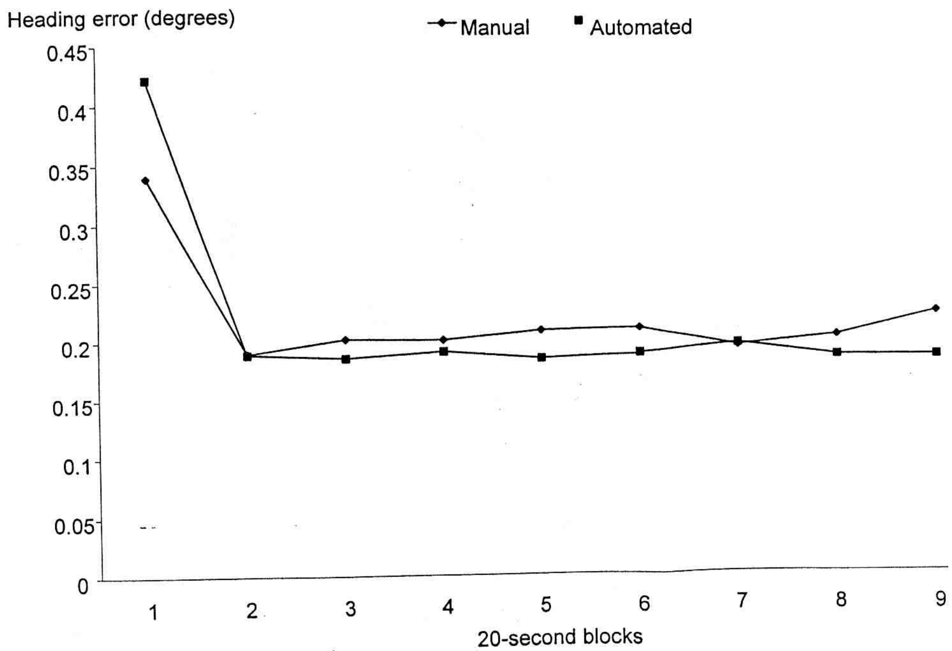

FIGURE 3 Mean heading error across early, intermediate and late phases of manual driving in automated and manual driving conditions.

perceptual fatigue symptoms, but also increased tension, annoyance, and cognitive interference. The decrement in task motivation and active coping following both drives may be indicative of complacency problems in fatigued drivers. The pattern of change in subjective measures found in the study is consistent with changes in subjective state found in previous studies of driver fatigue (*18,7,16*). The findings appear to suggest that monitoring an automated driving system may be just as effective in inducing subjective fatigue and stress states as prolonged driving under monotonous driving conditions. Moreover, the subjective workload data indicated that both drives appeared to impose similar levels of workload on drivers. This finding is consistent with Parasuraman et al.'s view (*19*) that implementation of automation does not necessarily result in a decrease in the individual's mental workload. Instead, Parasuraman

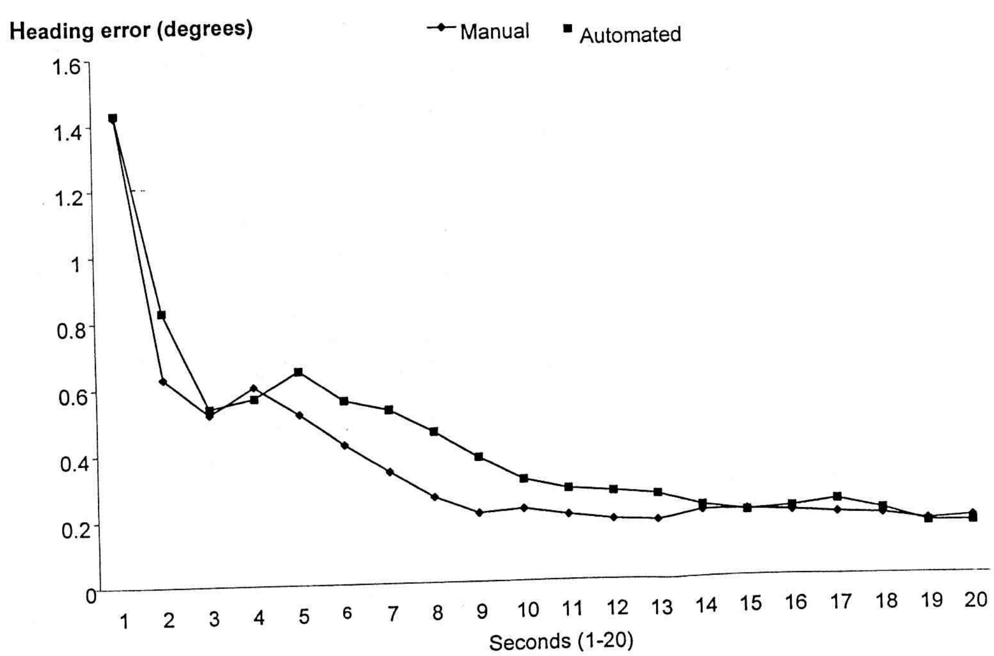

FIGURE 4 Mean heading error during the first 20-s block across early, intermediate and late phases of manual driving in manual and automated driving conditions.

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et al. argue that the demands of monitoring an automated system may be sufficiently high such that a reduction in mental workload is offset by these demands. Further experimental work is needed to determine if the pattern of subjective fatigue found in the present study would change with more extended driving periods.

The results of the study provide support for the findings of previous studies (e.g. *5*) that have found impairments in performance when operators are required to assume manual control following automation failure. In the present study, lateral control of the vehicle showed impairment during a 20-s period immediately following automation failure. This finding is consistent with Scallen et al.'s study (*17*) in which pilot performance was found to be impaired during a 15-s period of manual performance following automation failure. Further examination of the present study's findings indicated that 2 s following the perturbing event, drivers in the automated and manual driving conditions showed the same level of performance recovery (see Figure 4). Moreover, drivers in the automated condition did not show a consistent pattern of impairment in lateral control until 5 s following the failure in automation. This finding is particularly compelling, since it suggests that the poorer lateral control of the vehicle found in the automated condition cannot be attributed simply to these drivers having their hands removed from the steering wheel prior to automation failure. If this were the case, one would not expect drivers in the manual and automated conditions to show equivalent levels of lateral control at the 3rd and 4th s following automation failure. Thus, we suggest that these findings support our main hypothesis that automated systems may result in the driver undermobilizing his or her effort.

The findings from the present study have important practical implications for automated highway systems. The study suggests that such systems should aim to keep the driver within the driving loop in order to guard against performance impairments. This realization has led to the development of human-centered design approaches (*20*). The dangers of implementing automation and using the human operator as a form of system backup have been illustrated in operational environments such as air traffic control and process control. These results suggest that, as a general principle, it is important to maintain driver involvement in all aspects of the driving task in order to avoid underload. A possible solution to automation-induced performance impairments of this kind is the use of adaptive systems (*21*). Adaptive systems advocate the use of both human and machine adaptive capability to enable rapid response to unpredictable events and unusual incidents. In the context of aviation, adaptive systems have been shown to result in improved operator response to unpredictable system failures (*22*). It is possible that adaptive systems may also prove to be beneficial in the driving environment. The study also supports the view of Desmond and Matthews (*16*) that secondary tasks, such as monitoring an in-car guidance system, may actually benefit the fatigued driver when other task demands are low. The extra task load may prevent undermobilization of effort and maintain the driver's active engagement with the task.

The generalizability of the present research to real-life driving should be considered. It is acknowledged that the present results obtained from the Minnesota Wrap-Around Environment Simulator may not be generalizable to real-life driving. However, it should be pointed out that the physical fidelity of the simulator is very high. Moreover, as Sanders (*23*) argues, it is more important that a simulator has functional fidelity—that is, it behaves like the system in reality. There is some evidence to support the functional fidelity of the WES. The pattern of subjective response obtained in the present study is similar to the pattern of subjective fatigue found in real-life driving (*24*). On the basis of these findings, it is assumed that the present results can be related to real-life driving behavior.

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