The Effect of Prior Task Loading on Mental Workload : An Example of Hysteresis in Driving

Justin F. Morgan and Peter A. Hancock

Published by:
⑤SAGE

http://www.sagepublications.com

On behalf of:

Human Factors and Ergonomics Society

The Effect of Prior Task Loading on Mental Workload: An Example of Hysteresis in Driving

Justin F. Morgan, Virginia Tech Transportation Institute, Blacksburg, and
Peter A. Hancock, University of Central Florida, Orlando

Objective: This study examined how transitions in task demand during a driving and navigation task manifested themselves as delayed adaptation in driver mental workload.

Background: A delayed reaction to changes in demand levels, termed *hysteresis*, has been identified in a number of settings. However, little research has specifically examined the driving task for hysteresis effects.

Method: A total of 32 drivers completed drives while using a navigation system that would fail within the drive. Subjective mental workload was recorded prior to and following system failure as well as at the conclusion of the drive.

Results: Results indicated that a gradual reduction in overall mental workload across trials and a lagged recovery to reduction in task demand was present within trials. Analysis of the mental workload subscales within trials indicated that this effect was produced by the mental effort component of workload.

Conclusion: A moderate hysteresis effect is present in mental workload transitions within the driving task. Although subjective mental workload decreases across trials, the magnitude of the lagged recovery within trials remains unchanged.

Application: Scaling of in-vehicle information is beneficial with respect to driver mental workload. Display and communication technologies designers should consider not only the immediate task demand but also the driver's task demand history when determining what and how to provide information.

Keywords: mental workload, stress, workload transitions, driving simulation, driver performance, hysteresis

Copyright © 2011, Human Factors and Ergonomics Society.

INTRODUCTION

The task of driving and navigating a vehicle requires continually varying levels of attention. Driving through the traffic of a major city can impose a level of demand approaching a driver's absolute response limits, especially if that individual is a novice driver. However, time spent driving through relatively empty countryside with little in the way of roadway features or distractions can present vigilance-like conditions (Desmond & Hancock, 2001). Transitions between such intervals of monotony and moments of potential mayhem can be sudden and unexpected (Huey & Wickens, 1993) and raises concerns as to whether such demand-level transitions manifest themselves in the form of mirrored variations in driver mental workload.

Drivers must constantly sample the roadway environment for critical control cues (Senders, Kristofferson, Levison, Dietrich, & Ward, 1967). Although these cues are frequently predictable, occasionally they are composed of unexpected events that require an immediate response. This situation impels the driver not only to repeatedly sample the roadway environment and maintain information about the current state but also to attempt to anticipate likely future states. In addition, this process is occurring in the presence of any number of distracters, both within and external to the vehicle (Horrey, Wickens, & Consalus, 2006; Regan, Lee, & Young, 2008; Strayer, Drews, & Johnston, 2003). Therefore, the roadway environment serves as a source of information for the driver, allowing the interaction between driver and the driving environment to be viewed as an information processing exchange. Factors such as roadway curvature, the presence of other traffic, roadway signage, and in-vehicle displays increase the amount (bits) of information conveyed from the roadway to the driver. This

perspective encourages the application of various human information processing models to the driving context (Wickens, 2002).

Although the impact of various stressors and manipulations of mental demand within both human information processing and the driving task have been well articulated (Wierwille & Eggemeier, 1993), we have only a meager understanding of the process of transitions within these events. Not only is the period when the driver is experiencing an increase in demand pertinent to his or her performance, but the epoch that follows a period of high task demand is also of great interest. That is, the history of previously experienced events may be as influential on driver response and levels of workload as are current levels of demand. The term most applicable for the ongoing influence of such prior historical influences is *hysteresis*.

Hysteresis is a common term in the material and physical sciences referring to history of an object as it affects its present condition (e.g., Verhave & Herman, 1967). In the physical sciences, definitions of hysteresis speak to the current properties of an object being affected by forces no longer active on it (such as degradation of magnetic tapes over time or springs that lose the ability to return to a fully coiled state). Interestingly, although the psychological sciences are beginning to appropriate this term from the realm of physics and the material sciences, the term *hysteresis* itself may actually have been initially borrowed from the older, psychological, term *hysteria*. Hysteresis was used as a description of Barkhausen noises emitted by certain metals during transformation (Durin & Zapperi, 2006). Researchers likened the sound the metals emitted during magnetic transformations to the sound of a hysterical scream. It may, therefore, be of benefit to recover this concept from physics as an appropriate explanatory construct for the memory-based momentary responses of human operators.

Hysteretic effects in task performance and workload have traditionally been studied with monitoring tasks. Colquhoun and Baddeley (1964) used a vigilance monitoring task to investigate the effect of shifting event rates within the context of a vigilance decrement. They noted that expectancy is maintained well after conditions within the experiment are altered. In their study, participants trained at a high signal probability

retained performance associated with this high signal probability well after a switch to lower signal probability conditions. Similar effects were present for participants trained in lower signal probability conditions who were switched to higher signal probabilities. This hysteretic effect of expectancy on performance has since been replicated by a number of other studies (see Colquhoun & Baddeley, 1967; Krulewitz, Warm, & Wohl, 1975; E. L. Wiener, 1977).

Both Cumming and Croft (1973) as well as Goldberg and Stewart (1980) have used shadowing tasks to examine information processing under transitioning demand levels. Cumming and Croft used an auditory shadowing task in which the presentation rate varied between 0.25 and 2.5 items per second. By varying this presentation rate between high-demand conditions (instances with a faster presentation rate) and the contrasting lower-demand conditions, they demonstrated that performance was greater in the increasing- as compared with the decreasing-demand situations. Similarly, Goldberg and Stewart asked participants to shadow characters presented on a monitor with a presentation rate that varied between 0.5 to 4.0 characters per second. Both sets of researchers found that with decreasing demand levels, participants did not perform as expected; instead of a rebound of performance with the decrease in task demand, absolute performance levels remained low. Both studies demonstrated two distinct performance-demand functions: one representing performance with increasing levels of demand and a second describing performance with decreasing levels of demand. The findings of both Cumming and Croft as well as Goldberg and Stewart can be viewed as support for a short-term memory overload explanation of the hysteresis pattern exhibited.

An alternative conceptualization of this effect was proposed by Matthews (1986), who examined workload transitions in a visual task. Describing a form of perseveration of expectancies, Matthews concluded that people were retaining their current strategy (i.e., strategic persistence) well after task demand level had changed. However, Matthews did not attempt to examine whether the demand transition actually exceeds the operator's own criterion for detecting such a change. Theoretically, it is possible the operator never consciously notices a change. In effect, when the

demand change increment is small enough and is below the workload change of just noticeable difference (JND), the expectancies of the operator may be preserved. With larger-magnitude changes, the mechanism through which hysteresis occurs is likely to be both a delayed adjustment in operator expectancy and the change in task demand affecting short-term memory. Thus, both hypotheses have some degree of support depending on the nature and degree of the demand change experienced (Farrell, 1999).

The present work focused on situations in which drivers' task demand rapidly transitioned from a lower to higher level of demand and then subsequently returned to a lower level of demand. This manipulation was performed to understand hysteresis within driver subjective mental workload. This experiment presented drivers with a driving and navigating task in which the in-vehicle navigation device periodically failed. Such device failures served to change the level of task demand from which hysteretic changes were to be measured. The results are examined in terms of the establishment of hysteretic effects in driving and the implication of such an effect for in-vehicle technologies and their interactions with the driver as well as operator performance in all demand transition circumstances.

METHOD

Participants

A total of 38 adult drivers served as participants. All participants held a valid U.S. driver's license and self-reported either normal, or corrected-to-normal, visual acuity and color vision. Because of data corruption issues, data from 2 participants were not included in the final analysis. Also, 4 participants were either withdrawn by the experimenter or self-withdrew from the experiment because of visual discomfort or nausea associated with simulator use (see Kennedy, Lane, Berbaum, & Lilienthal, 1993). Thus, the final analysis included data from 32 participants, including equal numbers of females and males, with an average age of 21.3 (SD = 3.4). Participant demographic information is provided in Table 1.

Apparatus

Driving simulator. All driving tasks occurred in a fixed-base driving simulator manufactured by ISim (L3 STS, Inc.). This simulator provided

TABLE 1: Driver Demographic Information

Variable	M	SD
Age	20.8	3
Years licensed	4.8	3.1
Minor accidents	0.5	0.7
Major accidents	0.3	0.7
Speeding tickets	0.3	0.5
Reckless driving tickets	0.1	0.3
Other tickets	0	0

Note. N = 32. Age and years licensed are represented in years; all other values represent an average for the category.

approximately 120° horizontal field of view via projection onto three screens mounted at a distance of approximately 1.0 m from the driver's eye. All visual channels operated at a resolution of 800 × 600 pixels. The simulator included a partial dashboard from a Ford Crown Victoria and contained all major operational controls (e.g., steering, braking, throttle, gear selection, and ignition) and adjustments (e.g., steering wheel and seat position adjustment). All data produced by the simulator network were logged (at a 60-Hz synchronized rate) for subsequent analysis.

Navigation system. A heads-up display (HUD) electronic route navigation system was constructed for use in the simulated environment. Modeled after commercially available GPS navigation systems, this facility allowed for the display of turn-by-turn driving directions. Updates to the system were triggered by the vehicle's position within the driving environment. The HUD image consisted of an image inset within the lower left of the center image channel; this location was chosen to correspond with the HUDs currently available in some vehicles.

Driving environment. A total of four driving routes were created, each consisting of a 5.6-km (approximately 3.5-mile) route inside an urban environment with low traffic density. Each route was designed with equivalent frequency and direction of turns and road types. The posted speed limit across all roads in the environment was 72 km/h (45 mph). This allowed for the appearance of differing driving environments while holding the roadway characteristics themselves constant. Each route required approximately 5 min to complete.

Measures

Mental workload. The Simplified Subjective Workload Analysis Technique (S-SWAT; Luximon & Goonetilleke, 2001) was used as the measure of driver mental workload. This self-report scale loads onto three factors: time, mental effort, and psychological stress. Each has a range of 0 to 100. An unweighted average of these three scores was used to create a single total subjective mental workload score. Participant-drivers were asked to provide ratings on this scale for their perception of the three factors at that moment during the drive, and they reported these scores verbally. This procedure allowed trials to continue with minimal interruption during the reporting process itself.

Driver response. The S-SWAT was used as the measure of subjective mental workload. In addition to subjective mental workload, additional reflections of driver behavior were chosen. These were vehicle speed, the speed differential between actual and posted speed, accelerator actuation, and braking actuation. Each measure was calculated as a mean across the respective segments of the trial, resulting in three measures of each driver response variable per trial.

The speed differential is the difference between the posted speed limit of 72 km/h (45 mph) and the participant's mean speed within the specified segment. This measurement allows the magnitude of any differences to be made apparent and also is a reflection of task compliance. Accelerator and brake actuations are the pedal displacement, provided in percentage of total actuation of the accelerator or brake pedal (ranging from 0%, or no pedal use, to a maximum of 100%, which would indicate a full pedal application). These responses were chosen as measures of momentary vehicle control and provided information on the variability of driver control across conditions.

Procedure

After obtaining informed consent, participants completed a brief demographic questionnaire. Following completion of this questionnaire, the S-SWAT and its subscales were described to the participant. As a familiarization exercise, participants were asked to give a rating of their subjective mental workload along each scale. After recording this information, the experimenter asked the participant to be seated in the driving simulator, and the location and operation of all controls and adjustments in the driving simulator were explained. The layout and information on the HUD navigation system was also described as well as how to interpret the instructions this system provided. After an opportunity to ask further questions, participants were given instructions that if the navigation system failed, a 10-digit alphanumeric code would be displayed on the unit. This code had to be verbally relayed to the experimenter to reactivate the navigation system. Participants were instructed to continue to drive at their normal pace if the navigation system did fail and to attempt to clear the failure as soon as possible.

The navigation system failure occurred at a fixed point within the drive, set to coincide with the participant entering the middle third of the drive (allowing for the higher task demand period with the navigation system failure to be the temporal middle section of the drive). Although failures occurred at points with intersections and crossroads, no participant made an incorrect turn or other navigational error during this (or any other) period within any trial. Participants were asked to drive normally and to follow the posted speed limit signs (all were posted at 72 km/h). Measures of the S-SWAT were obtained at three points. Measurement times occurred across approximately temporal equivalent time intervals within each individual respective trial. The first was after the initial third of the trial had been completed. The second measurement was immediately after the driver successfully cleared the failure of the navigation system (resulting in the second temporal bin being one of higher task demand). The final measurement was taken at the conclusion of the drive.

RESULTS

All data were screened for violations of normality prior to analysis. During screening for violations of the assumptions of ANOVA, minor violations of the assumption of sphericity occurred. Two adjusted significance tests were examined (Greenhouse-Geisser and Huynh-Feldt). However, in neither case did the adjusted significance level differ from the noncorrected level. Therefore, the noncorrected levels are those reported here. All analyses were conducted at $\alpha = .05$ unless otherwise specified.
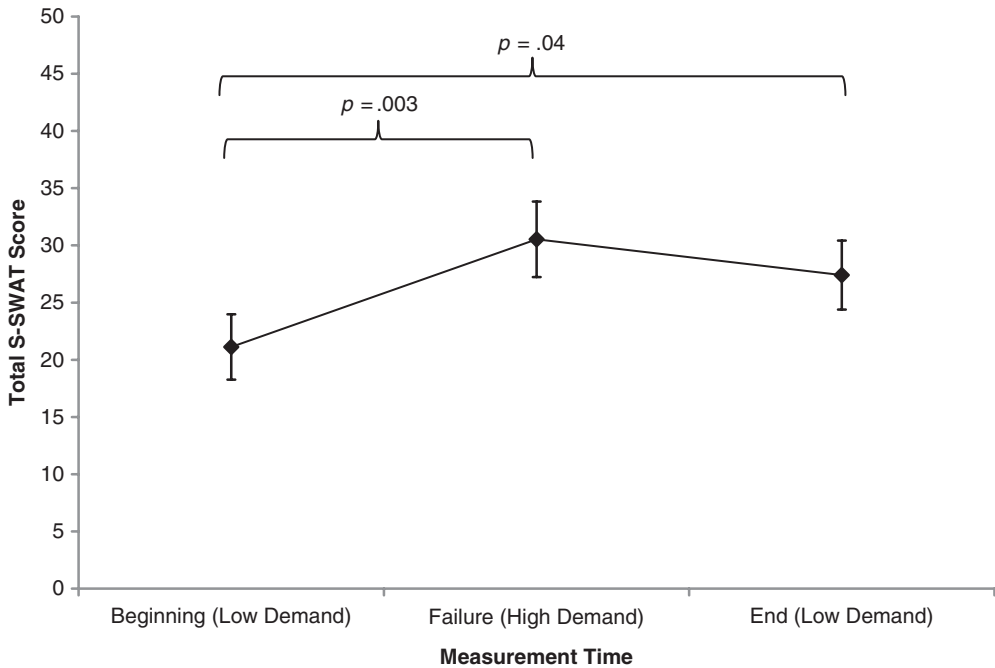
Figure 1. Subjective mental workload within trials.

Results Within Individual Trials

A significant main effect of measurement period was present for the overall mental workload scores, $F(2, 56) = 45.28$, $p < .0005$. Planned comparisons were conducted, revealing that significant differences were present between each measurement period, except for the difference between the second and third periods ($p = .33$; see Figure 1). Thus, overall mental workload significantly increased from the first measurement period (at the beginning of the drive, $M = 21.12$, $SD = 11.41$) to the second (measured immediately post navigation system failure, $M = 30.53$, $SD = 13.20$) but decreased slightly and nonsignificantly by the third measurement interval (measured at the end of the drive, $M = 27.41$, $SD = 12.07$).

The results of each individual subscales of the S-SWAT (time demand, mental effort, and psychological stress) at the three measurement intervals within trials were examined (Table 2). There was a significant main effect for measurement interval on time demand, $F(2, 62) = 27.10$, $p < .0005$. Participants' subjective time demand increased from the first measurement to the second measurement ($p < .0005$) but decreased between the second and third ($p = .03$). The differences between time

demand means at the first and third measurements was significant at $p < .0005$.

There was also a significant main effect for measurement interval on mental effort, $F(2, 62) = 22.70$, $p < .0005$. Mental effort increased from the first measurement to the second measurement ($p < .0005$) and dropped from the second to the third measurement ($p = .003$). However, mental effort was still significantly elevated at the third measurement as compared with the first measurement, $p < .0005$.

Analysis of the effect of measurement interval on psychological stress was significant, $F(2, 62) = 12.12$, $p < .0005$. Psychological stress increased from the first measurement to the second measurement ($p < .0005$) but did not significantly decrease between the second and third measurements ($p = .19$). The differences between psychological stress means at the first and third measurements was significant, $p = .001$.

When driver performance data were analyzed using measurement intervals within the individual trials (Table 2), a significant main effect was present for speed, $F(2, 54) = 9262.24$, $p < .0005$. The speed as measured before the failure of the navigation system was significantly slower than

TABLE 2: Driver Mental Workload and Performance Within Trials

Subscale	Beginning (Low Demand)	Failure (High Demand)	End (Low Demand)
Time	20.48 (0.64)	30.96 (0.73)	28.14 (0.66)
Mental effort	26.32 (0.67)	37.49 (0.74)	32.64 (0.72)
Psychological stress	16.56 (0.51)	23.13 (0.59)	21.44 (0.59)
Speed[a]	30.0 (2.6)	54.0 (6.2)	54.3 (4.9)
Speed differential[a]	26.3 (0.1)	11.5 (0.1)	11.2 (0.1)
Braking[b]	0.07 (0.20)	1.10 (0.40)	2.60 (0.70)
Acceleration[b]	10.50 (2.60)	10.30 (1.20)	9.60 (1.30)

Note. Standard deviations shown in parentheses.
[a]In km/h.
[b]In percentage actuation of the control.

the measurement immediately after the failure ($p < .0005$) and at the end of the drive ($p < .0005$). The measures of speed immediately postfailure and at the end of the drive did not differ statistically from each other ($p = .57$).

Not surprisingly, given the foregoing findings, there was a significant effect of measurement interval on the speed differential, $F(2, 54) = 735.43$, $p < .0005$. The speed differential at the first measurement was significantly greater than that at the second measurement immediately postfailure ($p < .0005$) as well as significantly greater than the speed differential at the third measurement at the end of the drive ($p < .0005$). Again, and consistently, there were no significant differences between speed differentials at the second and third measurements ($p = .61$).

Reflections of braking also proved significantly different when analyzed across measurement intervals, $F(2, 54) = 130.47$, $p < .0005$ (Table 2). Thus, significantly more braking inputs were required after the navigation system failure than either at the beginning of the drive or immediately postfailure. All differences between measurement intervals for brake actuation were significantly different at the $p < .001$ level.

No similar trend was observed with accelerator actuation, $F(2, 54) = 24.00$, $p = .052$ (Table 2). Drivers' mean accelerator actuation was approximately equal for the time before and immediately after failure. Less accelerator actuation was observed in the interval from the time immediately postfailure to the end of the drive. The only statistically significant differences between measurements of accelerator actuation occurred between the time immediately postfailure and the end of the drive ($p = .03$).

Results Across Trials

A significant main effect was present for overall mental workload across trials, $F(3, 84) = 35.64$, $p < .0005$. Post hoc analysis revealed a significant reduction in overall mental workload scores across sequential trials. This manifested itself as a gradual drop in mean score as the trials progressed. The first trial demonstrated the highest overall rating ($M = 33.26$, $SD = 20.88$) and demonstrated a significant reduction at the second trial ($M = 28.42$, $SD = 17.82$, $p < .05$). The step from the second to the third trial ($M = 23.90$, $SD = 15.96$) was not significant, nor was the step from the third to the fourth trial ($M = 19.83$, $SD = 16.32$). However, the difference between the first and fourth, as well as between the second and fourth, trials was significant at $p < .05$. Such an effect implies that observed hysteresis effects are short-lived and largely mediated by short-term memory scaling effects. However, longer-term hysteretic influences may be present although more subtle in their impact.

The subscales of the S-SWAT were also examined. Significant main effects of trial were present for time, $F(3, 93) = 14.10$, $p < .0005$; mental effort, $F(3, 93) = 18.08$, $p < .0005$; and psychological stress, $F(3, 93) = 11.34$, $p < .0005$. Planned comparisons indicated that across all the subscales of the S-SWAT, mean scores significantly decreased across trials ($p < .05$ in all cases). The one exception to this pattern was for psychological stress, for which the difference between the second and third trials was not significant ($p = .18$). The means and standard deviations for S-SWAT subscale scores are provided in Table 3.

The effect of trial on speed was also significant, $F(3, 81) = 1810.20$, $p < .0005$. The average speeds

TABLE 3: Driver Mental Workload Across Trials

Subscale	M	SD
Time		
Trial 1	33.11	0.80
Trial 2	28.64	0.71
Trial 3	23.52	0.63
Trial 4	20.84	0.64
Mental Effort		
Trial 1	40.60	0.80
Trial 2	35.13	0.74
Trial 3	29.14	0.74
Trial 4	23.74	0.68
Psychological Stress		
Trial 1	26.07	0.60
Trial 2	21.50	0.61
Trial 3	19.04	0.60
Trial 4	14.90	0.52

observed in the first ($M = 34.09$ km/h, $SD = 2.93$), second ($M = 36.85$ km/h, $SD = 3.03$), third ($M = 22.67$ km/h, $SD = 2.92$), and fourth trials ($M = 20.96$ km/h, $SD = 2.69$) all differed significantly from one another at $p \leq .02$. Likewise, the effect of trial on braking was also significant, $F(3, 81) = 11.47$, $p < .0005$. Braking differed significantly between virtually all trials, with the first trial ($M = 1.54$, $SD = 0.48$) and the second ($M = 1.74$, $SD = 0.52$) exhibiting the highest amount of braking actuation. The third trial ($M = 1.30$, $SD = 0.39$) and the fourth ($M = 1.33$, $SD = 0.40$) required less braking. The differences between all trials except for the pairwise comparison of Trials 1 and 2 and of Trials 3 and 4 were significant at $p \leq .05$. There was no significant effect for trial on accelerator actuation, $F(3, 81) = 2.14$, $p = .12$.

Comparison of Subjective Mental Workload to a Baseline Condition

As prior research has noted that a gradual increase in subjective mental workload across time can occur in baseline conditions (Dember et al., 1993; Szalma et al., 2004), driver mental workload was assessed in the same driving conditions as the present study, although in the absence of a navigation system failure. A total of 10 drivers (5 males and 5 females with an average age of 19.6 years, $SD = 1.2$, and an average driving experience of 4.0 years, $SD = 0.9$) from the same university population as the primary study served as drivers for this baseline study. Drivers in this study completed the same driving routes, in the same driving conditions, as participants in the main study. However, they did not experience a failure in the route navigation system.

Results indicated that a significant decrease in driver mental workload was present across trials, $F(3, 24) = 3.92$, $p = .02$. This effect presented itself as a significant decrease in S-SWAT scores across the individual trials. There was a steady decline between the first and second trials ($p < .05$), followed by a further significant decline between the third and fourth trials ($p < .05$). No such effects were present in the within-trials or individual S-SWAT scale measurements. This effect may be one of familiarization and, unlike the within-trial effect reported by Dember et al., this across-trial effect is much more likely related to situational learning than to within-driving-event demand.

DISCUSSION

The present results suggest that hysteresis effects occur in drivers' subjective mental workload. Of the possibilities present in transitions of mental workload that are illustrated in Figure 2, the obtained pattern of data portrays a moderate hysteretic effect, with the results being between no hysteretic effect and a perfect hysteretic effect. Although there was a significant drop in subjective mental workload between the interval immediately following the in-vehicle navigation system failure and at the end of the trial, the latter level of mental workload observed was still significantly higher than that observed at the beginning of the same trial. This effect was present in every trial. Obviously, as this is one of the first explorations of hysteresis in driving, both replication and further exploration are needed in terms of both persistent changes in perceived workload and primary task performance as an index of this effect.

Within trials, the sharp increase in subjective mental workload observed from the first measurement period to the second, followed by only a slight and nonsignificant decrease from the second measurement period to the end of the drive, supports the presence of, and is characteristic of, a hysteretic effect (Farrell, 1999). The form of this mental workload function is similar, although not identical, to those observed by previous researchers examining hysteresis effects in other aspects of human performance (e.g., Chamberlain, 1968;
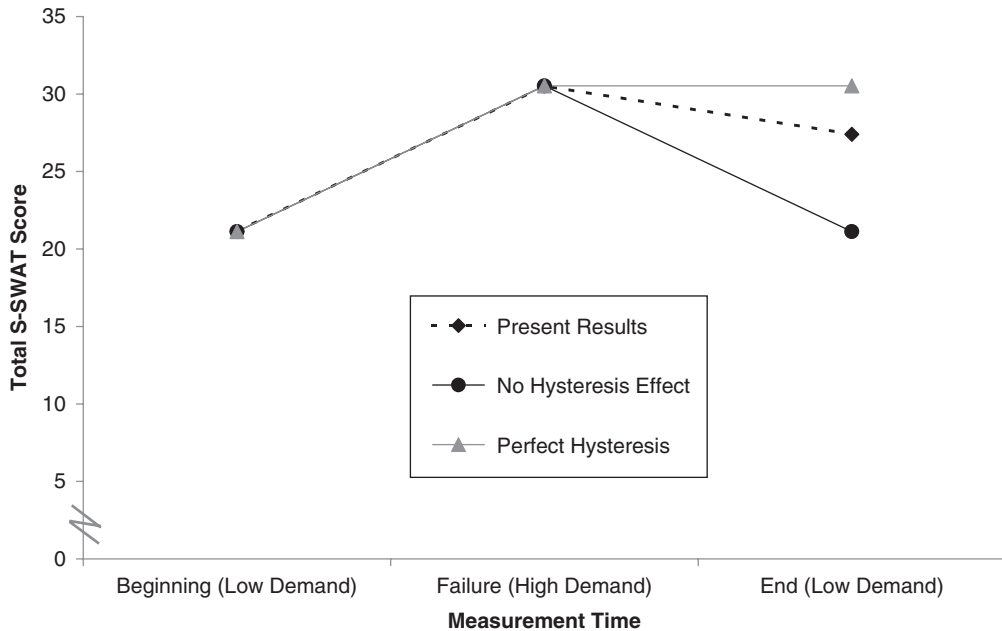
Figure 2. Results of present study in contrast to possible outcomes.

Cumming & Croft, 1973; Farrell, 1999; Goldberg & Stewart, 1980).

The general decrease in average mental workload across trials, especially as seen in comparison with the baseline condition, is not entirely unexpected, considering the nature of general familiarization with the driving task and the participants' progressive familiarity with the present performance setting and expectations. However, the findings of the comparison with the baseline condition do provide assurance that the basic driving task was not meeting or exceeding the level of demand presented by the experimental navigation system. Although there was a decrease in global scores from Trial 1 ($M = 32.54$, $SD = 7.12$) to Trial 3 ($M = 22.10$, $SD = 5.70$), the change between Trial 3 and Trial 4 ($M = 21.53$, $SD = 5.72$) was not significant.

This form of trial to trial change is indicative of a learning effect or a possible general habituation to the task (and see Hancock, 1996). As the participants completed each trial, they became more familiar with the routine required of them. They became more familiar with the driving simulator, with the navigation system, and with reporting data for the measure of mental workload. These results thus appear to demonstrate an effect, such as learning or habituation, that was also represented in the relatively stable nature of the variance in mental workload scores observed after the initial measurement. This pattern is also perhaps partly attributable to the regular temporal characteristics of the trials (see also Scerbo, Warm, & Fisk, 1986). However, it is also possible that the reduction in mental workload across trials was related to the overall reduction in speed across trials, with the reduction in speed yielding a reduction in demand levels; future work should specifically examine this possibility. It is likely that any subsequent trials, had they been conducted, would have shown little variation from the outcome of Trials 3 and 4.

Interestingly, the examinations of the individual subscales of the S-SWAT did not produce results similar to that of the total, collapsed, score. Whereas the overall score, an unweighted average of the three subscales, demonstrated a significant increase between the first and second measurement intervals with no significant difference between the second and final measurements, the step between all three measurement intervals was significant for the individual subscales. That is, the function of workload within trial was largely symmetrical. Even though the values of most

subscales at the conclusion of each trial were still elevated as compared with the initial values within the trial, the decrease in values from the second to the third measurement negates the possibility of declaring a hysteretic effect present in most of the subscales of the S-SWAT.

The exception to this was mental effort, which displayed a nonsignificant difference between the second and third measurements, as seen in the overall value, and was the result of the significance of the hysteretic effect observed in the total score. However, in all cases, the pattern for the mean scores for the individual subscales displayed replicated the pattern for those of the summated score. The fact that no other component had a significant hysteretic effect present is suggestive that mental effort was driving the overall effect observed. Furthermore, this single-component finding provides support for a short-term memory overload explanation of hysteresis effects (Smolensky, 1990). The time demand and psychological stress components of subjective mental workload are not necessarily coded in short-term memory, in contrast to the mental effort component (Reid & Nygren, 1988).

Similar to the findings of Smolensky (1990), the present study finds support for the short-term memory hypothesis in driving tasks in which the driver's memory capacity may be temporarily reached and/or exceeded. Thus, the hysteresis effect must be relatively transient; it manifests only within trials, suggesting it is a scaling effect mediated by short-term memory. This is not to suggest that this effect necessarily has a long-term effect. Instead, only the last few consciously processed moments (Baddeley & Hitch, 1974) would likely result in a hysteretic effect based on short-term memory.

Some of the objective measures of driver performance also demonstrated a mild to moderate hysteretic effect within trials. Speed increased significantly from initial to postfailure measurement periods, and similar results were found in an examination of the speed differentials (difference between actual and posted speeds). There were no significant differences in speed or speed differentials between the second and final measurements, meeting expectations for a hysteretic effect in both speed and speed differentials. Although the speed measure is an interesting

indication of performance, it is possible to interpret the consistency of this measure of performance postfailure in different ways. However, it should be noted that speed still provides a good overall measure of compliance with the instructions of the driving task and, in particular, compliance with posted speed limits.

Brake actuation, as a momentary reflection of longitudinal control, arguably provides a more comprehensive test of a possible hysteretic effect (Stanton, Young, Walker, Turner, & Randle, 2001; Verwey, 2001). The mean level of brake actuation increased after the navigation system failure and thereafter remained high throughout the drive. This effect was not attributable to any innate characteristic of the driving task. This hysteretic effect is also demonstrated by the increase in the variance observed in braking actuation. The standard deviation of brake actuation increased from the point of failure and remained high until the end of the drive. However, all of the objective measures must be viewed in light of the potential for performance-workload dissociations (Yeh & Wickens, 1988), allowing for the potential of the two measurement dimensions to dissociate in conditions of resource competition. In the present study, subjective workload may not be sensitive to performance variations, and likewise, performance may not precisely mirror subjective workload.

A possible mechanism for the phenomena of hysteretic effects, and one that perhaps influenced Goldberg and Stewart's (1980) hypothesis, is Norman and Bobrow's (1975) distinction between resource-limited and data-limited processes. The idea of various programs competing for finite cognitive resources allows for either data- or resource-limited processes. Most tasks shift from resource limitations at an early stage to data limitations at later stages (Kantowitz & Knight, 1976; Norman & Bobrow, 1975). The short-term memory hypothesis of hysteresis may illustrate the transitional period as a task moves from resource- to data-limited processing and then subsequently returns to resource-limited operation. Although Norman and Bobrow illustrated the unidirectional shift in terms of the performance-resource function, the reverse direction of this function may well be hysteretic in nature.

These findings must be viewed in light of some limitations of the study. Principal among these is

the fact that only a single direction (increasing then decreasing levels of task demand) and magnitude (a critical navigation system failure) of workload transition was examined. Because of the number of possible combinations, it was not feasible to examine other scenarios of interest (such as multiple transitions or transitions of intermediate task demand levels). Nevertheless, these scenarios deserve investigation as the effort to fully understand such hysteretic effects proceeds.

Additionally, it is reasonable to expect that some degree of task habituation may have occurred (as was evidenced by the decrease in mental workload across trials). However, the fact that the hysteretic effect in overall mental workload appeared within trials regardless of the drop in overall mental workload across trials partially offsets this concern. Finally, additional measures (such as psychophysiological measures responsive to task loading and additional performance metrics, such as lateral control measures) will be helpful in further quantification of hysteretic effects and should be considered in future research efforts.

CONCLUSIONS
AND PRACTICAL IMPLICATIONS

The question of what effects modern in-vehicle technologies have on drivers' mental workload is a common one (see Hancock, Lesch, & Simmons, 2003; Michon, 1993; Verwey, 1993). This is a critical issue, as any technology almost always brings along questions of its impact on the user (Hancock, 2009; N. Wiener, 1954). Most recently, discussion of in-vehicle displays has centered on the associated effects on driver distraction (see Hancock, Mouloua, & Senders, 2008; Regan et al., 2008). Although the widespread adoption of more modern technologies, such as in-vehicle entertainment systems and GPS navigation systems, have raised many questions about their safe usage during driving, specific questioning regarding the effect of new technologies on driver performance are actually nothing new.

Therefore, it becomes even more important to understand the nature of subjective mental workload that is associated with these added driving tasks. Any reduction in overall capacity as a result of increases in driver mental workload attributable to technology-related factors may have serious consequences for the driver and, indeed, all road

users (DeWaard, 1996; also see Kantowitz, 1992). If increased task demands (presented by the introduction of new in-vehicle technologies) coupled with an overall reduction in a driver's spare cognitive capacities (again, presented by the introduction of new in-vehicle technologies) negatively affects roadway safety, then it follows that a better understanding of workload transitions in these situations should prove beneficial.

In actuality, many automakers have attempted to define levels of workload associated with the use of these systems within their vehicles. These systems are being examined for the immediate impact on levels of driver workload (Angell et al., 2006). However, an understanding of the impact in terms of the immediate past history of the individual driver's mental workload has yet to be incorporated into such assessments, largely because hysteretic effects remain hidden to designers and manufacturers since our science has yet to feature and quantify its effects. Overall, these results point to the necessity of future investigations, including a workload history profile, especially to feature further examinations of the impact of more varied levels of task demand and scenarios.

The present results demonstrate that understanding the historical profile in addition to the present context is important in presenting information to drivers in a less taxing manner. These concepts are critical to performance and safety as the automotive industry continues to make tremendous advances in the amount of information that may be made available to the driver. Acknowledging hysteretic effects not only can have practical implications for resident in-vehicle technologies but also may apply to the devices drivers carry into the vehicle. As newer in-vehicle technologies allow for vehicle-to-mobile telephone communication, it is theoretically possible to perform similar sequencing and scaling of information presented to the driver while and immediately following critical driving maneuvers. This action may mitigate hysteretic effects that can occur following increased periods of task demand.

These systems must then carry situational context forward with the understanding that the driver has a memory not only for bits of information but also for the workload associated with their use. Therefore, it is imperative that future systems

include some manner of accommodating the immediate past as well as the immediate present demands on the driver. Such systems can provide cognitive load leveling for the driver and allow for this accommodation by scaling information presentation to not only the immediate temporal demands (e.g., whether to present an incoming call to a driver following directions from a navigation system on a busy road) but also the history of the drive (e.g., whether to present an incoming call to a driver, following directions from a navigation system on a busy road, who had just experienced a navigation system error). Future research and applications within this domain should have an immediate impact on the overall safety and efficiency of our surface transportation system.

ACKNOWLEDGMENTS

KEY POINTS

- There is a lagged recovery in levels of subjective mental workload following a reduction in task demand indicative of a hysteretic effect in subjective mental workload.
- Subjective mental workload decreased across trials; this decrease did not eliminate the occurrence of hysteretic effects in subjective mental workload.
- The hysteretic effects observed in subjective mental workload appear to be produced by the mental effort component of the Simplified Subjective Workload Analysis Technique.
- Workload histories should be taken into consideration when scaling information presentation to drivers, especially in the time immediately following a period of high task demand.

REFERENCES

Angell, L., Auflick, J., Austria, P. A., Kochhar, D., Tijerina, L., Biever, W., Diptiman, T., Hogsett, J., & Kiger, S. (2006). *Driver workload metrics Task 2 final report* (DOT HS 810 635). Washington, DC: National Highway Traffic Safety Administration.

Baddeley, A. D., & Hitch, G. J. L. (1974). Working memory. In G. A. Bower (Ed.), *The psychology of learning and motivation: advances in research and theory* (Vol. 8, pp. 47–89). New York, NY: Academic Press.

Chamberlain, G. P. (1968). *Human information processing under varying demand* (Unpublished master's thesis). University of Melbourne, Australia.

Colquhoun, W. P., & Baddeley, A. D. (1964). Role of pretest expectancy in vigilance decrement. *Journal of Experimental Psychology*, *68*, 156–160.

Colquhoun, W. P., & Baddeley, A. D. (1967). Influence of signal probability during pretraining on vigilance decrement. *Journal of Experimental Psychology*, *73*, 153–155.

Cumming, R. W., & Croft, P. G. (1973). Human information processing under varying task demand. *Ergonomics*, *16*, 581–586.

Dember, W. N., Warm, J. S., Nelson, W. T., Simmons, K. G., Hancock, P. A., & Gluckman, J. P. (1993, October). *The rate of gain of perceived workload in sustained attention.* Paper presented at the 37th Annual Meeting of the Human Factors Society, Seattle, WA.

Desmond, P. A., & Hancock, P. A. (2001). Active and passive fatigue states. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload and fatigue* (pp. 455–465). Mahwah, NJ: Erlbaum.

DeWaard, D. (1996). *The measurement of drivers' mental workload* (PhD thesis). University of Groningen Traffic Research Center, Garen, Netherlands.

Durin, G., & Zapperi, S. (2006). The Barkhausen effect. In G. Bertotti & I. Mayergoyz (Eds.), *The science of hysteresis* (Vol. 2, pp. 181–267). Amsterdam, Netherlands: Academic Press.

Farrell, P. S. E. (1999). The hysteresis effect. *Human Factors*, *41*, 226–240.

Goldberg, R. A., & Stewart, M. R. (1980). Memory overload or expectancy effect? "Hysteresis" revisited. *Ergonomics*, *23*, 1173–1178.

Hancock, P. A. (1996). Effect of control order, augmented feedback, input device and practice on tracking performance and perceived workload. *Ergonomics*, *39*, 1146–1162.

Hancock, P. A. (2009). *Mind, machine, and morality.* Chichester, England: Ashgate.

Hancock, P. A., Lesch, M. F., & Simmons, L. (2003). The distraction effects of phone use during a crucial driving maneuver. *Accident Analysis & Prevention*, *35*, 501–514.

Hancock, P. A., Mouloua, M., & Senders, J. W. (2008). On the philosophical foundations of driving distraction and the distracted driver. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver distraction: Theory, effects, and mitigation* (pp. 11–31). Boca Raton, FL: CRC Press.

Horrey, W. J., Wickens, C. D., & Consalus, K. P. (2006). Modeling drivers' visual attention allocation while interacting with in-vehicle technologies. *Journal of Experimental Psychology: Applied*, *12*, 67–78.

Huey, B. M., & Wickens, C. D. (Eds.). (1993). *Workload transitions: Implications for individual and team performance.* Washington, DC: National Academy Press.

Kantowitz, B. H. (1992). Selecting measures for human factors research. *Human Factors*, *34*, 387–398.

Kantowitz, B. H., & Knight, J. L. (1976). Testing tapping timesharing: II. Auditory secondary task. *Acta Psychologica*, *40*, 340–362.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator Sickness Questionnaire (SSQ): A new method for quantifying simulator sickness. *International Journal of Aviation Psychology*, *3*, 203–220.

Krulewitz, J. E., Warm, J. S., & Wohl, T. H. (1975). Effects of shifts in the rate of repetitive stimulation on sustained attention. *Perception & Psychophysics*, *18*, 245–249.

Luximon, A., & Goonetilleke, R. S. (2001). Improvement of the Subjective Workload Analysis Technique. *Ergonomics*, *44*, 229–243.

Matthews, M. L. (1986). The influence of visual workload history on visual performance. *Human Factors*, *28*, 623–632.

Michon, J. A. (Ed.). (1993). *Generic intelligent driver support: A comprehensive report on GIDS.* London, England: Taylor & Francis.

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource limited processes. *Cognitive Psychology*, *7*, 44–64.

Regan, M. A., Lee, J. D., & Young, K. L. (Eds.). (2008). *Driver distraction: Theory, effects, and mitigation.* Boca Raton, FL: CRC Press.

Reid, G. B., & Nygren, T. E. (1988). The Subjective Workload Assessment Technique: A scaling procedure for measuring mental workload. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 185–218). Amsterdam, Netherlands: Elsevier Science.

Scerbo, M. W., Warm, J. S., & Fisk, A. D. (1986). Event asynchrony and signal regularity in sustained attention. *Current Psychological Research & Reviews*, *5*, 335–343.

Senders, J. W., Kristofferson, A. B., Levison, W. H., Dietrich, C. W., & Ward, J. L. (1967). The attentional demand of automobile driving. *Highway Research Record*, *195*, 15–33.

Smolensky, M. W. (1990). *The effect of work load history on operational errors in air traffic control simulation: The hysteresis effect. Expectancy perseverance or short-term memory overload?* (Unpublished doctoral dissertation). Texas Tech University, Lubbock.

Stanton, N. A., Young, M. S., Walker, G. H., Turner, H., & Randle, S. (2001). Automating the driver's control tasks. *International Journal of Cognitive Ergonomics*, *5*(3), 221–236.

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone induced failures of visual attention during simulated driving. *Journal of Experimental Psychology: Applied*, *9*, 23–32.

Szalma, J. L., Warm, J. S., Matthews, G. D., William, N., Weiler, E. M., Meier, A., & Eggemeier, F. T. (2004). Effects of sensory modality and task duration on performance, workload, and stress in sustained attention. *Human Factors*, *46*, 219–233.

Verhave, T., & Herman, R. L. (1967). A hysteresis-effect with amount of reinforcement as the independent variable [Abstract]. *Psychonomic Bulletin*, *1*(2), 36.

Verwey, W. B. (1993). Effects of extended practice in a one-finger keypressing task. *Acta Psychologica*, *84*, 179–197.

Verwey, W. B. (2001). Evaluating safety effects of in-vehicle information systems. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload, and fatigue* (pp. 409–425). Mahwah, NJ: Erlbaum.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomic Science*, *3*, 159–177.

Wiener, E. L. (1977). Stimulus presentation rate in vigilance. *Human Factors*, *19*, 301–303.

Wiener, N. (1954). *The human use of human beings.* New York, NY: Da Capo Press.

Wierwille, W. W., & Eggemeier, F. T. (1993). Recommendation for mental workload measurement in a test and evaluation environment. *Human Factors*, *35*, 263–281.

Yeh, Y-Y., & Wickens, C. D. (1988). Dissociation of performance and subjective measures of workload. *Human Factors*, *30*, 111–120.

Justin F. Morgan, PhD, is a research associate with the Center for Truck and Bus Safety at the Virginia Tech Transportation Institute in Blacksburg, Virginia. He received his doctorate in applied experimental and human factors psychology from the University of Central Florida (2008).

Peter A. Hancock, DSc, PhD, is Provost Distinguished Research Professor and University Pegasus Professor in the Department of Psychology and at the Institute for Simulation and Training and the Department of Civil, Environmental, and Construction Engineering at the University of Central Florida, Orlando. He received his doctorate in motor performance from the University of Illinois (1983) and was awarded a DSc from Loughborough University (human-machine systems) in 2001.

Morgan, J.F., & Hancock. P.A. (2011). The effect of prior task loading on mental workload: An example of hysteresis in driving. Human Factors, in press.