Fatigue States are Multidimensional : Evidence from Studies of Simulated Driving

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Abstract

A recent NIOSH report on driver fatigue (Hitchcock & Matthews, 2005) discussed evidence that subjective fatigue states are multidimensional; comprised of several components. Vehicle driving may provoke different patterns of response on these components, depending on the source of fatigue, with differing implications for safety. However, existing fatigue inventories do not adequately survey these different components of fatigue state. For example, changes in the driver's cognitions of personal competence are poorly sampled by existing measures. This paper will review key findings from two recent experimental studies of fatigue (Ns = 108, 180) that used a STISIM Model 400 simulator. Building on earlier work (e.g., Matthews & Desmond, 2002), simulator drives were designed so as to induce fatigue. The first aim of these studies was to differentiate qualitatively different patterns of subjective response corresponding to 'active' fatigue (derived from prolonged high workload) and 'passive' fatigue (derived from chronic understimulation). The second aim of these studies was to explore the psychometric properties of a new multidimensional fatigue inventory developed for NIOSH. Results will be presented that support the multidimensional fatigue model, and that demonstrate the different patterns of subjective response that may be labeled as "fatigue". Methodological implications for investigating fatigue using simulator methods will be discussed.

Introduction

Fatigue is a highly elusive concept for which researchers have yet to provide a precise definition. Fatigue is difficult to define in part due to its overlap with other constructs such as stress. It may be best to conceptualize fatigue and stress as overarching umbrella terms that comprise a vast array of subjective states (Hitchcock and Matthews, 2005). Despite the ambiguity surrounding fatigue, it is a critical factor for occupational safety. Studies show fatigue to be a particularly damaging factor in vehicle driving. For example, fatigue may be implicated in approximately 15% of all fatal large-truck-related crashes (Pratt, 2003). Thus, the need to provide clarity to this vague construct is critical.

Desmond and Hancock (2001) suggested that the current meaning of fatigue might be enhanced by conceptualizing it as two distinct components: active and passive. Active fatigue may result from "overload" conditions that tax the operator's ability to maintain effortful compensation (Hancock and Warm, 1989). It is estimated that a driver must make over 1000 acceleration changes and a similar number of steering adjustments per interstate driving hour. Conversely, passive fatigue may result when the operator appears to be doing little or nothing at all (i.e., underload) (Desmond and Hancock, 2001). For example, rapid increases in automated vehicle technology such as Adaptive Cruise Control (ACC) may place drivers at an increased risk for passive fatigue. Active and passive fatigue may elicit different patterns of subjective state response. They may also have differing impacts on physical responses such as eye strain and muscle tension, as well as on drivers' cognitions. Vehicle driving may provoke different patterns of response on these components, depending on the source of fatigue, with differing implications for safety. Yet, existing fatigue inventories do not adequately survey these different components of fatigue state. For example, changes in drivers' cognitions of personal competence are poorly sampled by existing measures.

There is currently no "gold standard" for the assessment of fatigue. Evidence has been found in support of both unidimensional and multidimensional approaches (Matthews and Desmond, 1998). Some disagreement amongst researchers regarding both approaches may be due to psychometric issues. Hitchcock and Matthews (2005) proposed that the *range* of constructs sampled on different fatigue instruments is highly variable. For example, if researchers are only using items related to some form of tiredness, than one might expect a general factor to dominate. To the extent that a wider range of constructs is sampled, multiple dimensions might emerge, so that it is important to sample systematically a broad spectrum of constructs in assessment of driver fatigue.

Two studies were conducted in order to assess the impact of active and passive fatigue on subjective fatigue state. Because distress may be linked to high levels of task demand that overload attention (Matthews et al., 1999), we predicted that levels of distress would be higher with active fatigue than with passive fatigue. Conversely, we anticipated that levels of task engagement would be lower with passive fatigue than with active fatigue. The time course of fatigue was investigated on an exploratory basis, with the aim of determining whether fatigue responses reach a plateau after a given duration, or continue to rise monotonically over the durations investigated. The effects of active and passive fatigue were also investigated on an exploratory basis with factor analysis using a newly developed questionnaire to assess the impact of both manipulations on multiple components of fatigue state. Exploratory factor analysis is a procedure that assists researchers in identifying the latent constructs that may explain the covariances of a set of measured variables. This type of analysis may enable researchers to understand a pattern of correlations among variables in terms of a smaller number of fundamental underlying dimensions (Fabrigar, Wegener, MacCallum, and Strahan, 1999).

Methods

Participants

In both studies, participants were all undergraduates from the University of Cincinnati and all had a valid driver's license. In the first study, 108 participants (42 men, 66 women) took part and participants ranged in age from 18-40 (M = 19.92 years, SD = 2.65). One hundred and eighty participants took part in the second study. Participants (66 men, 114 women) ranged in age from 18-30 (M = 19.5 years, SD = 1.88).

Design

In the first study, two parameters of the simulated drive, fatigue condition and task duration, were manipulated independently to create a 3 (drive duration) x 3 (fatigue condition) between-subjects design. This resulted in nine experimental conditions (N = 12 per condition). Drive durations were 10, 30 and 50 minutes; fatigue conditions were passive and active conditions, and a control condition. For the second study, the design was nearly identical; however, the 50 minute duration was excluded. This yielded a 2 (drive duration) x 3 (fatigue condition) between-subjects design, resulting in six experimental conditions (N = 30 per condition).

Fatigue Manipulations

In the first study, all groups performed the driving task on a Systems Technology, Inc., STISIM Model 400 simulator, equipped with a 38" NEC XM3760 monitor. The simulator is programmable to create a variety of driving situations, which can produce stress and fatigue. A 36-inch NEC computer monitor was used to display the roadway and other elements of the driving task. The simulator is equipped with full-size steering and braking/acceleration controls. The steering component is capable of 360^{o} steering with speed sensitive "steering feel" provided by a computer controlled torque motor.

The road consisted of both straight and curved sections and included oncoming vehicles, but no vehicles in the driver's lane. All three drives followed the same road setting. In the active fatigue condition, simulated "wind gusts" were implemented to make the vehicle more difficult to steer and to increase the number of acceleration changes that had to be made. In the passive fatigue condition, speed and steering were under full automation. In the control drive, the participant was in full control of steering and acceleration, with no simulated "wind gusts". To ensure some task involvement in the passive fatigue condition, the driver was asked to monitor the screen and press the turn signal on detecting an occasional "automation failure." In the active fatigue and control condition, drivers were asked to drive as they would normally. The simulator was programmed with the intention of creating road geometry and background scenery that would be moderately engaging. Hills and curves were implemented throughout and visual stimuli were programmed throughout the drive to help maintain participants' attention. Visual elements included bridges, overpasses, farms, gas stations, and pedestrians.

The simulated roadway in the second study was created using System Technologies, Inc., STISIM Drive, Build 20802. The simulation was run on a Dell Optiplex GX620 PC, equipped with a 3.79 GHz processor and 2 GB of RAM. The simulation was presented to participants through a Westinghouse LVM-42w2 42-inch LCD monitor. Participants interacted with the simulation by means of a Logitech MOMO Racing Force Feedback Wheel (model 963282-0403), which includes a steering wheel capable of providing realistic feedback by means of a computer-controlled torque motor, gas and break pedals, and an adjustable car seat. In the second study, the level of background scenery and the number of hills and curves were increased in order to further enhance engagement and interest in the task. For example, the height range of hills was expanded and the driver was required to maneuver through hills and curves simultaneously. Various visually engaging events were added. For example, the driver navigated through a series of tunnels and overpasses, through a military town complete with barracks and Humvees, as well as marching soldiers. The driver also drove through busy cities with pedestrians filling the sidewalks as well as a number of subdivisions.

Questionnaires

Participants completed the pre and post-task Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999), a 96-item measure designed to assess transient states associated with stress, arousal, and fatigue, and to reflect the multidimensionality of these states. Both laboratory and field studies have shown it to be sensitive to driver stress factors (Matthews, 2002). Factor analyses revealed three second-order factors associated with task engagement (energetic arousal, motivation, and concentration), distress (tense arousal, hedonic tone, and confidence and control) and worry (self-focused attention, self-esteem, and both cognitive-interference scales). Scores on these factors are standardized; consequently, changes in state are expressed in SD units.

Participants were also administered the newly developed Driver Fatigue Questionnaire (DFQ). Items were derived from items on the DSSQ and an existing driver fatigue instrument (Matthews and Desmond, 1998), as well as by informally interviewing professional truck drivers at a truck stop in Spring Hill, Tennessee. Items were qualitatively separated into four major categories: Physical Fatigue, Tiredness-Demotivation, Cognitive-Attentional, and Coping/ Fatigue Management, following a multidimensional taxonomy of fatigue states (Hitchcock and Matthews, 2005).

Results

Psychometric properties of the DFQ

Data from both studies were pooled ($N = 288$), in order to check the psychometric properties of the DFQ. An exploratory factor analysis of the items was conducted, using the post-drive data. The scree test and Horn's (1965) parallel analyses were used as guides to determining the optimal number of factors: seven factors explaining 58.8% of the variance were extracted. An oblique rotation (direct oblimin) yielding correlated factors was employed. Factors generally conformed to expectation. The factors extracted were labeled as muscular fatigue, tiredness (sleepiness + low energy), boredom, performance impairment, confusion/distractibility, comfort-seeking and self-arousal. Factor correlations did not exceed 0.5.

Scales corresponding to the seven factors were constructed by selecting six items for each one. Coefficient alpha ranged from .83 (self-arousal) to .94 (tiredness). Alphas were also acceptable for scale scores calculated for the pre-drive data and ranged from .83 (self-arousal) to .91 (tiredness). DFQ scales showed some overlap with the general state factors assessed by the DSSQ. Post-drive boredom correlated at -.68 ($p < .01$) with DSSQ task engagement, and may be redundant with this factor. The other fatigue scales correlated negatively, but more weakly, with task engagement (range of *r*s: -.21 – -.49). Coefficient alpha measures the measurement reliability or internal consistency of the scale concerned.

Task effects: Study 1

The effects of task parameters on subjective state change during the drive were analyzed primarily in relation to the three DSSQ factors. The seven scales derived from the DFQ were also used for this purpose, but space limits preclude a full description of these analyses. Instead, we report illustrative data relating to two DFQ scales that appear distinct from overall tiredness and loss of task engagement: muscular fatigue (e.g. muscles ache, lower back is stiff and painful) and confusion/ distractibility (e.g. I catch myself daydreaming, I spend a lot of time focusing on little things I see and hear).

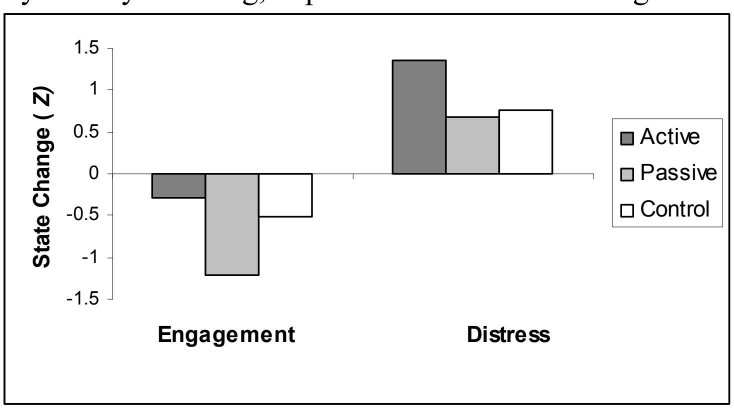

Figure 1. Changes in subjective state for active, passive and control conditions (Study 1)

In the first study, the DSSQ was administered at pre- and post-drive phases, in order to test for temporal change in subjective states. Effects of conditions on states (task engagement and distress) were then analyzed using a series of 3 x 3 x 2 (fatigue x duration x phase) ANOVAs. Interactions between phase and experimental factors indicate that state change varied across conditions. For task engagement a main effect of phase ($F(1,99) = 85.03$, $p < .01$) was moderated by phase x condition ($F(2,99) = 15.05$, $p < .01$) and phase x duration ($F(2,99) = 13.29$, $p < .01$) interactions. For distress a main effect of phase ($F(1,99) = 138.44$, $p < .01$) was moderated by a phase x condition interaction ($F(2,99) = 7.31$, $p < .01$), but the phase x duration interaction was not significant. As predicted, lowered task engagement was most strongly educed by the passive condition, followed by the control and active conditions. Furthermore, distress was highest in the active fatigue condition, as shown in Figure 1, which shows *changes* in state from pre- to post-drive (averaged across duration).

Figure 2 shows that task engagement declined rapidly over the first 10 minutes in the passive condition, followed by a more gradual decline over longer durations.

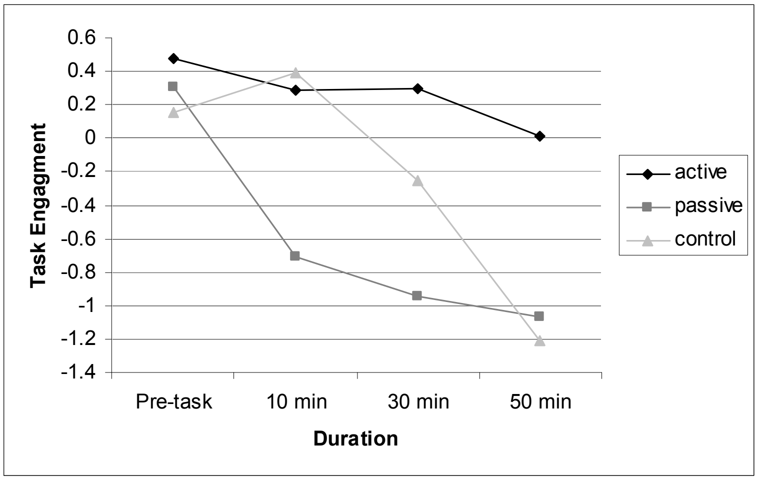

Figure 2. Level of task engagement by time and condition (Study 1)

Several DFQ scales were also sensitive to task-induced changes during the drive, exemplified here by effects on muscular fatigue and confusion/ distractibility. For muscular fatigue, a main effect of phase ($F(1,97) = 27.17$, $p < .01$) was moderated by phase x duration ($F(2,97) = 6.46$, $p < .01$) and phase x duration x condition ($F(4,97) = 6.22$, $p < .01$) interactions. In general, muscular fatigue tended to increase over time. However, in the active fatigue condition, muscular fatigue was especially high at the 30 minute duration, with a smaller fatigue increase apparent at 50 min. Possibly, drivers work hard physically to control the vehicle during the first 30 minutes, but tend to give up the attempt somewhat at longer durations.

For DFQ confusion/ distractibility a main effect of phase ($F(1,93) = 13.67$, $p < .01$) was moderated by phase x condition ($F(2,93) = 3.76$, $p < .05$) and phase x duration ($F(2,93) = 6.36$, $p < .01$) interactions. Confusion/ distractibility increased most strongly in the passive condition, to a lesser degree in the control condition, and declined slightly in the active condition. The increase in confusion/ distractibility was largest at 30 minutes.

Task effects: Study 2

In the second study, the DSSQ was administered at pre- and post-drive phases, in order to test for temporal change in subjective states. Effects of conditions on states (task engagement and distress) were then analyzed using a series of 3 x 2 x 2 (fatigue x duration x phase) ANOVAs. For task engagement a main effect of phase ($F(1, 174) = 35.19$, $p < .01$) was moderated by phase x condition ($F(2 ,174) = 4.86$, $p < .01$) and phase x duration ($F(2, 174) = 25.45$, $p < .01$) interactions. For distress, there was a main effect of phase ($F(1, 174) = 151.88$, $p < .01$), such that distress was generally elevated post-drive, but the interactions were non-significant. As with the first study, task engagement was significantly lower in the passive fatigue condition and decreased over time compared to the active and control conditions. Figure 3 illustrates the time course of task engagement for the three conditions.

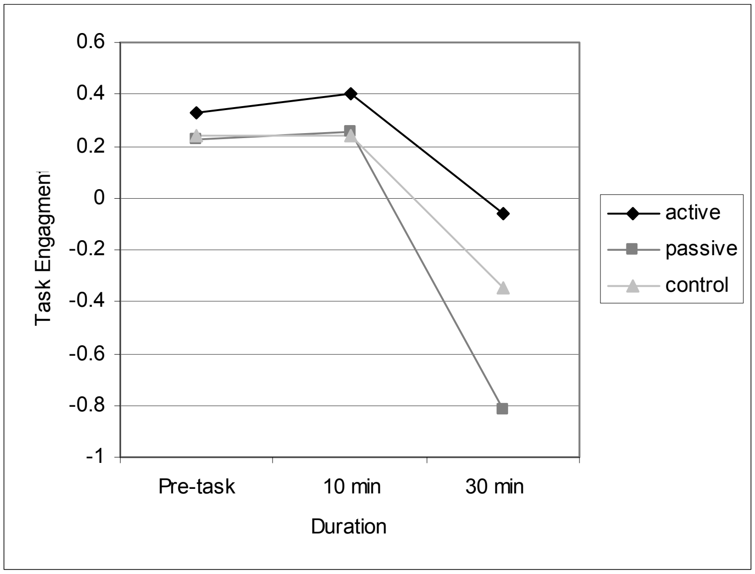

Figure 3. Level of task engagement by time and condition (Study 2)

For both studies, the DFQ was administered at pre- and post-drive phases. Again, we present illustrative data. For muscular fatigue, a main effect of phase ($F(1,169) = 20.92$, $p < .01$) was accompanied by a phase x duration ($F(1,169) = 6.99$, $p < .01$) interaction. As in Study 1, muscular fatigue was higher at 30 min than at the 10 min duration, although the effect was not further moderated by condition. For confusion-distractibility, there was no main effect of phase, but the phase x condition interaction was significant ($F(2,171) = 3.49$, $p < .05$). Similar to Study 1, confusion increased markedly in the passive condition, slightly in the control condition, and decreased in the active condition.

Discussion

The results of these studies confirm the utility of a multidimensional approach to conceptualizing and assessing subjective fatigue states. Findings show that fatigue response differs substantially according to the nature of the fatigue induction, task duration and the monotony or interest of the background scenery. The multidimensional perspective is important in several ways – for developing the theory of fatigue, refining the methodology of experimental fatigue studies, and specifying its safety consequences.

The results provide support for Desmond and Hancock's (2001) theory of active and passive fatigue. Active fatigue results from the physical demands that are imposed upon drivers such as steering and acceleration changes, whereas passive fatigue results from low workload driving tasks and monotony. While active fatigue appears to be characterized by symptoms of distress, passive fatigue appears primarily to elicit task disengagement, mental confusion and distractibility. Driving in the control conditions here also seemed eventually to produce these symptoms, but the decline in task engagement was slower to develop than in the passive fatigue conditions.

Differentiating the effects of active and passive fatigue on driver performance may be critical for enhancing road safety. Intuitively, automation may be seen a likely way to reduce workload, thereby reducing fatigue. Yet, research has demonstrated that reduced workload is not always beneficial (Funke, Matthews, Warm, Emo, and Fellner, in press). Matthews and Desmond (2002) found that drivers consistently had significant performance deterioration on straight road sections during a fatigue induction condition; however, no significant change was found for curved road sections. Fatigue may be especially dangerous in underload conditions (Hancock and Warm, 1989). In this study, the active fatigue induction appeared to elicit a stress response in which drivers were able to maintain a higher level of task engagement during a high workload task. Individuals in the passive fatigue condition were more prone to reductions in task engagement despite reduced workload. The results provide additional support for Hancock and Warm's (1989) effort-regulation model, and link underload to passive fatigue.

The studies here also have methodological implications for experimental manipulation of fatigue, and for its assessment. Generally, the data show large-magnitude differences between the various task conditions. Findings related to fatigue from different published studies may be inconsistent because of failure to control adequately for the different states that may develop in different driving scenarios. The results here may help researchers to induce the specific fatigue state of interest, to choose an appropriate task duration, and to choose an appropriate control manipulation.

The data also indicate the pivotal role of the monotony or interest of background scenery, a factor that is often not controlled explicitly in research. A recent study by Thiffault and Bergeron (2003) revealed that monotony of road environment has an adverse effect on driver performance. Monotony was varied by including either very few stimuli (only rows of trees), or by implementing intermittent background scenery. Comparison of findings from the two studies confirms Thiffault and Bergeron's (2003) observation. In Study 2, in which the scenery was enhanced, drivers seemed less vulnerable to loss of task engagement at the short, 10 min duration. However, at 30 minutes, the magnitudes of task disengagement in the passive conditions of the two studies appeared to be similar. Engaging roadside scenery may delay the onset of passive fatigue during automated driving, but eventually a large-magnitude response develops.

Results also indicate that fatigue is not just tiredness; rather, it is multi-dimensional in nature. The DFQ data offer psychometric support for Hitchcock and Matthews' (2005) multivariate fatigue taxonomy. Fatigue may be experienced not only through tiredness and sleepiness, but also through physical symptoms (muscle fatigue), cognitions (e.g., confusion/distractibility) and changes in coping (e.g., self-arousal). The DFQ may be used to further elucidate differences between active and passive fatigue.

Practically speaking, it appears that reducing workload may not be a viable way of reducing fatigue. In reality, the results demonstrate that passive fatigue may be exacerbated, which may be detrimental to performance and safety. Real-life studies seem to confirm this expectation. Nearly all studies investigating factors contributing to driver fatigue involve monotonous road environments (Thiffault and Bergeron, 2003) and/or straight roads and low traffic density (Sagberg, 1999). In addition, Meindorfner et al. (2005) investigated the phenomenon of unintended sleep episodes in patients with Parkinson's disease. Such episodes occurred most frequently in easy and monotonous driving situations. The consequences of automation also require further consideration.

Induction of passive fatigue is a likely consequence over moderate durations, even when the roadside scenery is varied. The results also indicate the different danger of active fatigue in raising distress. Drivers who are already stress-vulnerable may be adversely impacted by active fatigue (cf., Matthews, 2002). Finally, the DFQ and/or DSSQ questionnaires may be of value in monitoring fatigue in real-life driving environments.

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