

A Proposed Relationship between Time and Load to Quantify Fatigue

Shaheen Ahmed, Dept. of Computer Information Systems and Technology,
The University of West Alabama, Station 24, 109 Guy Hunt, Livingston, AL 35470, USA

Kari Babski-Reeves, Dept. of Industrial and Systems Engineering,
Mississippi State University, 260I McCain Eng. Building, Mississippi State, MS 39762, USA

Janice DuBien, Dept. of Mathematics and Statistics,
Mississippi State University, 448 Allen Hall, Mississippi State, MS 39762, USA

Heather Webb, Dept. of Kinesiology,
Mississippi State University, 121 McCarthy Gymnasium, Mississippi State, MS 39762, USA

Research has shown that both workload and time are associated with fatigue; however, a functional relationship does not exist. This study observed sixteen participants in their workplace (computer programming and simulation) to quantify the workload-time-fatigue relationship for sedentary tasks. Equal numbers of participants were observed in the morning and afternoon sessions. Workload was measured both subjectively and objectively; while fatigue was measured using the Swedish Occupational Fatigue Inventory (SOFI) and a modified Borg scale. Forward selection stepwise regression analysis was performed to determine the underlying mathematical relationship between workload, time, and fatigue. Results indicate that for sedentary tasks, fatigue is a hyperbolic function of workload and time; meaning an inherent interaction-only relationship between workload, time, and fatigue exists. Therefore, an individual can work for longer periods of time if the workload is minimal, and vice versa.

INTRODUCTION

In the United States, 38% of workers reported fatigue, and 66% of those reported health-related losses of productive time compared with 26% of those without fatigue. Workers with fatigue cost employers \$136 billion annually, which is \$101 billion higher compared with workers without fatigue (Ricci, Chee, Lorandean, & Berger, 2007). The prevalence of fatigue is growing every year. For example, in The Netherlands, 50% of women and 33% of men reported fatigue in the workplace in 2008 as compared to 38% of women and 24% of men 15 years before (Boksem & Tops, 2008).

Fatigue has been reported at the end of a regular working day, and fatigue increases over time. Duration of work-tasks or amount of hours spent in the workplace is one of the primary factors affecting reported fatigue levels (El Falou et al., 2003; Jensen, 2003; Østensvik, Veiersted, & Nilsen, 2009). Other factors, such as workload and sleep deprivation, have also been found to contribute to fatigue levels (Dorrian, Baulk, & Dawson, 2011; Guastello et al., 2013; Hancock & Desmond, 2001).

Numerous definitions and tools to measure fatigue, both subjectively and objectively, have been observed in the literature (Ahmed, 2013). Fatigue has also been observed to be measured both qualitatively and quantitatively (Ahmed, 2013). Neither a consensus definition of fatigue nor a precise method or tool for measuring fatigue has been universally adopted (Fukuda et al., 1994; Schwartz, Jandorf, & Krupp, 1993; Shen, Barbera, & Shapiro, 2006). Moreover, research describing the fundamental relationship between workload, time, and fatigue is not as clear as what factors contribute to the development of fatigue.

In the muscle fatigue literature, especially for localized fatigue, a well-accepted functional relationship exists between the endurance, time and muscle fatigue. Time interacts with load hyperbolically to affect muscle fatigue (Chaffin, 1973;

Fitts, 1994; Monod & Scherrer, 1965). The research question here is, does this relationship hold for total or overall fatigue?

Hypothesis

The mathematical relationship of the resultant interaction for fatigue is hypothesized in Equation 1.

$$xy = constant$$

Equation 1

Where,

x = time spent on work-tasks;

y = fatigue load = quantitative factors (e.g. change in resting heart rate, workload, daily sleep, etc.) that affect fatigue is defined as "fatigue load";

$constant$ = iso-fatigue constant, which is fixed for a particular situation or working condition.

METHODOLOGY

Experimental Design

An observational study in the field was performed to evaluate fatigue in prolonged, mentally demanding work tasks. However, the strategy of data collection has resulted in a repeated measure design where participants were randomly selected, and each participant was measured over a four-hour time period. A fifteen-minute break was provided in the middle of the four hours.

Independent Variable

Time was studied as an independent variable in the research. The time variable consisted of ten levels, including assessments every thirty minutes and two baseline assessments at the beginning of each two-hour session.

Dependent Variable

Multiple dependent measures, including both objective and subjective measures, were studied. The data collection, instrumentations and data cleaning procedures are discussed for each dependent variable in respective sections below. Two subjective instruments, the Modified Borg CR-10 scale (Borg Scale) and the Swedish Occupational Fatigue Inventory (SOFI), were used to measure participants' subjective perceptions of fatigue. NASA-TLX and change in heart rate were used as the subjective and objective measures of workload, respectively.

Modified Borg CR-10 scale to measure fatigue: Both the Rating of Perceived Exertion (RPE) scale and the Category Ratio (CR-10) scale have been widely used to measure both perceived exertion and overall fatigue (E. Åhsberg, Gamberale, & Gustafsson, 2000; G. Borg, 1970). A modified Borg CR-10 (modified because perceived overall fatigue was solicited instead of perceived exertion) scale was used to measure perceived fatigue every 30 minutes over a four-hour study period. A total of 10 assessments were performed including the baseline measurements at the beginning of each two-hour session before and after a short 15-minute break. Participants rated their perceived fatigue for specific body parts presented in random order. Perceived fatigue was collected for: (1) leg, (2) buttock, (3) lower back, (4) upper back (5) shoulder- neck, (6) eyes, and (7) whole body. A total fatigue score for each 30-minute block was calculated by adding fatigue ratings for each body part, including the whole body (Equation 2) (G. A. Borg, 1982; Loge, Ekeberg, & Kaasa, 1998).

$$\begin{aligned} \text{Fatigue Rating in Borg Scale (BORG)} \\ = \text{Fatigue}_{\text{leg}} + \text{Fatigue}_{\text{buttock}} + \text{Fatigue}_{\text{lower back}} \\ + \text{Fatigue}_{\text{upper back}} + \text{Fatigue}_{\text{shoulder neck}} + \text{Fatigue}_{\text{eye}} \\ + \text{Fatigue}_{\text{whole body}} \end{aligned} \quad \text{Equation 2}$$

Swedish Occupational Fatigue Inventory (SOFI): The short version of SOFI was used, and participants completed the survey every 30 minutes (Ahmed, 2013; Elizabeth Åhsberg, Garnberale, & Kjellberg, 1997). A total multi-dimensional fatigue score for each 30-minute block was calculated by adding the fatigue ratings for five dimensions of SOFI (Equation 3) (E. Åhsberg, et al., 2000; Loge, et al., 1998).

$$\begin{aligned} \text{Fatigue Rating in SOFI Scale (SOFI)} \\ = \text{Fatigue}_{\text{physical exertion}} + \text{Fatigue}_{\text{physical discomfort}} \\ + \text{Fatigue}_{\text{lack of motivation}} + \text{Fatigue}_{\text{sleepiness}} \\ + \text{Fatigue}_{\text{lack of energy}} \end{aligned} \quad \text{Equation 3}$$

Subjective measure of workload: Subjective perceptions of workload were measured using the NASA-TLX. While fatigue and workload are generally considered two distinctly different concepts, they have been found to be related in previous studies. A total workload score for each 30-minute block was measured by adding the scores for six dimensions of

NASA-TLX (Hart & Staveland, 1988). Similar studies have not identified any significant difference between weighted and un-weighted scores of NASA-TLX (DiDomenico, 2003; Ikuma, Nussbaum, & Babski-Reeves, 2009). Therefore, simple un-weighted scores were used to calculate total workload measured by NASA-TLX (Equation 4).

$$\begin{aligned} \text{Workload Rating in NASA (NASA)} = \\ \text{Workload}_{\text{mental demand}} + \text{Workload}_{\text{physical demand}} + \\ \text{Workload}_{\text{temporal demand}} + \text{Workload}_{\text{effort}} + \\ \text{Workload}_{\text{performance}} + \text{Workload}_{\text{frustration level}} \end{aligned} \quad \text{Equation 4}$$

Objective measures of workload: Change in heart rate was continuously collected over the four-hour study period (Duchon, Smith, Keran, & Koehler, 1997). A Polar RS 400 heart-rate monitor (Polar Electro Oy, Professorintie 5, FI-90440 Kempete, Finland; www.polar.fi) was used to measure heart rate continuously at a sampling rate of 1Hz. Raw heart rate data was downloaded to the Polar Pro-Trainer 5 software (Polar Electro Oy, Professorintie 5, FI-90440 Kempete, Finland; www.polar.fi) for analysis at a later time.

The heart-rate monitor was placed across the chest so that the sensor sits right of the sternum. A wrist watch was worn on either hand or placed on the working desk to minimize interference, but close enough to the chest sensor for continuous heart rate monitoring. To start the experiment, resting heart rate was calculated in a sitting position while participants were requested to sit back and relax until they reached a steady state resting heart rate defined to be 2 consecutive heart rate readings within 5 bpm. This procedure took 2 to 5 minutes. After recording resting heart rate, the heart rate wrist watch clock was started to begin the experiment. Average heart rate was also calculated during the steady state condition by collecting three heart rate readings. Change in heart rate (ΔHR) was used in all analyses. To compute ΔHR , the task heart rate was averaged for each 30-minute block and the resting heart rate was subtracted from the average, heart rate for the 30-minute block.

Participants

Sixteen self-reported healthy participants with no medical conditions (back pain, shoulder or neck pain, buttock pain, or headache) and 20/20 natural or corrected eye vision volunteered for the study. No other exclusion criteria were used. Overall demographic statistics are provided in Table 1.

Table 1. Overall demographic statistics

	Number of Subjects	Mean	Standard Deviation	Minimum	Maximum
Age (years)	16	28.69	4.43	23	39
Sleep (hours)	16	7.31	0.73	6.5	9.5
Hours worked weekly	16	46.88	8.48	30	60
Total weekly working hours in all occupations	16	56.94	10.51	35	74
End of the day fatigue	16	3.69	1.41	1	7
Monday morning fatigue	16	0.25	0.66	0	2
Weekly exercise frequency	16	2.25	1.61	0	4
Daily rest after work (hours)	16	2.44	0.61	1	3

Procedure

Each participant was given a verbal and written description of the experiment and was required to complete an Informed Consent document approved by the Institutional Review Board (IRB) for Research Involving Human Subjects at Mississippi State University. Participants were asked to complete a demographic questionnaire after the informed consent procedure (summarized in Table 1). The heart-rate monitor was then attached according to manufacturer guidelines, and a resting heart rate assessment was conducted. At each 30-minute interval within each two-hour testing block, the subjective fatigue and workload assessments were collected. After the end of the first two hours of testing, a 15-minute break was provided, and all measures were collected. Procedures for the first-two-hour test session were replicated for a second-two-hour testing session.

Data Analysis

Stepwise regression was used to determine the relationship between time, load and fatigue. A significance level for entry and significance level to stay for the stepwise procedure was set to 0.15 (Kutner, 2005). Model performance was assessed by using adjusted R^2 values and other standard criteria (Kutner, 2005). The population model used to determine the hyperbolic relationship is given in Equation 5.

$$Y = \beta_0 + \beta_1 T + \beta_2 X_2 + \beta_{12} T X_2 + \varepsilon \quad \text{Equation 5}$$

Where,

Y = Perceived fatigue measured either in Borg or SOFI;
 β_0 = Intercept; β 's = parameters; T = Time, the running clock during the experiment; X_2 = A factor that causes fatigue, for example workload; ε = Error $\sim N(0, \sigma^2)$, independent and identically distributed.

RESULTS

Based on the previous literature, it was hypothesized that workload, time and fatigue follow a hyperbolic functional relationship. To investigate this inherent relationship, stepwise regressions were performed using time, workload (increase in heart rate and workload measured in NASA-TLX) and their interaction as predictors of fatigue.

Table 2. Summary of stepwise regression

Variable Entered	Model R^2	F Value	Pr > F
Borg T*NASA	0.43	118.40	<0.0001
Borg T*ΔHR	0.39	100.16	<0.0001
SOFI T*NASA	0.26	56.50	<0.0001
SOFI T*ΔHR	0.35	83.88	<0.0001

T=Time in minutes, NASA=perceived workload measured in NASA-TLX and ΔHR=change in resting heart rate.

The stepwise regression analysis results are given in Table 2 and Table 3. Only the interaction term between time and a factor (e.g. workload) that causes fatigue was kept by the stepwise regression analysis in all four cases (Table 2). Table 3 shows the parameter estimates and the associated statistical

tests. All interaction terms were observed to be significant with p-value ranges between 0.02 and less than 0.0001.

Table 3. Parameter estimates from the stepwise regression

	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F	
Borg	Intercept	2.122320	0.62277	315.05	11.61	0.0000
	T*NASA	0.001670	0.00015	3211.99	118.40	< 0.0001
Borg	Intercept	2.156460	0.66039	309.70	10.66	0.0000
	T*ΔHR	0.003270	0.00032	2909.16	100.16	< 0.0001
SOFI	Intercept	1.516660	0.46807	160.89	10.50	0.0000
	T*NASA	0.000869	0.00012	865.86	56.50	< 0.0001
SOFI	Intercept	0.995270	0.45173	65.97	4.85	0.0300
	T*ΔHR	0.002050	0.00022	1139.89	83.88	< 0.0001

T=Time in minutes, NASA= workload measured in NASA-TLX, and ΔHR=change in resting heart rate averaged over each assessment period.

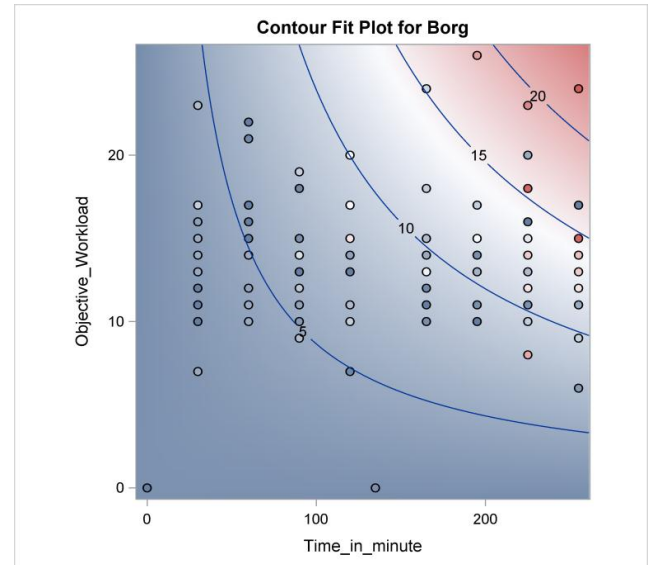


Figure 1. Visualization of the proposed hyperbolic relationship between the workload measured by change in resting heart rate and time to measure fatigue by Borg.

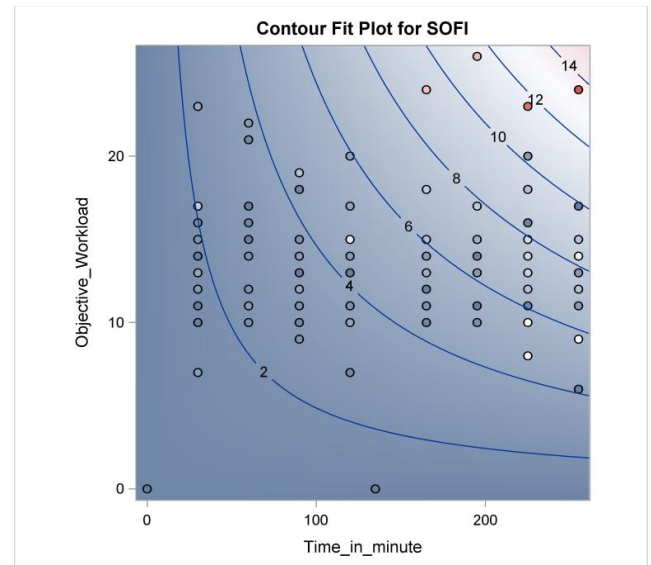


Figure 2. Visualization of the proposed hyperbolic relationship between the workload measured by change in resting heart rate and time to measure fatigue by SOFI.

In Figure 1, Figure 2, Figure 3 and Figure 4, the color gradient on the response surface represents the increase in fatigue from blue to red. The stronger contrast between the color of the fitted surface and an observation indicates a higher residual at that point. The lines on these figures represent iso-fatigue curves; meaning that, for a particular combination of time and workload (measured either subjectively or objectively), fatigue will be constant. Only one fatigue value is perceived on a specific hyperbolic curve in the figures. All these figures indicate a perfect hyperbolic relationship as it has been observed in the stepwise regression analysis.

DISCUSSION

As expected, this study observed that fatigue increased over time. Interestingly, in the stepwise regression analysis process, time significantly interacted with workload in the study, indicating that the time trends in the fatigue measures are dependent on other factors. Similar to localized muscle fatigue curves (Rohmert's curves) (Edwards, 1981; Hill, Poole, & Smith, 2002; Monod & Scherrer, 1965), previous studies have hypothesized that there could be a possible hyperbolic relationship between time and workload (El Falou, et al., 2003; Jensen, 2003; Østensvik, et al., 2009). Moreover, in physical ergonomics, the standardized weight limits over time for manual material handling also provide an indication of the hyperbolic relationship proposed in this study (Snook & Ciriello, 1991; Snook & Irvine, 1969). For example, the standardized data cleaning process for repeated measure cortisol hormone using the area under the curve over time (Pruessner, Kirschbaum, Meinlschmid, & Hellhammer, 2003), which is basically the interaction between cortisol response and time that explains total fatigue.

This study has utilized two factors, including (1) change in resting heart rate and (2) workload measured by NASA-TLX, separately with time to determine the hyperbolic relationship between workload and time that explains total (overall) fatigue. In both cases, the only term left in the stepwise regression process was the interaction term, which could justify the possible hypothesized hyperbolic relationship between a workload and time to measure total fatigue. The estimated parameters were highly significant with R^2 values ranging from 0.22 to 0.43. For a single variable to explain human fatigue, R^2 values could be considered good because of the complex nature of fatigue caused by many intrinsic and extrinsic factors (Di Milia et al., 2011).

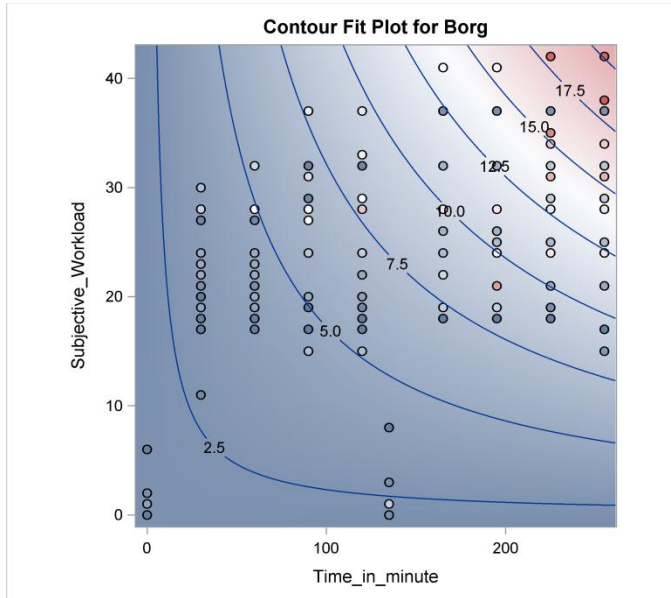


Figure 3. Visualization of the proposed hyperbolic relationship between the workload measured by NASA_TLX and time to measure fatigue by Borg.

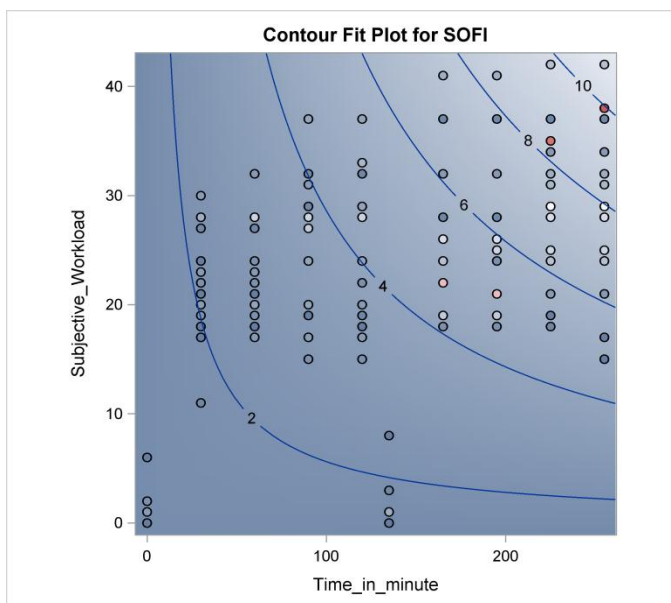


Figure 4. Visualization of the proposed hyperbolic relationship between the workload measured by NASA_TLX and time to measure fatigue by SOFI.

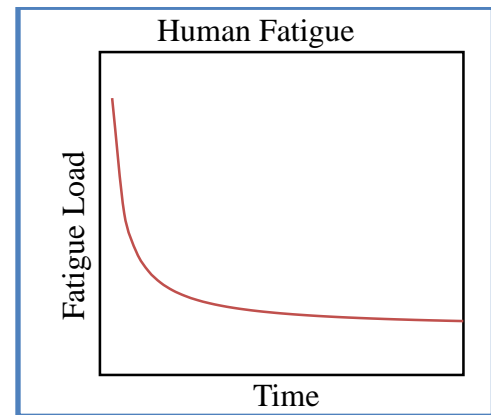


Figure 5. The proposed hyperbolic relationship between the workload and time to explain fatigue.

In this study, more interestingly, the asymptotes parallel to both axes indicate that an individual would not report fatigue for a long period of time if there were no workload. In contrast, an individual would report fatigue within a very short period of time if the workload were too high for that person. The observed hyperbolic relationship could be elaborated on

as “the higher intensity of a workload induces fatigue quicker and vice versa.” The relationship is depicted in Figure 5.

CONCLUSION

This study has utilized both subjective and objective measures of workload. Moreover, the perception of fatigue was obtained using single-dimension Borg and multi-dimensional SOFI scales to test the hypothesized mathematical relationship between workload and time that could be useful to measure fatigue in the workplace.

The findings of this study suggest that workload and time significantly interact to affect fatigue. Future studies should focus on these interactions, not just the time effect alone, because the main effect becomes less relevant when a significant interaction is presented.

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