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Sleep Deprivation Effect on Human Performance: A Meta-Analysis Approach

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SUMMARY/ABSTRACT

Human fatigue is hard to define since there is no direct measure of fatigue, much like stress. Instead fatigue must be inferred from measures that are affected by fatigue. One such measurable output affected by fatigue is reaction time. In this study the relationship of reaction time to sleep deprivation is studied. These variables were selected because reaction time and hours of sleep deprivation are straightforward characteristics of fatigue to begin the investigation of fatigue effects on performance.

Meta-analysis, a widely used procedure in medical and psychological studies, is applied to the variety of fatigue literature collected from various fields in this study. Meta-analysis establishes a procedure for coding and analyzing information from various studies to compute an effect size. In this research the effect size reported is the difference between standardized means, and is found to be -0.6341, implying a strong relationship between sleep deprivation and performance degradation.

INTRODUCTION

Fatigue degrades human performance. The degree to which fatigue affects an individual can range from slight to catastrophic. Unlike alcohol or drugs which can be detected by biochemical tests, fatigue is more difficult to prove as a cause of accidents and is typically inferred from the context of the situation. Despite this limitation, increasingly, fatigue has been claimed as the primary cause of many major accidents. For example, the incidents of Bhopal, Exxon Valdez, Three Mile Island, and Chernobyl list fatigue as a root cause [17]. Reason [18], states that fatigue causes the reverse of the learning process – it moves decision making from skill based to knowledge based; fatigue causes people to rely more on their working memory rather than on their long term memory for task completion. Fatigue first affects speed, then economy of action – fatigued workers work harder with lower performance [18]. The qualitative relationship between fatigue and performance is intuitively understood, but the quantitative relationship is not adequately defined or presented in a format that is readily usable by the HRA analyst.

Fatigue research has been conducted in a wide range of fields such as transportation (ground and aviation), military, academia, and medicine. Commercial aviation has strict limitations on hours worked [12]. Unfortunately other industries that impact public safety such as ground transportation [5, 8], medicine, and nuclear power plants [16] do not have such limitations enforced or even established. An attempt to better illustrate the effects of fatigue on performance has been conducted through several studies comparing sleep deprivation to blood alcohol content (BAC %) in affecting performance [23]. There are many quality studies being conducted in above mentioned various fields, but a methodology to combine this information in a reproducible manner for use in HRA is not yet established.

In this study the data collected from military, medical, transportation, and psychological literature is analyzed using the meta-analysis procedure to begin to quantify the relationship between fatigue and performance. Meta-analysis creates a structured format through statistical procedures and a coding manual to extract information from selected studies for the purpose of synthesizing the findings. The empirical findings from the various studies are converted to a standardized *d*-index effect size, calculated by using Eq.1-5. An effect size is a non-dimensionalized variable that is compared across studies to provide insight into the strength of the relationship under investigation. The effect size represented by the standardized difference between the means, see Eq. 1-4. The meta-analysis method was chosen in part because there is a large body of research on fatigue that comes from a myriad of disciplines and industries that needs to be combined to make statistically significant conclusions. But more importantly, meta-analysis provides a way to combine the data from different studies and industries and compare them on an even plane by converting the empirical findings to a standardized statistic, the effect size, to compare across all selected studies.

A simplified model of fatigue, one input (sleep deprived vs. non-sleep deprived - a binary variable) and one output (reaction time - a continuous variable), was used to explore the application of meta-analysis to the fatigue literature. Seven studies were selected from the fatigue literature and analyzed according to the meta-analysis procedure.

NOMENCLATURE

$$ES_{sm} = \frac{(X_1 - X_2)}{s_{pooled}} \qquad \text{Eq. 1}$$

$$ES_{sm} = \sqrt{\frac{F(n_1 + n_2)}{n_1 n_2}} \qquad \text{Eq. 2}$$

$$ES_{sm} = t\sqrt{\frac{(n_1 + n_2)}{n_1 n_2}} \qquad \text{Eq. 3}$$

$$ES_{sm} = 2\sqrt{\frac{\chi^2}{N-\chi^2}} \quad \text{Eq. 4}$$

$$s_{pooled} = \sqrt{\frac{(n_1-1)s_1{}^2+(n_2-1)s_2{}^2}{n_1+n_2-1}} \quad \text{Eq. 5}$$

Where,

ES_{sm}	=	standardized mean difference effect size
X_1	=	mean of control
X_2	=	mean of test
n_1	=	control sample size
n_2	=	test sample size
N	=	total sample size
t	=	t-test value
F	=	F-test value
s_{pooled}	=	pooled sample variance

$$HEP = NHEP \bullet PSF_{composite} \quad \text{Eq. 6}$$

Where,

HEP	=	human error probability
NHEP	=	nominal human error probability
$PSF_{composite}$	=	pooled performance shaping factor (PSF) weight from eight PSFs

Equations 1-5 are taken from reference [14] and equation 6 is taken from reference [10].

PRVEIOUS WORK

Current human reliability analysis (HRA) methods are lacking in detail and strength in the quantitative relationships between performance shaping factors (PSF) and human performance. In order to improve the reliability of HRA methods, a larger knowledge base for quantitative relationships needs to be established; an example of this endeavor is the Human Event Repository and Analysis (HERA) database that is being developed by the Nuclear Regulatory Commission in conjunction with INL. Specific PSFs, such as fatigue, need to be examined along with a method of populating the HERA database to include data from other industries

HRA methods such as SPAR-H [10], assume fatigue to be covered under the Fitness for Duty performance shaping factor. SPAR-H calculates human error probability by multiplying the nominal error probability (1.0E-2 for diagnosis and 1.0E-3 for action) by weights associated with the level of influence from the eight PSFs of SPAR-H, see Eq. 6. The weights for each of the eight PSFs are combined in a multiplicative way to produce the $PSF_{composite}$. The PSF for Fitness for Duty is broken down into three levels in SPAR-H, *unfit* (which gives a guaranteed probability of human failure of one), *degraded* (weight of 5), and *nomina*l (weight of 1), with the additional option of selecting the category of insufficient information (weight of 1). This does not adequately reflect the impact of fatigue on worker performance. These three levels of duty fitness were initially designed for chemically induced impairment, not impairment due to fatigue. The NRC has recognized that fatigue is an important component to safe operations and is in the process of adapting their Fitness for Duty guidelines to be more inclusive of fatigue effects and not just chemical impairment. The negative effects of fatigue need to be better understood and represented in the HRA methods. A refinement in HRA is needed to model facilitate the inclusion of the quantitative and qualitative aspects of fatigue effects. This will lead to an improvement in HRA methods resulting in better probabilistic risk assessment, PRA, outcomes. An improved PRA will allow for an increased understanding of the safe operating bounds of human behavior in the twenty-four-hour economy world.

There is no universal testing procedure to study fatigue. Each study is inherently different, in regards to the sample studied. Studies are typically either conducted in a laboratory or simulator setting or are retrospective analysis of real incidents. Sleep deprivation is achieved by keeping the subject awake for a minimum of sixteen hours. Different measures of performance are employed and most studies look at multiple measures of performance. These performance measures are studied as either: subjective, behavioral, or physical measures. The subjective measures, such as the Karolinska Sleepiness Scale (KSS) [1, 15] or Stanford Sleepiness Scale (SSS) [13, 21] or some type questionnaire [3], are mostly used for validation that fatigue has been achieved in the subject through the manipulation of sleep deprivation. Studies also look at physiological measures. These range from blink rate readings [7] to positron emission tomography (PET) scans [21] and magnetic resonance imaging (MRI) images of the brain [7]. Behavioral effects of fatigue are measure through a variety of means such as; dual task [23], spatial memory [23], addition/subtraction [21], signal detection [3], and reaction time [3, 6, 7, 13, 21, and 23].

Since fatigue is being studied and reported in a wide variety of formats and industries, the meta-analysis research synthesis procedure is used to discover the underlying trends by integrating the analysis results from individual studies to be able to make significant conclusions. This method of analysis is especially useful for studying humans, since human behavior is not easy to control for study purposes nor does a single study provide sufficient information on which to base policy. This will be a novel application of the meta-analysis procedure to fatigue literature for use in HRA.

The following sections give a brief explanation of the meta-analysis concept and procedures, the rationale for the fatigue model selected for study, information on the studies selected, the results of the meta-analysis, and the implications of the findings.

PROPOSED METHODOLOGY

Meta-analysis is a synthesis of available literature about a topic. It creates a structured format, through statistical procedures and a coding manual to extract information from selected studies for the purpose of synthesizing the findings. It is not a literature review, nor is it a vote counting method of available research. The term meta-analysis was coined by Glass in 1977 with respect to psychotherapy [20]; Glass's study was the beginning of a now common practice of using quantitative synthesis techniques in social science. The idea of combining results from multiple studies was not originated by Glass, but was first introduced by Pearson in the early 1900's. In meta-analysis the effect size is compared as a dependent variable across different studies. The effect size is the degree to which the phenomenon under investigation is present in the population, it can also be thought of as the degree of difference from the null hypothesis, where the null hypothesis is that there is no effect.

The effect size is calculated from the empirical findings from various studies which can be represented by different statistics, such as means and standard deviations, ANOVA results, *t*-test statistic, and Chi-square statistic. In order to compare the research findings from different studies the statistical information reported in the original study must transformed to a non-dimensionalized numeric. This computation is done by employing a variety of mathematical relationships depending on the statistical information reported in the original study. For example, if the original findings are reported in means and standard deviations as they are in reference [15], first Eq. 5 is used to calculate the pooled standard deviation from the two groups and then Eq. 1 is used to calculate the *d*-index. This creates a standardized mean difference effect size between the two sample groups. As another example, if means and standard deviations are not reported but instead an *F*-statistic is reported [3], Eq. 2 is used to create the non-dimensionalized *d*-index effect size. Now that the original statistical data from [3] and [15] has been transformed into *d*-index effect sizes they can be compared.

There are five basic steps in the meta-analysis procedure: formulating the problem, collecting data, evaluating the data, analyzing the data, and then reporting the findings. The first step is to formulate the problem and define the hypothesis under investigation. This helps to define the preliminary bounds on the literature search and to identify the variables of interest. The next step is collecting the data. This involves defining a search strategy and establishing study criteria; these help to limit or define the "universe" from which the studies are drawn. The following step is evaluating the data. This involves developing a coding manual for recording information from the studies. This includes: study descriptors, methods and procedures, and effect sizes reported in their original format. The next step is analyzing the data; this involves converting effect sizes from studies which passed through the previous selection process from their original reported format to a standard statistic such as *r*-index or *d*-index. And the final step is reporting the findings.

The hypothesis under investigation is how fatigue, produced by circadian influence, sleep deprivation, and hours worked, affects human performance. For this study a simplified model of fatigue effects on performance was investigated using the meta-analysis procedure; the binary condition of sleep deprivation vs. non-sleep deprivation was used as the test condition; the sample could either be sleep deprived (test condition) or not (control). The effect of sleep deprivation on changes in reaction time, an example of a simple cognitive function, was explored. To do this a small sample of studies, five studies for effect size magnitude and seven studies for direction of effect size, were used for a feasibility study of the application of meta-analysis to human performance data for the purpose of informing the HRA process.

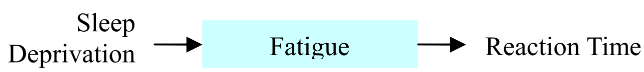

Figure 1. One Input - One Output Model of Fatigue

The studies used for this example were collected from several different disciplines and journals. These included*:* *Journal of Sleep Research* [15, and 21], *Journal of Neuroscience* [6], *Behavior Research Methods*, *Instruments, & Computers* [3], *NeuroImage* [7], *Occupational Environmental Medicine* [23], and *Organizational Behavior and Human Decision Processes* [13]. Five of the studies were laboratory experiments, while one (reference [13]) was conducted in the field during Royal Norwegian Naval Academy cadet training.

The studies were selected because they reported a numerical relationship between sleep deprivation and reaction time and met pre-established selection criteria; to be included the studies must: (1) report a quantitative relationship between sleep deprivation and reaction time, (2) be conducted post WWII, and (3) be reported in English (due to limitations of the researcher). The mechanics of inducing sleep deprivation were not explored at length in this example; the main focus was the relationship between reaction time and sleep deprived versus non-sleep deprived subjects. Reaction time was measured by different methods in the seven studies. Several studies reported multiple measures under the general heading of reaction time [3, 7, 13, 18, and 21], such as time on task, accuracy, and a correlation between accuracy and time on task. Each of these relationships produced an effect size for evaluation.

The meta-analysis of the seven fatigue studies are expected to show the amount of change in reaction time, expressed through the standardized mean difference, which is the standard score equivalent to the difference between the means, that sleep deprivation moves reaction time from the baseline reaction time (non-sleep deprived). Table 1 summarizes the data for meta-analysis from the various studies. In Table 1, study [6] reported the change in reaction time variability between the sleep deprived group and the non-sleep deprived group as a *t*-statistic, which implies the hypothesis that the sleep deprived group requires more time and effort for task completion is correct. In study [3] the changes in performance over different task blocks were reported as *F*-statistic. While in study [13] the reported *F*-statistics represented the change in planning time for rescue scenarios and the number of procedural errors between the sleep deprived and non-sleep deprived groups. The reporting of a chi-square statistic in study [13] implies that

Table 1. Statistical Information and Effect Size Results

Study Ref #	Variable	Stat info	$M_{Control}$ (SD)	M_{Test} (SD)	Test Stat Info	$n_{control}$	n_{test}		ES d-index	Direction
	Speed									
15	Speed (ms)	means & SD	225 (43.44)	265 (62.35)	-	11	11	2GC[2]	-0.7444	Worse
21	Speed (response/min)	means & SD	61.4 (24.6)	71 (27.2)	-	17	17	RM[3]	-0.3702	Worse
7	Speed (ms)	means & SD	552 (149)	668 (182)	-	12	12	RM	-0.6974	Worse
7	Speed (ms)	means & SD	588 (162)	746 (271)	-	12	12	RM	-0.7077	Worse
7	Speed (ms)	means & SD	617 (233)	718 (245)	-	12	12	RM	-0.4225	Worse
23	Speed (ms)	means no SD	489	540	-	39	39	RM	NA	Worse
6	RT[1]- variability	t-test	-	-	$t(13) = 2.2, p<.05$	13	13	RM	-0.8629	Worse
13	planning time	F-test	-	-	$F(1,89) = 71.12, p<.01$	21	69	2GC	-2.1018	Worse
	Accuracy									
21	% correct	means & SD	92.3 (6.4)	95.5 (5.2)	-	17	17	RM	-0.5488	Worse
21	# correct/min	means & SD	57.5 (25.2)	68.3 (27.3)	-	17	17	RM	-0.4111	Worse
23	# misses	means no SD	0.36	3.1	-	39	39	RM	NA	Worse
3	# correct vs. incorrect	F-test	-	-	$F(8,40) = 37.55, p<.001$	-	-	-	NA	Worse
3	# correct/min	F-test	-	-	$F(8,40) = 35.03, p<.001$	-	-	-	NA	Worse
13	procedural errors	F-test	-	-	$F(1,88) = 5.34, p<.05$	21	69	2GC	0.5758	*Better*
13	critical EoO[4]	Chi-Square	-	-	$\chi^2(1,89) = 9.43, p<.01$	21	69	2GC	-0.6842	Worse

Mean ES	-0.6341

RT[1] Reaction time
2GC[2] Two group comparison (2GC) experimental condition
RM[3] Repeated measures (RM) experimental condition
EoO[4] Error of Omission
Control Non-sleep deprived
Test Sleep deprived

more sleep deprived than non-sleep deprived cadets then expected by chance committed a critical error of omission by failing to ask for critical information on the missing soldier.

RESULTS

Table 2 shows the results of the effect size calculations. The intuitive belief that fatigue negatively influences performance was supported by the result of a negative effect for the relationship of sleep deprivation to reaction time. A cumulative effect size of -0.6341 was found, as shown in Table 2. This result came from fifteen test variables of reaction time, which came from seven studies from different fields such as medicine, military, and psychology.

The effect size was calculated using Eq.1-4, depending on the statistical information provided in the study. The effect size (ES) calculated from the standard mean difference indicates a difference between the sleep deprived population and the non-sleep deprived population in reaction time. Thus an ES of -0.6341 indicates that the sleep deprived population is 0.6341 standard deviations worse off on mean reaction time than the non-sleep deprived population.

An effect size from studies [23] and [3] could not be calculated because of the limitation on the statistical information that was reported in the original study; however the information from these studies was used to determine the direction of the effect. Study [23] did not report the standard deviation information while an effect size from study [3] was not able to be calculated due to the results being reported as a group F factor; to calculate an effect size we need a one-way ANOVA.

It is also possible to break down the results under the general heading of reaction time to the specific quantities that were measured: speed (e.g., responses per second) and accuracy (e.g., number of correct responses). The results for these individual measures are shown in Table 2. For tests that measured reaction time in terms of speed the ES_{Speed} was -0.8438. For studies that tested reaction time in terms of accuracy the $ES_{Accuracy}$ was -0.2671. Comparison of standard deviations corresponding to these two individual effect sizes and cumulative effect size indicates that there is similar scatter in measuring the cumulative ES, ES_{Speed}, and $ES_{Accuracy}$.

The cumulative ES has a ninety-five percent confidence interval (95% CI) of (-1.0016, -0.2667), which does not include zero, as seen in Table 2. This strengthens the conclusion that there is a significant negative effect across studies in relating sleep deprivation to reaction time. When the reaction time is broken down into the sub-groups of speed and accuracy, the effect size for speed, ES_{Speed} 95% CI (-1.2752, -0.8285), excludes zero, however the effect size for accuracy, $ES_{Accuracy}$ 95% CI (-0.8285, 0.2943), encompasses zero. This is not surprising, since $ES_{Accuracy}$ includes one study with a positive effect size.

Table 2. Individual Reaction Time Variables: Speed, Accuracy, and Speed vs. Accuracy Effect Size Results

Summary	Cumulative ES	ES_{Speed}	$ES_{Accuracy}$
N for ES =	11	7	4
mean =	-0.6341	-0.8438	-0.2671
# +, # -	1+, 14-	0+, 8 -	1+, 6 -
σ =	0.6218	0.5823	0.5729
95% CI =	(-1.0016, -.2667)	(-1.2752, -0.8285)	(-0.8285, 0.2943)
range (min, max) =	(-2.1018, 0.5758)	(-2.1305, -0.3702)	(-.6842, 0.5758)
Stand. Error of ES =	0.1875	0.2201	0.2864

Further research is necessary to determine how human reliability analysis can use this type of quantitative relationship between sleep deprivation and reaction time when calculating error probabilities. This information might also be used to alter the weights and levels in the closed form PSF worksheets of SPAR-H or at least to consider selecting the appropriate degraded condition when even moderate sleep deprivation is involved. Also these results can be used by the HRA community when using ATHEANA to highlight the error forcing context of sleep deprivation. The initial results show that sleep deprivation is related to significant changes in speed (-0.8438) and accuracy (-0.2671) on simple reaction tasks. Though self-motivation might help to overcome the effects of fatigue on higher level cognitive function, this detrimental relationship between sleep and reaction time needs to be considered when analyzing error forcing situations.

CONCLUSION

The meta-analysis shows a strong relationship between sleep deprivation and reaction time in the negative direction. Both speed and accuracy are decreased in sleep-deprived conditions compared to non-sleep deprived conditions; the evidence is much more conclusive with respect to speed than accuracy.

For future application of meta-analysis to the fatigue literature a more complex model of fatigue will be used. This fatigue model will have three main inputs: sleep deprivation, hours worked [1, 16], and circadian influence [2, 22]; and the effects of fatigue on performance will be measured through three groups of measures: physical (e.g. blood pressure), subjective (e.g. self-completed questionnaires), and psychological performance tests (e.g. reaction time). This way the relationships between performance measures and sleep deprivation, hours worked, and circadian influence can be calculated. Another important future use would be to establish a framework to extract information from medical, military, psychology, and other industries for use in HRA databases such as HERA, for use in the nuclear power industry.

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