MEASURING AND MANAGING CONSTRUCTION WORKER FATIGUE

by

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A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF CIVIL,
ENVIRONMENTAL, AND ARCHITECTURAL ENGINEERING
AND THE COMMITTEE ON GRADUATE STUDIES OF THE
UNIVERSITY OF COLORADO BOULDER
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
DEGREE OF DOCTOR OF PHILOSOPHY

April 2017

This dissertation entitled:
Measuring and Managing Construction Worker Fatigue
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has been approved for the Department of Civil, Environmental, and Architectural Engineering

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The final copy of this dissertation has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above-mentioned discipline

IRB protocol # 160354

ABSTRACT

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Measuring and Managing Construction Worker Fatigue

Dissertation directed by: Professor. Matthew R. Hallowell

The construction industry presents a fatality rate three times greater than the average considering all industries. Electrical transmission and distribution work presents one of the highest fatality rates inside the construction industry. Such accidents come at a great economic and social cost. Decades of accident causation research demonstrate that organizational and human factors, rather than technical failures, are the principal causes of accidents. Fatigue showed to be a significant trigger to human error, accident causation, and a bundle of other safety risks. This dissertation represents the first research effort to meta-analyze the causes and consequences of occupational fatigue and address the way in which fatigue can be identified, predicted and managed for electrical transmission and distribution (TD) workers. Over the course of a year and a half, a total of 343 TD workers, distributed across the US, participated in interviews, surveys, and tests to accomplish the purpose of this dissertation. Additionally, a group of 52 general construction (GC) workers also took part in the data collection process. The data was coded and analyzed applying several statistical methods such as: Meta-analysis, Chi-square test, Proportion test, Correspondence analysis, and Multiple Linear Regression. The results identified 9 of the principal causes and 5 of the most relevant consequences of occupational fatigue together with their relative impact. Furthermore, extreme temperatures and long shifts where identified as the major causes for TD workers´ fatigue and loss of attention and slowing down were recognized as significant consequences of fatigue among TD workers. Additionally, current fatigue identification and management techniques where documented. Lastly, fatigue predictive models for TD workers and GC workers were created based on empirical data collected in the field. The level of predictability of these models was low to medium, indicating that additional predictors need to be identified. Fatigue predictors, as measured by two of the most reliable and valid tools to objectively and subjectively assess fatigue, showed to vary between TD and GC workers. However, sleep deprivation showed to be a common predictor. Future research should engage in the strengthening of these models as well as the study of fatigue among other trades.

DEDICATION

To my parents, Lucía Rocha and Daniel Techera, for showing me the value of obtaining knowledge, for their example of hard work, and for their unconditional and tender love. To my grandparents, Walter Techera, Irma Mederos, Sixto Rocha, and Dinorah Morales, for their encouragement to achieve high goals. To my dear and beloved wife, Mary Techera, for her support, help, patience, and love during this challenging journey. To my son, Walter Ulises Techera, who filled my arms with love and always waited anxiously for my return. To my sons and daughters to come, as a testimony that with hard work and the guidance of people who trust you, any goal can be achieved in life. Additionally, to my beloved little sisters, Rafaela and Niza Techera, who by looking up to me pushed me to reach farther. Last but not least, to my Heavenly Father, who sustains me every day and watches over me.

Para mis padres, Lucía Rocha y Daniel Techera, por haberme mostrado la importancia de obtener sabiduría, por su ejemplo de trabajo arduo, y por su amor tierno e incondicional. Para mis abuelos, Walter Techera, Irma Mederos, Sixto Rocha, y Dinorah Morales, por darme aliento para alcanzar elevadas metas. Para mi querida y amada esposa, Mary Techera, por su respaldo, ayuda, paciencia, y amor durante este desafiante camino. Para mi hijo, Walter Ulises Techera, quien llenó mis brazos de amor y siempre esperó ansioso por mi regreso a casa. Para mis futuros hijos e hijas, como testimonio de que con esfuerzo y el apoyo de gente que confía en ti, cualquier meta puede lograrse en la vida. Adicionalmente, para mis queridas hermanas, Rafaela y Niza Techera, quienes al mirar hacia mí por un buen ejemplo me han animado a llegar más lejos. Por último, para mi Padre Celestial, quien me sostiene y cuida cada día de mi vida.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor Dr. Matthew R. Hallowell for trusting me even before we met. For his exemplary guidance, his constant support and encouragement, his words of wisdom delivered at the right time, and for always being by my side.

Also, I must express my gratitude to Dr. Ray Littlejohn for his friendship, constant advice, and support during countless hours of statistical analyses. For lighting in me a passion for statistics and for helping me understand fundamental concepts.

Moreover, I desire to acknowledge Dr. Sathyanarayanan Rajendran, who also went far beyond his duties as a committee member and offered immense help to collect data. I would have not accomplished such a populated and diverse sample without his help.

In addition, I must acknowledge Dr. Goodrum, who allowed me to use his computers to collect data for several months, and for his exemplary teaching. I would have not achieved this goal without his help.

Likewise, I wish to express my gratitude to Dr. Eric Marks, who helped me broaden the perspective of my research and gave me important conceptual guidance when I needed it.

I also wish to acknowledge the industry leaders and workers who gave their time, effort and support to collect the data that is the basis of this research. Their contribution makes this all possible.

Last but not least, I appreciate the example, support, help, and friendship of all my fellow students who were always present when I needed them the most.

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Chapter 1: Introduction

1.1Background and Motivation:

The construction sector is one of the most hazardous and deadly of the industry (Sawacha et al. 1999). According to the U.S. Bureau of Labor Statistics (2015) in 2014 there were a total of, 4,679 fatal work injuries, which equates to an all-industry and government jobs fatality rate of 3.3 fatalities for every 100,000 full-time equivalent workers (FEW). That same year, the construction industry showed a fatality rate of 9.4 for every 100,000 FEW; thus, presenting a fatality rate nearly 3 times greater than that of the overall working population. Three of the ten most dangerous jobs in the U.S. belong to the construction industry revealing its dangerous nature. From these 3 occupations, Electrical Transmission and Distribution workers (TD workers) experienced 19.2 fatalities for every 100,000 FEW during the year 2014. Furthermore, the average fatality rate for this sector of the industry over the last 20 years is 26.1 fatalities every 100,000 FEW. These statistics indicate that TD work is between 6 and 8 times more deadly than the average considering all other professions (U.S. Bureau of Labor Statistics 2015). Unfortunately, construction related accidents don’t only affect construction workers but also the public in general. In the U.K. on average, every month a member of the public is killed and 1200 people are injured as a consequence of a construction related accident (Sawacha et al. 1999).

Construction accidents come at a great economic cost for both the industry and society. Considering direct costs (medical cost), indirect costs (wages and household productivity), and the quality of life costs due to injury, the average construction fatality was estimated to cost $4 million. Regarding non-fatal accidents, the average injury with days away from work was estimated to cost

$42,000, while restricted work and no-lost-work cases were estimated to cost $618 and $ 777 respectively (Waehrer et al. 2007). All these values exceed the equivalent values for the overall private sector. According to data from 2002, the construction industry accounted for 5.2% of all private industry employment but it was responsible for 15% of all private injury cost. All of which indicates that the construction industry is disproportionally costly in regards to accidents and fatalities. This translates to a yearly cost of approximately $11.5 billion (Waehrer et al. 2007).

There are several characteristics of construction work that contribute to its hazardous nature. Construction work is constantly changing. The different stages of a project and the uniqueness and complexity of each worksite require constant adaptation to a new environment and a different way of performing activities. This jeopardizes the process of becoming familiar with the environment to the point where most possible hazards are recognized (Buchholz et al. 1996). Furthermore, this kind of job commonly requires working in awkward postures, in confined or dangerous spaces, lifting heavy equipment or performing forceful exertions (Schneider and Susi 1994).

Accidents have shown to be caused either by unsafe human acts and/or an unsafe design that generates a physical hazard (Kartam 1997). Furthermore, several decades of construction safety research have revealed that organizational and human factors, rather than technical failures, are the principal causes of accidents (Langford et al. 2000; Weick et al. 2008). This offers a possible explanation for the fact that despite the numerous advances in technology and communication during the past decades, which allowed for better equipment and training, accidents and fatality in construction still occur at a disproportionate rate. All of this makes it imperative to focus on the human aspect of accident causation.

Fatigue plays a significant role in the causes of occupational injuries and fatalities, particularly in high-energy situations. Fatigue can be defined as a decreased ability to perform activities at the desired level due to lassitude or exhaustion of mental and/or physical strength (Hallowell et al. 2010; Gander et al. 2011). When workers are fatigued, they experience compromised alertness, judgement, reaction time, mental acuity, physical strength, and the development of an uncooperative disposition (Gillberg and Åkerstedt 1994; Kajtna et al. 2011; van der Linden et al. 2003a; Lorist et al. 2005; Scott et al. 2006; Yaggie and Armstrong 2004). Such effects decrease a worker's ability to complete their work safely due to the increased rate of human error (Dembe et al. 2005). Thus, it is not surprising that many researchers include fatigue as a salient factor in most accident causation models and theories (Craig 1992; Czeisler, et al. 1992 ; Lorist et al. 2000; van der Linden et al. 2003; Tixier et al. 2014). As described by Spurgeon et al. (1997) there are mainly two reasons why fatigue compromises safety in an occupational environment. First, fatigue diminishes the ability of an individual to perceive and react to new information. (Grandjean 1979; Johnston et al. 1998; Lorist et al. 2000; Reiner and Krupinski 2011).

Second, fatigue diminishes the ability of an individual to perceive risk, and therefore, subconsciously this individual assumes higher risk than he/she normally would under a non-fatigued condition (Tixier et al. 2014). Along these lines, some authors have suggested that fatigue may affect hazard recognition abilities given the fact that fatigued individuals assume higher risks; however, as of now, no study has specifically studied the relationship between fatigue and hazard recognition ability among either industry workers in general or construction workers.

Despite the importance of fatigue in accident causation recognized by numerous researchers, fatigue has remained as a latent, hidden variable which rarely appears in injury reports and it is generally not mentioned until a major industry accident occurs (Harrington 2001; Reiner and Krupinski 2011). Perhaps the familiarity with the phenomenon (fatigue) has made people unaware of its real implications and effects. Furthermore, its dual nature presenting subjective and objective qualities has contributed to the lack of a formal and universal definition of fatigue. This lack of precision and formality has characterized fatigue related research until recent years.

The inability to properly define fatigue has inhibited the development of a cohesive list of causes and consequences of fatigue. This has also compromised the ability to properly assess or measure fatigue among individuals. Consequently, the current body of knowledge about fatigue has remained disperse and disorganized. Researchers have focused on different aspects of fatigue, thus achieving a deeper understanding of specific aspects, but no overall understanding of fatigue is shared by the whole research community. This greatly diminishes the ability to properly manage fatigue in the industry.

Early fatigue research focusses primarily on fatigue developed by patients of terminal or chronic diseases. Consequently, original research addressed fatigue in clinical settings among patients, and it studied mostly long term consequences of fatigue. In more recent years, fatigue research has also focused on healthy and working populations, but this research focusses primarily in the organizational, and managerial side of mitigating fatigue risk, giving place to good quality products such as Fatigue Risk Management Systems (FRMS) and fatigue proofing techniques

(Dawson et al. 2012; Gander et al. 2011). But even this latter research is in need of a deeper understanding of causes and consequences of fatigue among workers.

Currently, there is no study that addresses all principal causes and consequences of fatigue in an occupational setting. Furthermore, there is no study that allows for comparison among different causes and consequences of fatigue; therefore, it is difficult to establish an order of importance among these causes and consequences. Lastly, very few studies address fatigue among construction workers. These are trade specific studies and they reveal a need for further fatigue research among other high risk construction trades. For example Chan (2011) arrived to the conclusion that fatigue is the most critical aspect in accident causation among oil and gas construction workers. Hallowell (2010) also demonstrated that fatigue plays a major role in accident causation among rapid renewal highway construction. However, fatigue research among construction workers is still in its infancy and further research is needed.

The understanding of some of the negative consequences of fatigue on health and the industry has given place to an urgent need to assess fatigue levels among individuals. This need was primarily addressed by developing subjective fatigue questionnaires. These surveys were first developed to assess fatigue in clinical settings among unwell people. More recently, several subjective fatigue questionnaires were developed to assess fatigue in the industry but none of them focuses on the construction industry specifically. On the other hand, the technological advances of the last decades have allowed for the creation of multiple innovative devices that measure fatigue based on a physical aspect that changes under the effects of fatigue. Some of them base their assessment on encephalography, others on neurocognitive behavior, others on pupilometry, and others on oculometry, to mention a few. However, most of these devices lack validity and peer reviewed research to support their performance. Additionally, these instruments that objectively assess fatigue are usually very costly and time consuming, all of which limit their application in construction and the industry in general (Dawson et al. 2014). Consequently, there is a need for a valid and reliable way to measure and predict fatigue in construction workers.

The objective of this doctoral dissertation is to address all the aforementioned holes in the current body of knowledge and further advance the knowledge of fatigue among the construction industry with the ultimate goal of saving lives and improving productivity in the construction industry.

1.2 Current needs for additional research:

In light of existing literature, there are several gaps in the current body of knowledge about fatigue. Furthermore, even though fatigue has shown to greatly contribute to accident causation, fatigue research in the construction industry is barely in its infancy. Additional knowledge about the way in which fatigue affects construction workers and projects is needed. The foremost fatigue research needs in the construction industry are summarized below.

- Properly define fatigue for the industry.
- Identify and summarize causes and consequences of fatigue in the industry.
- Objectively quantify the impact of causes and consequences of fatigue.
- Develop empirical research among different construction trades.
- Develop a valid and reliable way to measure and predict fatigue in construction workers.

Addressing these gaps in knowledge is the purpose of this dissertation.

1.3 Dissertation organization

The present document is organized into 5 chapters, the first chapter consists of the introduction where the background, motivation, point of departure, and a summary of each conducted study is presented. In addition, the introduction presents current industry problems and how this dissertation will contribute to solve those problems. This document also contains 3 stand-alone studies developed by the author which address the research needs presented above. These documents are structured in a journal paper format with their corresponding abstract, introduction, methodology, results, and conclusion. These 3 studies can be found in chapters 2 through 4. The last chapter (Chapter 5) of this dissertation, presents a conclusion with a summary of the contributions to knowledge achieved by these studies and a reflection of future steps on fatigue related research in the construction industry.

1.4 Dissertation content and contributions

This section briefly explains the research needs addressed in and the knowledge contribution obtained from each paper.

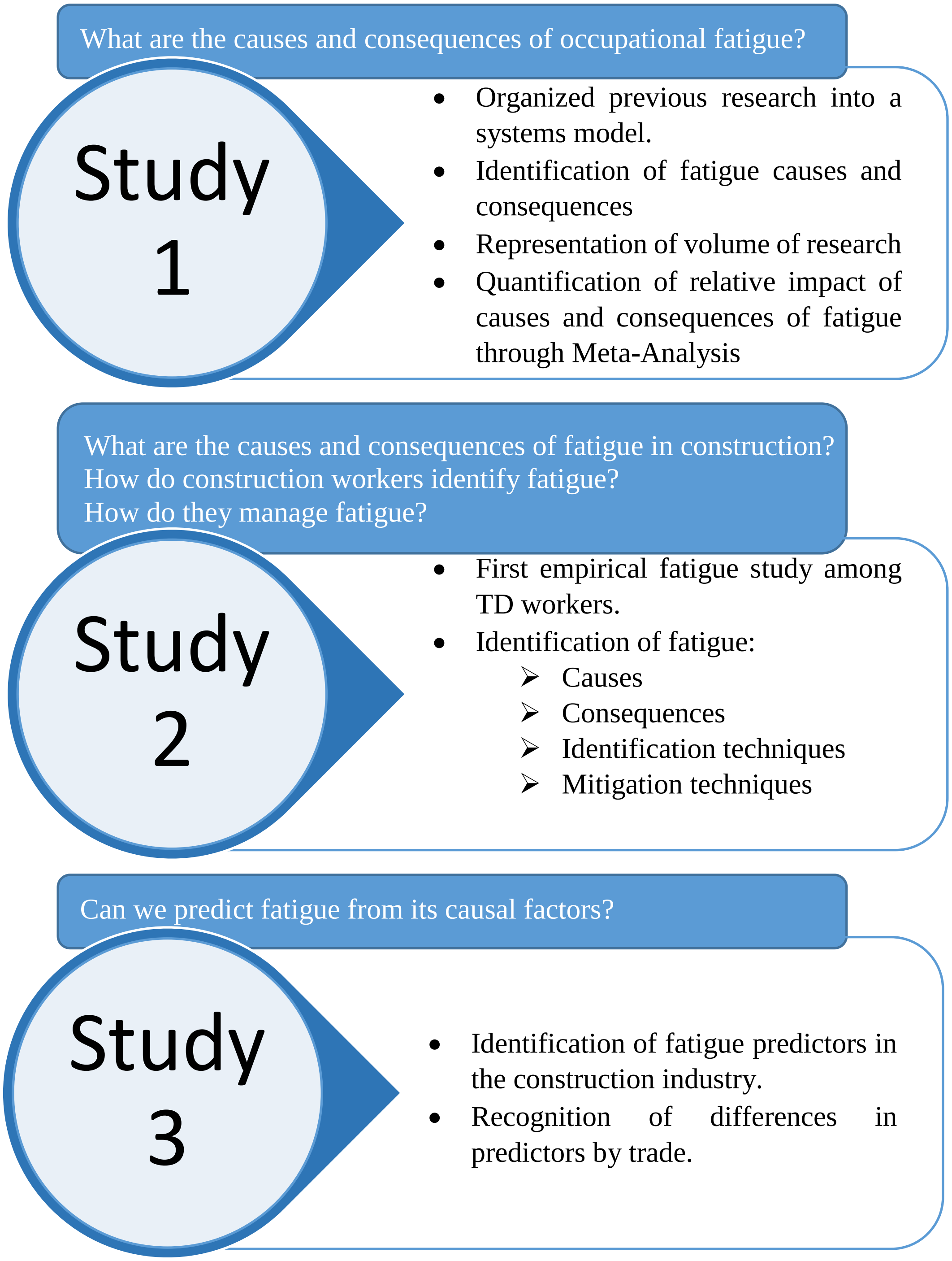
The first paper presented in this dissertation can be found in chapter 2 under the title: "Causes and Consequences of Occupational Fatigue: Meta-analysis and Systems Model". This paper addresses the need for a formal definition of fatigue and the identification and quantification of fatigue causes and consequences in an industry setting. The paper presents a definition of fatigue that alludes to two well-identified dimensions of fatigue which are mental and muscular. Additionally, this paper presents an exhaustive summary of the principal causes of fatigue and consequences of fatigue that affect industry workers, organized as a systems model where the volume of research behind each variable is presented. This analysis clearly identifies holes in the current body of knowledge and it can be used for future research as a point of departure to decide where further research is needed. Furthermore, this paper presents the first cohesive quantification of the impact of causes and consequences of fatigue allowing for comparison among different variables. This quantification was obtained as a result of a hefty meta-analysis of the existing fatigue literature. This paper has been published in the Journal of Occupational and Environmental Medicine.

The second paper presented in this document can be found in chapter 3 under the title "Fatigue Management in Electrical Transmission and Distribution Work". This paper is the result of an empirical research project among TD workers whose jobs are among the 10 most deadly professions in the country. This paper addresses the need for further fatigue research among at-risk construction trades. The research questions that originated this study are as follows: What causes fatigue among TD workers? What are the consequences of fatigue in TD work? How do workers and supervisors identify fatigue? What do they do to manage fatigue? What things could contribute to better management of fatigue in this trade? After an empirical study with the collaboration of 143 electrical TD workers, the researchers discovered that according to the opinion of TD workers, "Extreme Temperatures" and "Long Shifts" are the 2 most important and significant causes of fatigue among TD workers followed by "Lack of Sleep", and "Heavy Manual Labor". Among the consequences of fatigue, "Slowing Down" had a significant effect on fatigue among workers followed by loss of attention and concentration which was also important. These findings reveal that fatigue not only affects safety but also productivity in the construction industry. Additionally, this paper presents the most common ways of identifying and mitigating fatigue among TD workers which can be used for application in a FRMS for this sector of the industry. These findings shed light on the impact of fatigue among TD workers and operations which can be used to reduce accidents and fatalities in such a hazardous sector of the construction industry. This journal paper will be submitted for review to the Journal of Construction Engineering and Management.

The third and last paper presented in this dissertation can be found in chapter 4 under the title “Predicting Fatigue in Construction Workers”. Previous research identified numerous potential predictors of fatigue. Additionally, some of those were identified as especially important to the onsetting of fatigue by TD workers. This last study, investigates the predictive character of the potential aforementioned predictors. Two fatigue measurement tools were selected an objective tool and a subjective tool, to register as many dimensions of fatigue as possible; a questionnaire with the potential predictors was created; and a group of 253 US construction workers participated in the study.

The alternative hypothesis of the study stated that fatigue changes could be predicted by changes in some of the potential predictors identified by previous studies. Such a hypothesis turned out to be true and models with explained variability between 10% and 50% were developed. There results revealed the need to identify additional predictors that may be driving the percentage of unexplained variability. Additionally, this study allowed for the identification of specific predictors for two different types of workers: TD workers and general construction workers.

The reader will notice the dependency among these above presented research studies. Each study builds upon the knowledge obtained in the previous study, thus expanding the current body of knowledge. The study presented in Chapter 2 identifies and quantifies the relative impact of principal causes and consequences of fatigue per the existing literature. The study presented in Chapter 3 explores which of those causes and consequences play a role in the onsetting of fatigue among construction workers according to the opinion of construction workers. Lastly, the third paper quantifies the predictability of these causes based on the empirical assessment of these causes and the measurement of fatigue. Such work presents a unique and cohesive contribution to the current body of knowledge about fatigue in the construction industry. Figure 1 summarizes the research questions for this dissertation and the contribution in knowledge of each study.



What are the causes and consequences of occupational fatigue?

- Organized previous research into a systems model.
- Identification of fatigue causes and consequences
- Representation of volume of research
- Quantification of relative impact of causes and consequences of fatigue through Meta-Analysis

What are the causes and consequences of fatigue in construction?
How do construction workers identify fatigue?
How do they manage fatigue?

- First empirical fatigue study among TD workers.
- Identification of fatigue:
  - Causes
  - Consequences
  - Identification techniques
  - Mitigation techniques

Can we predict fatigue from its causal factors?

- Identification of fatigue predictors in the construction industry.
- Recognition of differences in predictors by trade.

Figure 1 Research questions and dissertation contributions

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Chapter 2: Causes and consequences of occupational fatigue: Meta-analysis and systems model.

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2.1 Abstract:

Occupational fatigue was a latent variable until recent years when researchers began to demonstrate the vast diversity of occupational and personal problems related to fatigue. The negative consequences of fatigue highly impact our society, instigating productivity losses that exceed $100 billion a year and injuries that total more than $50 billion yearly. Unfortunately, fatigue is difficult to measure empirically and the plethora of causes and effects of fatigue are described in literature published in fields as diverse as medicine, psychology, engineering, and sociology. Researchers who wish to study fatigue and build upon the existing body of knowledge find it difficult to access and codify the large, diverse, and scattered body of knowledge. To address this issue, this study aims to codify the literature related to occupational fatigue into a single systems model that: (1) identifies causal factors of fatigue; (2) evaluates interrelationships among causal factors; (3) identifies outcomes of fatigue; and (4) evaluates the interrelationships among fatigue outcomes. Furthermore, this study presents the first all-inclusive meta-analysis in this domain by computing a single statistic comparable across studies. The body of knowledge was cataloged and visually represented in the form of a systems model for the first time, allowing

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researchers and practitioners to easily access variables of interest and understand the dynamics of fatigue and the effect of its causes and consequences. The model also clearly shows where future research is needed to strategically address knowledge gaps.

2.2 Introduction:

Every day, more than 20% of the working population in the United States experiences occupational fatigue (Kroenke and Price 1993), resulting in $136.4 billion in lost productivity and healthcare costs each year (Ricci et al. 2007). Fatigue diminishes the quality of life of individuals and weakens the immune system. Despite these important implications, fatigue is a common occurrence, making it difficult for people to recognize its consequences and understand various primary and secondary causes.

Unfortunately, despite its implications, fatigue is often uncovered only after a major accident (Reiner and Krupinski 2011). For example, Harrington (2001) demonstrated how fatigue played a role in the Three Mile Island, Chernobyl, and the Exxon Valdez oil spill events, as they took place during the first hours of the morning after a night shift when the levels of fatigue among workers were at their highest. The negative outcomes of fatigue are not surprising since fatigue decreases the ability to process and react to new information and respond to hazards (Meijman and Schaufeli 1996; Harrison and Horne 2000; Lorist et al. 2000).

Past literature has called for a deeper understanding of the causes and consequences of occupational fatigue (Reiner and Krupinski 2011). In pursuit of this knowledge, researchers have aimed to study specific causes or consequences of fatigue using rigorous experimental methods and to validate each other's research findings. Despite the relatively large and mature body of knowledge in the field of occupational fatigue, there is no single resource that catalogs and organizes *empirical* literature or that integrates the findings in a meaningful and comprehensive manner. Thus, researchers may find it difficult to identify new theoretical points of departure and cumbersome to perform high-quality literature reviews.

To address this need, we aimed to codify the literature related to occupational fatigue into a systems model that: (1) identifies causal factors of fatigue; (2) evaluates interrelationships among causal factors; (3) identifies outcomes of fatigue; and (4) evaluates the interrelationships among fatigue outcomes. Although there are several hundred studies of fatigue, we built the model using only *empirical* and *validated* findings.

Additionally, a meta-analysis was performed using published data and formal statistics. Prior to the current paper, no formal or comprehensive meta-analysis had been performed on the causes or consequences of occupational fatigue. The meta-analysis allowed us to use a single statistic (Cohen's d) to explain the direction and magnitude of relationships among causes and consequences of fatigue. This value was computed based upon the effect sizes, sample sizes, and variance reported in past empirical studies. The meta-analysis complements the systems model, which focuses on illustrating the number of studies for each relationship by explaining the strength of the relationships and their statistical significance. Consequently, a revised model was created to illustrate validated effect sizes and directions of influence.

2.3 Fatigue definition and classification:

Before reviewing literature on the causes and consequences of fatigue, it is important to provide a pithy definition of the various types of fatigue. In general, fatigue is a condition of the individual that is recognized as a decreased ability to perform activities at the desired level due to lassitude or exhaustion of mental and/or physical strength (Hallowell et al. 2010; Gander et al. 2011). Humans commonly identify this state when feeling tired or weary. The condition of fatigue is experienced by every person (Aaronson et al. 1999) and, depending on its causes, can be classified as acute or chronic (Piper 1989).

Acute and chronic fatigue are distinguished from one another by their principal causes and long-term effects. Acute fatigue is experienced as a consequence of mental or bodily labor, emotional stress, insufficient recovery, or a temporary illness (Aaronson et al. 1999; Maslach 2001; Hallowell et al. 2010). It is considered to be a normal regulatory response to adverse condition and affects healthy people. Typically, acute fatigue can be relieved by quality rest, sleep, appropriate diet, and exercise (Piper 1989; Jason et al. 2010). Chronic fatigue, on the other hand, can manifest as a side-effect of a severe illnesses or treatments such as rheumatoid arthritis, diabetes, multiple sclerosis, radiation exposure, and chemotherapy (Piper 1989; Gander et al. 2011; Perry 2012). The symptoms of chronic fatigue are similar to those produced by acute fatigue except that they are experienced constantly and cannot be alleviated by rest alone (Brown 1994). In most occupational environments, the primary concern is acute fatigue, which is the focus of this paper.

In addition to the distinction between acute and chronic, fatigue can also be classified as muscular or mental. Mental fatigue is associated with a decreased motivation to continue performing a current activity and a sensation of weariness (Lee et al. 1991; Lorist et al. 2000). Mental fatigue decreases the ability to process and respond to information, ultimately diminishing competency, productivity, and error avoidance (Meijman and Schaufeli 1996; Harrison and Horne 2000; Lorist et al. 2000). Alternatively, muscular fatigue is a reduction in the physical ability to exert a force or perform a task. It is often a result of either metabolic or neural decay over the course of an extended physical activity. Muscular fatigue is most often caused by high intensity work, long duration of work, or improper work posture. Blue collar workers who are often required to perform heavy and repetitive tasks are more prone to muscular fatigue (Lipscomb et al. 2002). Although muscular and mental fatigue can be distinguished from one another, they are often experienced in concert to varying degrees and proportions. Thus, in literature and in professional practice, fatigue is often modeled and discussed in a general form. When possible, we will distinguish between muscular and mental fatigue for precision; otherwise, we will refer to fatigue as general condition.

2.4 Causes of fatigue:

In order to build a comprehensive systems model of fatigue, implied causal factors were identified, based on previous research, and the relationships among them were modeled in an organized fashion. To increase the internal validity of the resulting systems model, our review is limited to research-based studies that provide empirical evidence for conclusions and we focus our attention on causal factors and relationships that have been validated by multiple studies. Additionally, to reduce complexity and avoid repetition, factors that share similar root causes were codified into single, fundamental causal factor that is aptly labeled. It should be noted that this initial systems model includes all empirical evidence even if the data reported in the study did not have sufficient detail to be included in the subsequent meta-analysis. This was done to illustrate the focal areas of past fatigue research.

2.4.1 Sleep deprivation

Sleep deprivation is the most commonly discussed and arguably the most significant cause of both muscular and mental fatigue. It affects between 15 and 20% of US adults, and is becoming an increasing concern in our modern society due to various schedule irregularities and conflicting priorities that compromise sleep (Webb and Agnew Jr 1975; Åkerstedt 1990; Bliwise et al. 1992).

Belenky et al. (2003) produced a comprehensive analysis of the fatigue-related consequences of different sleep routines. In particular, they studied three different sleep restriction conditions: a mild sleep restriction (7 hours of sleep per night), a moderate sleep restriction (5 hours), and a severe sleep restriction (3 hours or less). The results were compared to control group which obtained 8 hours of sleep during the course of the study. They discovered that sleeping less than 8 hours generated negative outcomes. In particular, those who experienced only mild or moderate sleep deprivation showed a reduction in their mental and physical performance, which stabilized after a few days but still was under the normal level of performance. Furthermore, those who experienced severe sleep deprivation showed an ongoing degradation that didn't stabilized even after a few days. Several authors agree that a single night of partial sleep deprivation will generate a reduction in performance that can last several days (Van Dongen and Dinges 2005; Lim and Dinges 2008). Interestingly, Belenky et al. (2003) noted no significant improvements in fatigue for workers who obtain more than 8 hours of sleep compared to the control group.

Typically, sleep is compromised by early morning and night shifts that not only disrupt the circadian rhythm of the individual but also affect their social and family life (Folkard and Tucker 2003). Such adverse effects are most prevalent the first night after a period of rest when typical work shifts re-commence (Roach et al. 2004). In addition to fatigue, sleep disruption causes impaired physical performance, decreased work satisfaction, increased stress, and interrupted future sleep patterns (Harrison and Horne 2000; Philibert 2005). Unless this cycle is broken and workers recover completely from the previous work day, the sleep deprivation process can become chronic, ultimately resulting in serious long-term mental and physical health problems (Tepas and Mahan 1989).

Sleep quantity and quality is important as the mind and body of human beings need rest to avoid lassitude (Dawson and McCulloch 2005; Zhang and Liu 2008). Sleep deprivation is seen as such a strong precursor of fatigue that Dawson and McCulloch (2005) claim that fatigue can be accurately predicted by simply measuring the amount of sleep that a worker experiences in the 24-48 hours prior to a shift. In fact, they argue that sleep patterns prior to work are a better indicator of occupational fatigue than actual observations at work.

2.4.2 Mental Exertion

Some causes of fatigue can be purely mental. Mental exertion, defined as sustained cognitive activity that requires extraordinary mental effort, is the principal cause of mental fatigue (Lorist et al. 2005). Mental fatigue can be recognized by the individuals themselves as they experience difficulty in focusing attention, making timely decisions, planning, and responding to stimuli (van der Linden et al. 2003; 2003b; Boksem et al. 2005, 2006; van der Linden and Eling

2006). In addition to subjective indicators of mental fatigue, Lorist et al. (2005) used brain scanning technology, such as the electro encephalogram, to directly measure mental lassitude and unequivocally correlated mental exertion with mental fatigue.

2.4.3 Muscular Exertion

Muscular exertion, a purely physical occurrence, is a primary cause of localized fatigue (Grandjean 1979; Brown 1994; Jason et al. 2010). The link between muscular exertion and localized muscular fatigue has been studied in numerous ways. For example, fatigued is caused by the repetitive contraction of a specific muscle through electrical impulses (dynamic exertion), or by keeping a specific muscle contracted (static exertion) (Christensen et al. 1995; Edwards and Lippold 1956).

Beyond the static and dynamic state of exertion, there is either a metabolic or central nervous system degradation that explains the onset of muscular fatigue. For example, a fatigued quadriceps muscle consumes much more energy than a relaxed muscle, although metabolic energy production remains unchanged (Edwards et al. 1975). This results in exponential cumulative fatigue generation.

Although mental and muscular exertion yield obvious and distinct impacts on mental and muscular fatigue, respectively; other factors affect both mental and muscular capabilities. Some of these factors interact producing a compounding effect on the development of general fatigue.

2.4.4 Work Load Characteristics

Assigned occupational work load, defined as the product of physical demand and time, has been strongly linked to fatigue (Akerstedt et al. 2002). Ribet and Derriennic (1999) found that heavy workloads negatively impact sleep and, thus, interfere with the recovery process accumulating fatigue debt in the individual. In addition, high levels of required workload without the option for lower-effort alternatives cause an effort-to-reward imbalance that can ultimately lead to mental fatigue (Boksem et al. 2008). Hsiao and Simeonov (2001) and Gander et al. (2011) found that time on task alone was inadequate for fatigue prediction as accurate predictions require consideration of time on task, cognitive and physical demands, repetition, and scheduled breaks.

2.4.5 Overtime and Long Work Hours (LWH)

As defined by the Fair Labor Standards Act (1938), overtime in the US is the amount of work time in a week that exceeds 40 hours. Overtime can be accomplished either by working more than eight hours per day in a five-day-per-week schedule or by having fewer days off from work per week.

The occurrence of overtime is a common problem of industrialized environments (Kodz et al. 2003). More specifically, in Europe about 20% of the working population experiences at least 5 hours of overtime weekly and 13% of the full-time employees in Europe work at least 10 hours of overtime a week (Pascal and Damien 2001). In the US the situation is similar where about 26% of the male working population and 11% of the female working population work at least 10 hours of overtime weekly. Additionally, the amount of overtime has been growing over the past 50 years, especially among women due to their increasing presence in the workplace (Caruso 2006; Bureau of Labor Statistics 2015).

The fatigue-related consequences of overtime are directly connected to the perceived benefits and conditions under which overtime takes place. In this regard there are three different types of overtime situations:

(1) Mandatory, low reward, low autonomy, and highly demanding overtime. In this case the worker is forced to work overtime in an environment that the worker can’t control, required to perform highly demanding activities, or does not feel that the increased payment or future time off are sufficient compensation. This kind of overtime is associated with the most severe mental fatigue, dissatisfaction with the job, job burnout, negative work/home interaction, and slow recovery (Van Der Hulst and Geurts 2001; Beckers et al. 2008).

(2) Mandatory, high-reward overtime. The second kind of overtime is that which is performed solely because the extra payment is desired. This kind of overtime encourages people to work up to a point that exceeds their healthy state of functioning in order to earn more money, causing relatively high levels of fatigue (Gander et al. 2011).

(3) Voluntary overtime. This overtime is not driven solely by the economic reward, but also by personal fulfillment. When it is limited by the workers themselves, and it is performed with a high level of autonomy, overtime does not appear to have significant negative consequences, causing very low levels of both muscular and mental fatigue within natural

physiological limitations (Taris et al. 2007). Park et al. (2001) concluded that 20 hours of overtime per week is the point after which fatigue recovery becomes extremely difficult, even when overtime is voluntary.

Extended shifts can also cause fatigue. In contrast to overtime, which involves an accumulated number of work-hours in a week, extended shifts or long working hours (LWH) refers to single or compound shifts that involve more than eight hours of work in a twenty-four-hour period. It is important to notice that LWH don’t necessarily imply overtime. Some schedules such as 10 hour shifts for 4 days a week involve LWH but not in overtime.

LWH studies showed that memory efficiency decreases during cognitive activities when uninterrupted time on task exceeds 3.5 hours (Meijman 1997). Once 3.5 hours of continuous work has been accumulated, mental acuity can only be maintained at the expense of extra mental exertion. The prolongation of such effort will cause mental fatigue (Meijman 1997). LWH also causes fatigue by exposing the individual to other at work stressors such as noise, inadequate lighting, extreme temperatures, and other environmental and social factors, when present, for an additional period of time (Park et al. 2001; Dembe et al. 2005). The fatigue impact of LWH depends on the activity performed. If the activity requires mental effort, it will generate mental fatigue; otherwise, it will generate muscular fatigue or a combination of both.

2.4.6 Incomplete recovery

Recovery is the process of reversing the negative effects of mental and muscular exertion to return to a pre-fatigued state. Acute fatigue occurs when there is inadequate time to rest and recover from a work period (Jason et al. 2010; Swaen et al. 2003; Beurskens et al. 2000). Incomplete recovery can result from inadequate time off from work, misclassifying non-recovery time as recovery time (e.g., considering commute time as recovery), and inadequate use of the given recovery periods by the worker such as substance abuse or physically and mentally demanding recreational activities (Dawson and McCulloch 2005, Gander et al. 2011). Other common threats to recovery time are irregular or split shifts in which a worker has between two hours and four hours break before returning to work. Such shifts are usually insufficient to effectively recover from fatigue because of common commute times.

2.4.7 At work environmental Factors

Noise, light intensity, vibration, and temperature are all environmental factors linked to fatigue (Krause et al. 1997). Noise has been found to cause fatigue through over stimulation (Landström and Lundström 1985; Landström and Löfstedt 1987). For example, Kjellberg et al. (1998) showed that airplane mechanics and boat patrol crews experienced mental fatigue as a result of high duration of exposure to low frequency noise. Additionally, extreme temperatures (i.e., below 35F and above 95F) increase the rate of muscular fatigue (Gonzalez-Alonso 1999; Zivin and Neidell 2010). Similarly, Park and Gotoh (1993) found a significant positive correlation between poor lightning and fatigue and Jiao et al. (2004) found a positive correlation between vibration and fatigue.

2.4.8 Social environment at the workplace

Most of the working population spends one-third to one-half of their waking hours at work. Relationships with co-workers, managers, and subordinates play a major role in the development of mental fatigue (Bültmann et al. 2001). Some specific psychosocial experiences can exacerbate mental fatigue. For example, workplace abuse, defined as daily harassment from co-workers or abusive supervision for prolonged periods of time, can cause severe mental fatigue (Tepper 2000; Zapf and Gross 2001). Similarly, Hardy et al. (1997) found that conflicts and adversarial situations at work develop high levels of mental fatigue, even if they are essential attributes of the work type (e.g., negotiations). Other social factors that strongly influence the onset of mental fatigue are the perception of low autonomy, high emotional demands, and job insecurity (Taris et al. 2007).

2.4.9 Emotional predisposition and distress

Fatigue impacts everyone differently depending on their emotional predisposition and is often exacerbated under distress. Emotional disposition pertains to the propensity of an individual to experience negative emotions such as fear and sadness (Gibson et al. 2003). Bültmann et al. (2001) performed a field study with 11,020 workers from 45 different companies, and discovered that those who are more likely to experience negative emotions are more likely to encounter mental fatigue than individuals who are more emotionally resilient. Furthermore, in a study of 16,139 employees from the public sector, Ala-Mursula et al. (2005) showed that the onset of fatigue is accelerated under stressful conditions, especially for individuals who are emotionally vulnerable.

Table 1 summarizes these key causal factors of fatigue and provides the references associated with each factor. Additionally, when possible, the impacts of each factor on mental, muscular, and general fatigue are identified.

Table 1 Causes of fatigue

Factor	Factor Definition	Impacted Factor	Reference over
Sleep Deprivation	Sleep deprivation refers to a loss in the amount of consecutive hours of sleep. There are different degrees of sleep deprivation, which Belenky et al. (2003) classify as Mild SD (7h of time in time in bed), moderate SD (5h of TIB), severe SD (3h of TIB) or total SD (no sleep at all).	GEN*	Webb and Agnew Jr (1975); Tepas and Mahan (1989); Åkerstedt (1990); Harrison and Horne (2000); Belenky et al. (2003); Folkard and Tucker (2003); Roach et al. (2004); Dawson and McCulloch (2005); Philibert (2005); Van Dongen and Dinges (2005); Lim and Dinges (2008); Zhang and Liu (2008).
Mental Exertion	Sustained cognitive activity that requires extraordinary mental effort. (Lorist et al. 2005; Meijman and Schaufeli 1996)	MEN**	Okogbaa et al. (1994); Meijman (1997); Lorist et al. (2005); Hallowell and others (2010).
Muscular Exertion	Exhaustion of the muscle due to an extent period of sustained tension or repetitive activity.	MUS***	Edwards and Lippold (1956); Edwards et al. (1975); Grandjean (1979);Brown (1994); Christensen et al. (1995); Johnston et al. (1998); Jason et al. (2010);Yaggie and Armstorn (2004); Jason et al. (2010).
Work Load	High physical or mental demands at work.	MEN	Boksem and Tops (2008)
		GEN	Van Der Hulst and Geurts (2001);
Overtime & LWH	As defined by (FLSA 1938) “overtime” is the amount of time worked that exceeds 40h of work a week.	MEN	Meijman (1997)
		GEN	Park et al. (2001); Van Der Hulst and Geurts (2001); Dembe et al. (2005); Taris et al. (2007); Beckers et al. (2008)
Incomplete Recovery	Recovery is the process of reverting or reversing the negative effects of job demand to return to a pre-work state.	GEN	Dawson and McCulloch (2005)
Work Environment	Noise, light intensity, vibration, and temperature are all environmental factors linked to fatigue.	MEN	Melamed and Bruhis (1996); Kjellberg et al. (1998)
		GEN	Krause et al. (1997); Gonzalez-Alonso (1999); Ala-Mursula (2005); Zivin and Neidell (2010).
Social Environment	The quality and characteristics of worker relationships with pear and supervisors, as well as the perceived freedom at work.	MEN	Maslach and Jackson (1984); Hardy et al. (1997); Tepper (2000); Bültmann et al. (2001)
Emotional Predisposition	Emotional disposition pertains to the level of fear, stress or overall attitude a worker has towards a certain task or job	MEN	Bültmann (2001); Gibson et al. (2003);

*Notation: *MEN: Mental Fatigue; **GEN: General Fatigue; ***MUS: Muscular Fatigue*

2.5 Relationships among causes of fatigue

Causal factors of fatigue can compound one another when they co-occur. Interestingly, many of the interrelationships described in the literature relate to the organization of work by management. For example, work load, overtime, and extended shifts tend to interact with each other and with other causal factors. Thus, these managerial factors can be addressed through mindful work organization.

2.5.1 Impacts of increased work load on other causal factors

As work load increases with additional or more demanding activities, the extra mental and physical exertion can accelerate lassitude and, when extreme, it can lead to subsequent sleep deprivation (Åkerstedt et al. 2002). These consequences can affect all types of workers; however, women below 49 years of age who come from a high socioeconomic status are particularly vulnerable (Van Der Hulst and Geurts 2001). Additionally, Van Der Hulst and Geurts (2001) demonstrated that when workload is increased because of additional physical demands, the effects could remain resident for up to a day after the exertion period.

With regards to mental fatigue, Boksem and Tops (2008) found that increased work load is a significant mental stressor when the reward received by the worker is perceived as insufficient to compensate for the extra effort required. Furthermore, Ribet and Derriennic (1999) discovered that the pressure to hurry is the principal psychosocial occupational risk factor affecting sleep deprivation.

2.5.2 Impacts of overtime and LWH on other causal factors

The synergistic effects of overtime and LWH magnify the effects of fatigue caused by other factors. In fact, most of the aforementioned factors as discussed by the respective researchers in the context of extended periods of work or exertion, implicitly suggesting that LWH or overtime are pre-requisite factors. When the work requirements are mandated and workers have low autonomy, lengthened work periods become especially problematic (Axelsson et al. 1998; Park et al. 2001; Folkard and Tucker 2003; Dembe et al. 2005; van der Hulst et al. 2006).

When workers are required to work overtime or LWH, there is a natural reduction in recovery because fewer hours are available to rest. On many occasions overtime and LWH are combined with night or early morning shifts that disrupt circadian rhythms and interfere with family life (Webb and Agnew Jr 1975; Åkerstedt 1990; Bliwise et al. 1992; Axelsson et al. 1998; Folkard and Tucker 2003; Baulk et al. 2009). This affects the individual physically, emotionally, and mentally, slowing down the recovery process (Åkerstedt 1990; Van Der Hulst and Geurts 2001; Folkard and Tucker 2003; Beckers et al. 2008; Charles, De, Wolff et al. 2013).

Table 2 identifies and provides references for research of the interrelationships among the causal factors of fatigue.

Table 2 Relationships among causes of fatigue

Factor	Impacted Factor	References
Work Load	Sleep Deprivation	Ribet and Derriennic (1999); Åkerstedt et al. (2002)
	Mental Exertion	Boksem and Tops (2008)
	Muscular Exertion	Åkerstedt (2002).
	Overtime & LWH	Beckers et al. (2008)
Overtime & LWH	Sleep Deprivation	Webb and Agnew Jr (1975); Åkerstedt (1990); Bliwise et al. (1992);Axelsson et al. (1998); Folkard and Tucker (2003); Baulk et al. (2009)
	Mental Exertion	Meijman (1997); Park et al. (2001); Folkard and Tucker (2003); Dembe et al. (2005)
	Muscular Exertion	Folkard and Tucker (2003); Dembe et al. (2005)
	Incomplete Recovery	Åkerstedt (1990); Van Der Hulst and Geurts (2001); Folkard and Tucker (2003); Beckers et al. (2008); Charles, De, Wolff et al. (2013).

2.6 Consequences of fatigue:

Fatigue research tends to focus on either causal factors or outcomes of fatigue. Causal factors and outcomes are rarely modeled together. Here, implied causes and consequences of fatigue are analyzed exclusively underlying their relationship with fatigue as the main variable of interest. Occasionally, some causes and consequences of fatigue can be connected via mechanisms other than fatigue, particularly with mental disorders and long-term health concerns. However, this review did not include these secondary relationships.

Below is a comprehensive review of empirical literature that has linked occupational fatigue with specific mental and physical consequences. Some of these consequences are subtle or acute while others can manifest on delay or can be chronic. Understanding the interrelationships among consequences of fatigue is critical to modeling the true impact that fatigue can have on an individual.

2.6.1 Mood changes

Mood, related to short-term emotions and feelings, can be assessed by numerous variables such as tension, anger, vigor, sadness, anxiety, and depression. Mood is typically measured subjectively through the *Profile of Mood State* introduced by McNair et al. (1971). According to the prevailing literature, fatigue results in strong negative changes to mood states, which can change emotional stability, increase anxiety, and eventually lead to long-term depression (Pilcher and Huffcutt 1996; Dinges et al. 1997; Harrison and Horne 2000; Sagaspe et al. 2006; Scott et al. 2006; Boonstra et al. 2007; Kajtna et al. 2011). In addition, a negative mood or emotional state has been shown to decrease complex cognitive performance, clouding risk perception (Tixier et al. 2014).

Scott et al. (2006) studied the mood-related consequences of fatigue arising from 30 hours of sleep deprivation and concluded that tension and anger were not affected but that feelings of depression and sadness manifested quickly, even after only one missed sleep cycle. Mikulincer et al. (1989) studied the timing of mood-related change arising from fatigue and found that fatigued individuals experienced relatively high levels of anxiety between 0400 and 0800 hours and relatively low levels between 1600 and 2000 hours. Interestingly, using a series of complex and controlled experiments, Kajtna et al. (2011) found that the fatigue-induced mood changes compromise an individual’s ability to concentrate on a stimulus.

2.6.2 Cognitive degradation

Cognitive functions, classified as complex or basic, are essential for effective completion of work and for healthy life outside of work. Complex cognitive functions include, but are not limited to, the ability to plan, perceive risk, and make decisions under uncertainty. Basic cognitive functions include attention, vigilance, and response to stimuli (Jovanovic et al. 2012). When studying the impact of fatigue on cognitive performance, researchers typically manipulate degrees of sleep deprivation and measure performance with standardized cognitive activities (Angus and Heslegrave 1985; Van Dongen and Dinges 2005; Lim and Dinges 2008; Zhang and Liu 2008)

Studies on complex cognitive performance involve sophisticated experimental methods and the use of advanced technologies. Researchers have focused on the impacts of acute fatigue on verbal fluency and communication, decision-making capability, creative thinking, planning, executive control, and novelty performance. Overwhelmingly, data support that all of these complex cognitive functions are significantly deteriorated even with modest fatigue levels (Harrison and Horne 1999; 2000).

With the help of electroencephalographic (EEG) tools, functional neuroimaging, and psychophysiological assessments, researchers have found that the Prefrontal Cortex (PFC), which governs the executive functions of the brain, is the locus of deterioration when an individual is fatigued (Jones and Harrison 2001; van der Linden et al. 2003). Unlike basic functions that can be rote and automatic, complex tasks require uncompromised PFC functionality (Harrison and Horne 1999; Jones and Harrison 2001). Thus, the brain is highly susceptible to even modest fatigue levels when executive functions are required to make complex decisions (Meijman 1997; Nilsson et al.

2005; Boonstra et al. 2007). In an occupational environment, this translates to a differential in potential consequences depending on the tasks performed by different workers with the same levels of fatigue.

In addition to complex cognitive functions, other more basic and automatic cognitive functions can be compromised. One of the earliest and most comprehensive investigations of the relationship between fatigue and cognitive performance found that a single night of sleep deprivation decreased cognitive performance by 30% (Angus and Heslegrave 1985). Furthermore, their findings showed that cognitive performance was reduced by an additional 30% during the second 24-hour period of sleep deprivation and remained stable at 40% of the original cognitive performance after 48 hours without sleep. This study was empirically validated by Van Dongen and Dinges (2005); Lim and Dinges (2008); and Zhang and Liu (2008) who later replicated the experiment with a more heterogeneous sample of participants and a more diverse set of cognitive tasks and fatigue scenarios.

2.6.3 Attention and concentration

The pre-frontal cortex (PFC) helps an individual to concentrate attention on a task or stimulus. As the functionality of the PFC is compromised by fatigue, both static and dynamic functions are affected. Researchers have studied the impact of fatigue on concentration and attention for many years, starting with Yoshitake's (1978) seminal work with 17,000 participants. In this field study, three different dimensions of fatigue were identified: drowsiness and dullness, inability to concentrate, and physical discomfort. Even though inability to concentrate was experienced most strongly by workers with mentally demanding tasks, lassitude of concentration and attention are experienced similarly by a fatigued individual regardless of causal factors. In more recent years, fatigue has been studied in different naturalistic tasks such as driving (Brown 1994) and conflict tests (Fogt et al. 2010). As hypothesized, these studies demonstrated that fatigue decreased processing of stimulus, concentration capacity, and made individuals more prone to error.

2.6.4 Reaction time

When reacting to a stimulus, the human body must perceive, process, and physically react to the stimulus. Previously, we discussed the reduced attention capacity resulting from fatigue. In addition, reaction time, defined as the time between a stimulus onset and the response to such stimulus, is highly compromised by fatigue.

The prevailing method for measuring reaction time involves using the psychomotor vigilance test (PVT), which records the reaction time to a visual stimulus (Dinges and Powell 1985). Angus and Heslegrave (1985) used PVT to study the impact of fatigue on reaction time and found that the reaction time of fatigued workers decreased by 24% when compared to well-rested workers. Furthermore, higher levels of fatigue induced by a second night without sleep resulted in a 57% reduction in reaction time. Similar studies found more modest but still significant decreases in reaction time (Opstad et al. 1978; Naitoh 1981; Lorist et al. (2000).

2.6.5 Physical degradation and pain

The physical degradation caused by fatigue can be significant and pervasive. For example, Johnston (1998) tested static and dynamic balance of fatigued individuals and found drastic increases in the risk of falls compared to non-fatigued individual. In addition to reduced physical stability, fatigue can result in reduced muscular strength causing slower movement and increased number of errors (Grandjean 1979). The long-term impacts of physical degradation primarily involve musculoskeletal disorders of the neck, shoulders, and back (Lipscomb et al. 2002). Although acute, reduced balance was observed in fatigued subjects for at least 15 minutes after prolonged exertion of cervical muscles, leading to longer-term localized muscular fatigue (Gosselin et al. 2005; Yaggie and Armstrong 2004). The implication is that seemingly short-term effects of acute fatigue can remain resident for longer periods of time than may be intuitive.

2.6.6 Illnesses

Fatigue has also shown to have significant long-term impacts on the human body. For example, researchers have found evidence that night shift workers experience higher levels of fatigue and, consequently, present gastrointestinal disorders, irregular bowel activity such as constipation and diarrhea, bowel pain, and even ulcers at a rate that is nearly double their day-worker counterparts (Segawa et al. 1987; Scott and La Dou 1994; Knutsson 2003). Furthermore, Steenland and Fine (1996a), Bøggild and Knutsson (1999), and Knutsson (2003) found that shift workers present a 40% higher risk of suffering cardiovascular disease or myocardial infarction than day-time workers. Although gastrointestinal and cardiovascular conditions are the most common occupational illnesses related to fatigue (Iwasaki et al. 1998), some postulate that fatigue has greater consequences among those who are pregnant or have diabetes (Knutsson 2003).

2.6.7 Human error and injuries

As previously discussed, lassitude of cognitive functions decrease recall, reaction time, ability to plan, and ability to respond to stimuli. Additionally, lassitude of the muscular system decreases the ability to physically execute a plan. Thus, it is not surprising that researchers have found evidence of a direct relationship between the degree of fatigue and rates of human error (Craig 1992 ; Czeisler, et al. 1992 ; Lorist et al. 2000; van der Linden et al. 2003). Human error is said to occur when an individual takes unintentional actions or is unable to execute planned functions and an undesired outcome is realized.

Table 3 summarizes these key outcomes of fatigue. They are briefly described and references are provided for each factor. Additionally, for consistency with Table 1, the impacts of each factor on mental, muscular, and general fatigue are also distinguished.

Table 3 Consequences of fatigue

Fatigue	**Impacted Factor**	**Impacted Factor description**	**References**
MEN	Cognitive Degradation	Cognitive functions refer to both complex and basic cognitive functions. Complex cognitive activities are not the result of a natural impulse or a learned behavior as these activities require a high degree of processing information in order to be performed (Boonstra et al. 2007). Basic cognitive functions have been defined as attention, concentration, reaction time, and well learned behavior. (Jovanović et al. 2012)	Opstad et al. (1978); Naitoh (1981); Angus and Heslegrave (1985); Dinges and Powell (1985); Gillberg and Åkerstedt (1994); Lorist et al. (2000); van der Linden et al. (2003), (2003b); Boksem et al. (2005); Lorist et al. (2005); Boksem et al. (2006); Tixier et al. (2014).
	Illnesses	Illnesses refers to the affections that the individual can develop as a result of an extended period of fatigue. Fatigue debilitates our immune system and causes stress which opens the door for health problems.	Fredriksson et al. (1999);Van Der Hulst and Geurts (2001); Amick III et al. (2002); Kivimäki et al. (2002).

	Error or Injuries	Error or Injuries refers to any kind of procedure or action that is not perform in the correct way, due to fatigue, and that causes some kind of loss or damage to the workers.	Lorist et al. (2000); van der Linden et al. (2003), (2003b)
GEN	Bad Mood	Mood comprehends numerous variables such as tension, anger, vigor, anxiety, and depression. An important number of studies utilize the Profile of Mood State to assess mood.	Opstad et al. (1978); Mikulincer et al. (1989); Pilcher and Huffcutt (1996); Dinges et al. (1997); Philibert (2005); Sagaspe et al. (2006); Scott et al. (2006); Boonstra et al. (2007); Kajtna et al. (2011).
	Cognitive Degradation	See above	Opstad et al. (1978); Yoshitake (1978); Naitoh (1981); Angus and Heslegrave (1985); Brown (1994); Meijman (1997); Harrison and Horne (1999), (2000); Lorist et al. (2000); Jones and Harrison (2001); Lipscomb et al. (2002); Belenky et al.(2003); Van der Linden et al. (2003); Gosselin et al. (2005); Nilsson et al. (2005); Philibert (2005);~~Van~~ Dongen and Dinges (2005); Boonstra et al. (2007); Lim and Dinges (2008); Zhang and Liu (2008); Fogt et al. (2010)
	Physical Degradation	Physical Degradation refers to any bodily symptom that impairs the normal functioning of the body, such as pain, somnolence, and lack of strength.	Yoshitake (1978); Grandjean (1979); Lipscomb et al. (2002); Nindl et al. (2002).
	Illnesses	See above.	Segawa et al. (1987); Scott and LaDou (1994); (Xu et al. (1994); Steenland and Fine (1996); Krause et al. (1997); Alfredsson et al. (1982); Iwasaki et al. (1998); Bøggild and Knutsson (1999); Hansen (2001); Nylén et al. (2001); Åkerstedt et al. (2002); Liu and Tanaka (2002); Knutsson (2003).
	Error or Injuries	See above	Harrington (2001); Nylén et al. (2001); Folkard and Tucker (2003); Dembe et al. (2005).
MUS	Physical Degradation	See above.	Grandjean (1979); Scott and LaDou (1994); Johnston (1998); Yaggie and Armstrong (2004).
	Illnesses	See above.	Fredriksson et al. (1999)

2.7 Relationships among outcomes of fatigue:

Similar to section 2.5, there are some consequences of fatigue that exacerbate other outcome factors, which, can magnify or perpetuate the effects of acute fatigue. These factors are most often cited in medical, neuroscience, and psychology research because they are related to the function (or dysfunction) of the human body.

2.7.1 Impacts of cognitive degradation on other outcomes

As cognition degrades, a plethora of negative outcomes arise. From a mental standpoint, cognitive fatigue reduces complex and basic cognitive function, negatively affects mood, and increases reaction time. From primary impacts of fatigue arise a host of secondary outcomes. For example, weakened basic and complex cognitive functions increase human error, injuries, and decrease the quality and productivity of work completed (Craig 1992; van der Linden et al. 2003; Fogt et al. 2010). Also, mood changes often cause the affected worker to become more irritable, thereby degrading workplace, social, and family relationships (Williams and Alliger 1994). Finally, a delayed reaction time increases the rate of human error and increases safety risk (Harrison and Horne 2000; Fogt et al. 2010). It should be noted that most authors agree that basic cognitive functions are more resilient to fatigue than complex cognitive functions and mood. However, even modest levels of fatigue can affect basic cognitive functions.

2.7.2 Impacts of physical degradation on other outcomes

After an intense or prolonged period of physical stress, human bodies experience muscular fatigue, which is accompanied by a less noticeable, but equally important, reduction in motor function (Grandjean 1979; Johnston 1998). The chemical, neural, and hormonal changes that take place in human bodies when physically stressed is a natural defense that prevents further degradation (Piper 1989; Brown 1994; Jason et al. 2010). However, these defenses slow down physical reactions, decrease balance, and decrease coordination, making a worker prone to errors and injuries (Grandjean 1979; van der Linden et al. 2003). Dramatic reductions in balance have been shown to be a delayed consequence of fatigue that affects the worker even during rest periods and social activity (Gosselin et al. 2005).

2.7.3 Impacts of illnesses on other outcomes

There are many ways that fatigue causes physical debilitation; however, it also causes long-term impacts such as illnesses. When fatigue causes illness, the effects of the illness, in turn, often reinforce fatigue thereby causing a downward cycle. Jason et al. (2010) found that between 5% and 8% of the general population experience the fatigue-illness cycle for 1 to 5 months.

Table 4 Relationships among consequences of fatigue

Factor	Impacted Factor Name	References
Cognitive performance	Illnesses	Brown (1994); Belenky et al. (2003).
	Error or Injuries	Tepas and Mahan (1989); Craig (1992); Czeeisler, et al. (1992); Okogbaa et al. (1994); Meijman (1997); Harrison and Horne (1999), (2000); Lorist et al. (2000); Jones and Harrison (2001); van der Linden et al. (2003); Boonstra et al. (2007); Fogt et al. (2010).
Physical Degradation	Illnesses	Segawa et al. (1987); Scott and LaDou (1994); Knutsson (2003); Lipscomb et al. (2002); Gosselin et al. (2005).
	Error or Injuries	Grandjean (1979); Craig (1992); Czeisler et al. (1992); Johnston et al. (1989) Lorist et al. (2000); van der Linden et al. (2003); Yaggie and Armstrong (2004).

2.8 Systems model:

After analyzing the causes and consequences of fatigue we aimed to represent the findings in a systems model to illustrate the strengths and gaps in the current body of knowledge. Figure 2 illustrates the complexity of the relationships between causes and consequences of fatigue, where fatigue is the mediating factor. The relationships among factors are represented by arrows and the volume of research developed in that line of inquiry is represented by the thickness of the line. Therefore, it becomes easy to distinguish mature areas of research from those where additional research is needed. All the information presented in the model is a summary of the information presented in Tables 1-4. It should be noted that the subsequent meta-analysis illustrates the strength and direction of the effect sizes among these factors.

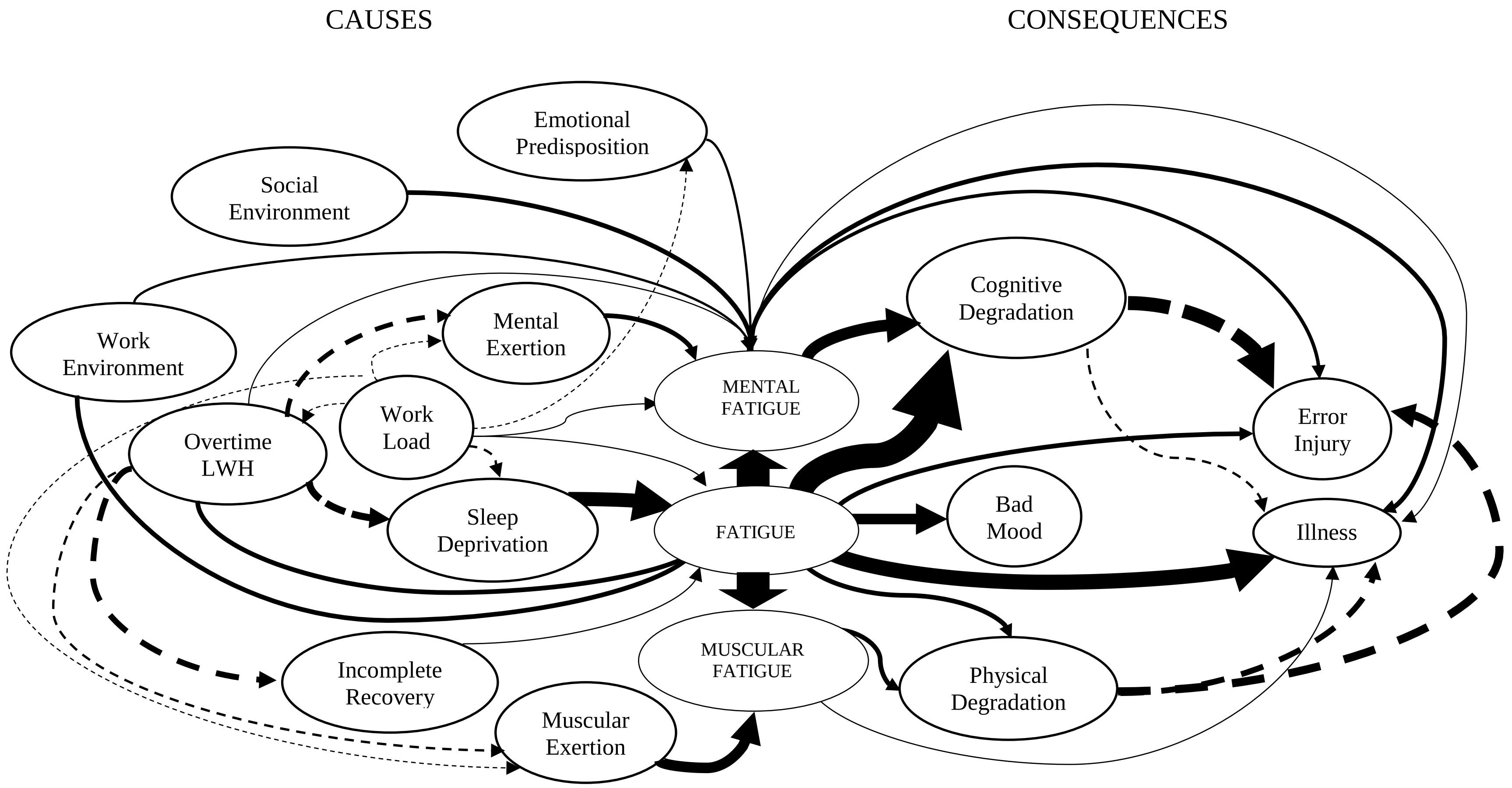

Figure 2: Systems model illustrating empirical literature on the relationships among causes and effects of fatigue.

Notation: Line thickness corresponds directly to the number of studies devoted to each relationship.

→ Immediate relationships between causes, fatigue, and consequences.

⇢ Inter-relationships within causes or consequences of fatigue.

2.9 Model limitations

The systems model has numerous limitations. First, the model is built completely from past research and the structure and content of the model was derived from what has been studied in the past. Thus, the model reflects any limitations associated with the topics of investigation to date. Second, the completeness of the model is commensurate with the completeness of the literature review. Our analysis mainly considered research published in English in top occupational safety and health, applied psychology, cognitive psychology, medical, industrial systems, engineering, sleep, and neuroscience journals. To ensure completeness, we also cross-referenced all references of past papers to ensure popular studies were not omitted. Nevertheless, it is possible that some research was missed and that the model could be improved. Third, we made the implicit assumption that the mechanics of fatigue are the same regardless of ethnic background, culture, and occupation. The body of research affirms this assumption; however, it remains just that: an assumption that has yet to be validated. Fourth, our review and the model only include the direct causes and consequences of fatigue. There may be a plethora of factors that indirectly affect fatigue or are an indirect outcome of fatigue through some mediating variable. These interactions are out of the scope of this research. Fifth, the model does not include direct connections between causal and outcome factors without fatigue as a mediator. Future researchers may wish to study these direct relationships as a means to identify when outcomes are falsely attributed to fatigue and when other mediating variables may be at play. Finally, our descriptions of each causal factor and outcome of fatigue were abbreviated. There is a wealth of information on research methods, nuances of findings, and implications that we simply could not include within the scope of one paper. Rather, our aim was to produce a single-source systems model of the many antecedents and consequences of fatigue and to acknowledge the key research used to build a valid model. The meta-analysis presented in section 2.10 offers a formal statistical analysis of published data in order to measure and model the effect sizes of the relationships shown in Figure 2.

2.10 Meta-analysis approach

Since our main objective was to summarize the body of knowledge related to the causes and consequences of occupational fatigue, we complemented the systems model with a formal analysis of the magnitude and direction of the relationships. To achieve this objective we performed a statistical meta-analysis. When formally performed, a meta-analysis allows one to codify the effect sizes from multiple studies into a single statistic. Since effect sizes are independent of the sample size and have a reportable standard error, they can be compared and aggregated across multiple studies. Such analysis allowed us to identify the factors that have the largest impact on fatigue and the factors that are most impacted by fatigue.

We used four basic steps in our meta-analysis as suggested by Lipsey and Wilson (2001) and Field and Gillett (2010). The first step, *studies selection*, involved a comprehensive literature review of studies that reported sufficient empirical data to calculate an effect size. Additionally, in this step each study is evaluated according to certain criteria of quality and methodology appropriates for their inclusion in the meta/analysis. Although each study included in the systems model reported empirical evidence, many studies did not report sufficient detail of their analysis and, thus, were not included in the meta-analysis. The second step, *studies coding*, involved extracting the data needed to compute an effect size for each relationship of interest. The result of this step is a matrix of effect sizes reported by all scientific studies for each relationship. The third step, *standardization*, involves translating the effect sizes between studies into common units so that they can be size aggregated. Finally, the fourth step, *overall effect size computation,* involves computing a single effect size that combines the standardized data from multiple studies. The details associated with each step are described below.

2.10.1 Studies selection

In order to be included in the meta-analysis, a study must: (1) contain results about a clear and specific relationship between a cause of fatigue and fatigue, or fatigue and a consequence of fatigue; (2) involve a healthy working sample of subjects between 18 and 65 years of age and represent the working population (i.e., studies limited to athletes, children, sick, or disabled persons were omitted); (3) include either an effect size or enough information to compute an effect size; and (4) involve 5 participants or more. Of the 105 studies of occupational fatigue that report empirical data, 23 met all four criteria.

It was also important also to ensure that only valid and reliable data were used in the analysis. From the 23 studies a total of 64 effect sizes were obtained, including correlation coefficients (r), Risk Ratios (RR), and Odds Ratios (OR). However, not all these effect sizes were acceptable for the analysis because they were not accompanied by proper demographic statistics (e.g., sample size of the control group). This restriction yielded a total of 29 salient effect sizes.

2.10.2 Studies coding

The coding strategy to extract effect sizes from a study depended on the target aggregate statistic. Since all of the variables of interest could be converted to a continuous scale and the standard deviations could be pooled, Cohen's d is the ideal statistic (Cohen 1988). Cohen's d yields information about the difference in means of two groups, measured in standard deviations. We were able to use Cohen's d because studies that reported the results of a questionnaire could be as a relative continuous score and studies that reported objective measures such as reaction time in a PVT were naturally continuous. When the raw data were available, the following process was used.

$$Cohen's\ d = \frac{\overline{X_2} - \overline{X_1}}{S_{Pooled}} \quad (1)$$

Where $\overline{X_1}$ *is the expected value of the control group sample,* $\overline{X_2}$ *is the expected value of the treatment group sample, and* S_{Pooled} *is the pooled standard deviation.*

We used the method introduced by Lipsey and Wilson (2001) to pool the standard error.

$$SE_d = \sqrt{\frac{n_1 + n_2}{n_1 n_2} + \frac{d^2}{2(n_1 + n_2)}} \quad (2)$$

Where SE_d *represents the standard error of the statistic d;* n_1 *is the sample size of the control group,* n_2 *is the sample size of the treatment group and* d *is the effect size (Cohen's d)*

In order for a study to be included in our sample, the effect size and the standard deviation had to be reported. Sometimes these variables are directly presented in a paper; other times these variables can be extracted from the results of a t-test, an F-test, or an analysis of variance (ANOVA), to mention a few. Since the effect size of small samples has been shown to be biased by outliers, we used a sample size correction introduced by Hedges (1981). This correction, shown in the equation below, reduces the relative impact of studies that report sample sizes less than 20. When sample sizes are greater than 20, the adjustment is nullified. The equation presented by Hedges (1981) is as follows:

$$d' = \left(1 - \frac{3}{4N-9}\right) d \quad (3)$$

Where d' represents the unbiased effect size and N is the total sample $(n_1 + n_2)$.

2.10.3 Standardization

In some cases, effects sizes were reported by authors using a statistic other than Cohen's d (e.g., regression coefficient). These statistics were transformed into a Cohen's d and a corresponding confidence interval of 95% was created. When a correlation coefficient was reported, Cohen's d was calculated using the following formula:

$$d_r = \frac{2r}{\sqrt{1-r^2}} \quad (4)$$

Where d_r *represents the Cohen's d effect size calculated from a correlation coefficient (r).*

The standard error was calculated as the standard error of a Fisher's distribution and then translated back with the hyperbolic function. This value was also transformed into a d effect size.

$$SE_{Z_r} = \frac{1}{\sqrt{n-3}} \quad (5)$$

Where SE_{Z_r} *represents the standard error of a correlation coefficient in a Fisher's distribution and n is the sample size.*

For the case where Risk Ratios and Odds Ratios were reported with their standard error, the statistics were standardized into a Cohen's d using the following equation:

$$d_{OR} = \frac{\ln(OR)\sqrt{3}}{\pi} \quad (6)$$

Where d_{OR} *represents the Cohen's d effect size calculated from an Odds Ratio (OR).*

Ultimately, this process yielded all affect sizes expressed as a Cohen's d with a corresponding 95% confidence interval as suggested by Lipsey and Wilson (2001).

2.10.4 Overall effect size calculation

In this last step the effect sizes for multiple studies investigating the same relationship were aggregated into an overall effect size. There are two basic ways of performing this aggregation: the homogeneous effect meta-analysis and the random effect meta-analysis. The homogeneous effect meta-analysis is only valid for exact replications of an experiment. Here, there were few replications and far more studies that used a variety of methods and sample sizes. Thus, we used the random effect meta-analysis in those situations. This method not only accounts for variability within a sample due to chance, but also accounts for true variability among samples from different studies. This ensured that each effect size was weighted according to the quality of the study from which it was taken. Furthermore, random effect meta-analysis doesn't allow any study to dominate. The inverse variance weight method was employed and each effect size (d) was weighted by the inverse of its variance. An overall effect for each relationship was calculated using Eq. (7). In some cases, when only one study reported an effect size for a relationship, the effect was converted to Cohen's d and reported for such relationship.

$$ES_d = \frac{\sum w_i d_i}{\sum W_i} \quad (7)$$

Where ES_d *represents the overall effect size,* W_i *stands for each individual effect size weight and* d_i *denotes each individual effect size.*

The standard error was computed using Eq. (8):

$$SE_{ES_d} = \sqrt{\frac{1}{\sum W_i}} \quad (8)$$

Where SE_{ES_d} *represents the overall effect size standard error and* W_i *stands for each individual effect size weight.*

The equations presented above are sufficient for the fixed effect meta-analysis, however, in order to compute a random effect meta-analysis three additional equations are required to evaluate the homogeneity, random effect variance, and random effect weights using Eq. 9, 10, and 11, respectively.

$$Q = \sum w_i (d_i - ES_d)^2 \quad (9)$$

Where Q *represents the homogeneity statistic,* d_i *denotes each individual effect size, and* ES_d *represents the overall effect size.*

The homogeneity statistic is used to calculate the variance associated with true differences among different studies, such variance receives the name of *random effect variance* (t^2) as shown in q. 10.

$$t^2 = \frac{Q - df_Q}{\sum W_i - \frac{\sum W_i^2}{\sum W_i}} \quad (10)$$

Where t^2 *represents the random effect variance,* Q *is the homogeneity statistic,* df_Q *represents the degrees of freedom of Q, and* W_i *stands for each individual effect size weight.*

With this random effect variance, a new set of weights for each effect size can be calculated.

$$W_i' = \frac{1}{SE_d^2 + T^2} \quad (11)$$

Where W_i' *represents the random effect weights for each effect size,* SE_d *is the standard error of the statistic d, and* t^2 *stands for the random effect variance.*

With this new set of weights, the random effect sizes are calculating by applying Eq. (7) and substituting W_i by W_i'.

2.11 Results of the meta-analysis

The application of our meta-analysis method yielded the results summarized in Tables 5 through 8. Note that when only one study is reported on a specific relationship, the Cohen's d in the tables represents the effect size of that single study. In these tables, the column heading **"n.t"** represents the sample size of the treatment group, **"n.c"** represents the sample size of the control group, and 95% CI represents the upper and lower bounds of the 95% confidence interval. The relationships derived from this meta-analysis are depicted in a revised systems model in Figure 3. Here, the line thickness corresponds directly to Cohen's d, the aggregated effect size.

Table 5 Effects of causes of fatigue

Relationship	Source	n.t.	n.c.	Cohen's d	95% CI		p-value
Sleep Deprivation – General Fatigue	Gillberg and Akerstedt (1994) Herscovitch and Broughton (1981)	15	15	1.22	-0.86	3.98	0.125
Mental Exertion – Mental Fatigue	Meijman (1997) Van der Linden et al. (2003)	49	45	0.91	0.47	1.34	0.000
Workload – General Fatigue	Åkerstedt et al. (2002)	18828	18828	0.25	0.23	0.28	0.000
Overtime and LWH – Mental Fatigue	Van Der Hulst and Geurts (2001)	325	325	0.43	0.11	0.75	0.000
Overtime and LWH – General Fatigue	Park et al. (2001) Van Der Hulst and Geurts (2001) Åkerstedt et al. (2002) Beckers et al. (2008)	19652	19864	0.49	0.16	0.82	0.002
Environment – General Fatigue	Gonzalez-Alonso (1999)	7	7	2.83	1.30	4.36	0.000
Social Environment – Mental Fatigue	Maslach and Jackson (1984) Bültmann et al. (2001)	30 11020	30 11020	0.39	0.04	0.74	0.015

Note: n.t. = treatment group sample size; n.c.= control group sample sizew; 95% CI= 95% confidence interval.
One tailed p-values.

Table 6 Effects among causes of fatigue

Relationship	Source	n.t.	n.c.	Cohen's d	95% CI		p-value
Overtime – Incomplete recovery	Van Der Hulst and Geurts (2001)	323	323	0.65	0.36	0.95	0.000

Note: n.t. = treatment group sample size; n.c.= control group sample sizew; 95% CI= 95% confidence interval.
One tailed p-values.

Table 7 Effects of fatigue

Relationship	Source	n.t.	n.c.	Cohen's d	95% CI		p-value
Mental Fatigue - Cognitive Degradation	Van der Linden et al. (2003) Boksem et al. (2005)	48	44	2.24	-0.41	4.90	0.049
Mental Fatigue – Illnesses	Fredriksson et al. (1999)	484	484	0.33	0.26	0.40	0.000
Mental Fatigue – Error and Injury	Van der Linden et al. (2003b)	36	32	0.32	-0.23	0.88	0.126
General Fatigue - Bad Mood	Scott et al. (2006) Kajtna et al. (2011)	15	15	0.95	0.02	1.88	0.023
General Fatigue - Cognitive Degradation	Gosselin et al. (2005) Philibert (2005)	1039	1039	1.00	0.91	1.09	0.000
General Fatigue – Illnesses	Alfredsson et al (1982) Liu and Tanaka (2002)	594	1328	0.10	-0.04	0.23	0.079
General Fatigue - Error and Injury	Dembe et al. (2005) Gosselin et al. (2005)	10804	10805	0.64	-0.01	1.29	0.026
Muscular Fatigue - Physical Degradation	Yaggie and Armstorn (2004)	16	16	0.99	0.25	1.73	0.004
Muscular Fatigue - Illnesses	Fredriksson et al. (1999)	232	232	0.41	0.00	0.82	0.000

Note: n.t. = treatment group sample size; n.c.= control group sample sizew; 95% CI= 95% confidence interval.
One tailed p-values.

Table 8 Effects among consequences of fatigue

Relationship	Source	n.t.	n.c.	Cohen's d	95% CI		p-value
Illnesses – Cognitive Degradation	Vercoulen et al. (1994)	298	60	1.97	1.65	2.28	0.000

Note: n.t. = treatment group sample size; n.c.= control group sample sizew; 95% CI= 95% confidence interval.
One tailed p-values.

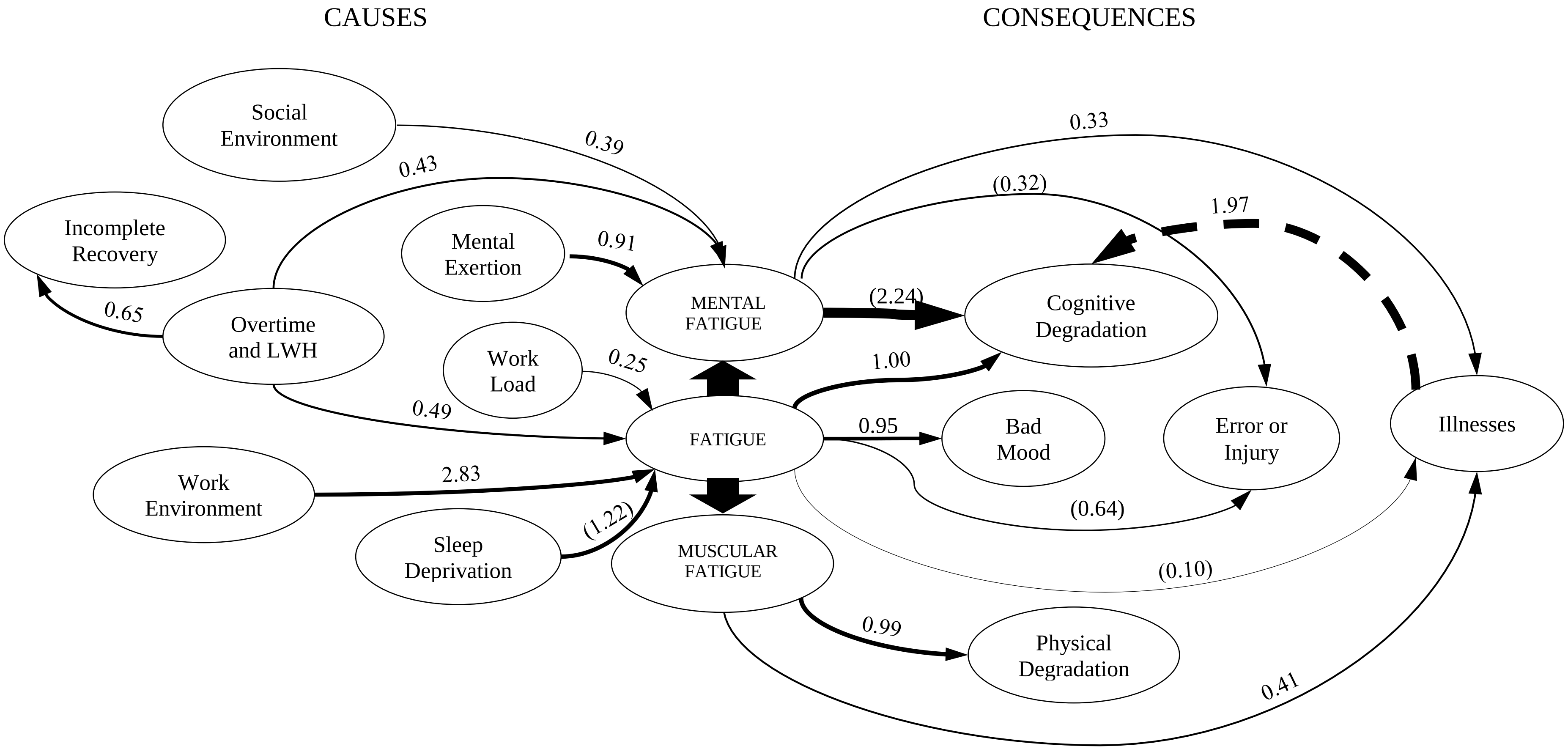

Figure 3: Systems model represents effect sizes (Cohen's d values) for each relationship.

Notation: Arrows indicate direction and line thickness corresponds directly to the magnitude of the effect size from the meta-analysis; (n) indicates a 95% CI that includes zero or non-significance for such an effect size.

2.12 Discussion of the meta-analysis:

In a meta-analysis, an effect between 0 and 0.20 is considered small; between 0.20 and 0.50 is considered medium; and over 0.50, preferable closer to 0.80, is considered large (Cohen 1988). Although most results achieved levels of high statistical significance, some were weak, either because they didn't achieved significance or because their confidence interval was too wide, even including negative values. For example, the effect of sleep deprivation on fatigue was not statistically significant and despite the large effect sizes reported, its confidence interval includes the possibility of a null effect. This was observed because one study in this domain reported results that were not statistically significant (Herscovitch and Broughton 1981). However, the other study included in this relationship presented a large and significant effect (d=2.33; 95% C.I. = 0.97 to 3.68; p-value = 0.000) indicating an important influence of sleep deprivation in the development of fatigue (Gillberg and Åkerstedt 1994). Intuitively some may think that a study that does not report statistical significance should be discarded; however, a meta-analysis all past research results must be considered for a relationship as long as they were obtained through high-quality methods.

The largest significant effect, the relationship between environmental conditions at work such as noise, vibration, and temperature and fatigue, was observed by Gonzalez-Alonzo (1999) in a single study. Such a strong finding with little previous validation indicates the strong need for scientific replication. Other medium effects include the impact of mental exertion, overtime, and LWH on mental fatigue and the impact of social environment and workload on general fatigue.

Only one study provided useful information about relationships among causes of fatigue (Van Der Hulst and Geurts 2001), showing a strong relationship between overtime, LWH, and incomplete recovery. This study confirms that overtime plays an important role as inhibitor of a proper recovery but, again, should be replicated by future researchers to confirm the effects.

Most impacts of fatigue on physiology proved to be large. This was especially true for the effect of general fatigue among cognitive degradation (d=1.00; 95% C.I. = 0.91 to 1.09) and muscular fatigue among physical degradation (d=0.99; 95% C.I. = 0.25 to 1.73). This is not surprising given the relatively large body of knowledge focused on this domain.

The effect sizes of the relationship between mental fatigue and illnesses showed to be moderate and significant. However, this was not the case for general fatigue. A large and significant effects can be observed between general fatigue and error. These results make sense since errors are common consequences of acute fatigue. The influence of fatigue on mood has been characterized as important with a large effect size, (d=0.95; 95% C.I. = 0.02 to 1.82) which agrees with previous research.

2.13 Conclusions and recommendations:

The systems models presented in Figure 2 shows clearly that there is much less research on the system of causal factors of fatigue than on the system of outcomes of fatigue. This may be due to the fact that the outcomes of fatigue are more readily identifiable, and measurable than the causal factors, which can be more difficult to empirically measure. Also, the psychological, health, and medical research community that deals with the health and wellness aspects of fatigue is quite large in comparison to the industrial systems, safety and health, and human factors research community that often deals with the occupational causes of fatigue.

With respect to the causes of fatigue, Figure 2 clearly reveals some knowledge gaps that may be useful for framing new research. For example, there is a wide range of research about the way that fatigue arising from sleep deprivation impacts workers, and also about the way that irregular and extended shifts impact workers. However, there is a clear need for additional research about the way that workload impacts muscular exertion and the recovery process. Both have a logical foundation that could be supported through rigorous research. These are simply a sample of obvious gaps in the knowledge system. The reader may find additional connections upon which to build a future study.

With respect to the consequences of fatigue, even though there is an abundant body of literature addressing the relationship between general fatigue and mood changes, there is no significant research that investigates the relationship between exclusively muscular or mental fatigue and mood changes. Additionally, during our research we also found it strange that there is no substantial research about the way in which mood changes affect work relationships, which seems to be a reinforcing process. The relationship between mood and cognitive functions is ripe for both confirmatory and seminal investigation.

The meta-analysis of the causes and consequences of fatigue illustrated in Figure 2 revealed significant gaps in empirical evidence of fatigue-related factors. In fact, only 23 studies provided sufficient empirical data. Furthermore, there is a dearth of replication among fatigue studies, indicating a strong need for scientific validation. Future research is especially needed to confirm proposed relationships among causal factors and among outcomes of fatigue. Since the medical field has examined the relationship between fatigue and physiology, the impact of fatigue on other, less direct outcomes like work performance, is needed.

This paper adds to the efforts of previous researchers to help formalize the study of fatigue among the working population. It can serve as a point of departure for future research to evaluate what has been done, where extra research is needed, and how to organize such research to contribute to the enlargement of the current body of knowledge.

2.14 Acknowledgements

We would like to thank the ELECTRI International for supporting this research. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of ELECTRI International.

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Chapter 3: Fatigue Management in Electrical Transmission and Distribution Work

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3.1 Abstract

Objective: The electrical transmission and distribution power line (TD) sector presents a high fatality risk. Fatigue greatly contributes to human error and injuries. The objective of this study is to determine the fatigue risk factors in TD work.

Methods: A sample of 143 TD workers from the northeast coast of the U.S. participated in the study. Standardized interviews were performed.

Results: Extreme temperatures (p-value 0.004) and long shifts (p-value < 0.001), were identified by the workers as the principal contributors to their fatigue. Reduced work pace (p-value < 0.001), and the loss of attention (p-value < 0.001) are the main consequences of fatigue observed.

Conclusions: The current study presents the basis for the development of a fatigue risk management system in the TD sector. Further research with a larger and more diverse sample is suggested.

3.2 Introduction

Most communities require a continuous supply of electrical power for the production of basic goods, processing of water, and establishment of public safety(Balducci et al. 2003). Simply,

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electrical power grids help to define the way we live. The delivery of electric power from its point of generation to its point of use is conveyed through transmission and distribution (TD) power lines and associated infrastructure that is constructed, operated, and maintained in the US by over 110,000 TD workers. These workers are exposed to high voltage, work at height, confined spaces, and extremely harsh weather conditions. These risks translate to electrocutions, electrical shocks, falls from high elevations, injuries from falling objects, overexertion, contusions, cuts, and lacerations(U.S. Department of Labor 1996).

In comparison to the average occupation, TD construction, operation, and maintenance is nearly an order of magnitude more dangerous. According to the U.S. Bureau of Labor Statistics (2015)(U.S. Bureau of Labor Statistics 2015) in 2014 the all-industry fatality rate was 3.3 per 100,000 full-time equivalent workers (FEW) and the construction fatality rate was 9.4. That same year, the TD subsector accounted for a rate of 19.2 fatalities per 100,000 FEW. During the past 20 years, the mean fatality rate for TD workers has been, on average, eight-times greater than the all-industry average. These statistics set TD work among the 10 deadliest jobs in the country.

In 2014 the Occupational Safety and Health Administration (OSHA) created new regulations for the TD sector (U.S. Department of Labor 2015), replacing regulations that were nearly 40 years old. The new regulations address several new subjects such as proper training, job briefings, fall protection, insulation, protection equipment, and minimum distances to live charge sources. With this new set of rules, OSHA expects to save approximately 20 lives and prevent 118 serious injuries annually (U.S. Department of Labor 2015).

Unfortunately, the regulations provide very little guidance for the detection and management of worker fatigue. However, research has shown consistent evidence that fatigue plays a significant and important role in accident causation (Craig 1992; Czeisler et al. 1992; van der Linden et al. 2003a; Lorist et al. 2000; Tixier et al. 2014). In fact, fatigue has been shown to trigger human error, which when combined with hazardous environments led to catastrophic events like Three Mile Island, Chernobyl, and the Exxon Valdez oil spill (Harrington 2001). Given that TD operations often involve working with live charges of over 500,000 volts, TD workers are especially vulnerable to fatal accidents. The most significant causes of occupational fatigue are lack of sleep, long shifts, involuntary overtime, high temperatures, and heavy workload(Techera et al. 2016). These factors are ubiquitous in TD operations.

The objectives of this paper are to specifically study TD work and identify and describe the: (1) specific causes of worker fatigue; (2) consequences of fatigue, (3) role of fatigue in injuries, (4) methods for self-diagnosing fatigue and recognizing fatigue in co-workers; and (5) methods to prevent or mitigate fatigue. Importantly, we also aim to understand the role that demographics play in all of these aspects of TD worker fatigue. This is the first detailed study of occupational fatigue in the TD sector.

3.3 Background

3.3.1 The importance of TD operations

The demand for electrical power has grown exponentially during the past 3 decades as the use of technology has swiftly increased. In the United States, about 4 billion megawatts per hour (mWh) of electrical power is produced yearly to meet demand. This production generates approximately 388.1 billion dollars in revenue (U.S. Energy Information Administration 2016).

The ability to reliably deliver energy is a primary driver of the economy of developed countries (Balducci et al. 2003). The public and private sectors have collaborated to ensure reliable delivery of power to prevent the costly negative consequences of power outages, especially for the industrial and commercial sectors. For example, the U.S. bulk power grid provides power for the operation of lights, appliances, and electric motors with a reliability of 99.96% translating to 3.5 hours of power grid downtime per year (Balducci et al. 2003). This level of reliability is achieved by the deployment of TD workers who construct and maintain the electrical grid. It is also these workers who respond in emergency situations to restore power during outages caused by weather events, disasters, and other disruptions.

3.3.2 Safety in TD work

Because of the regular exposure to electrical lines, TD workers are constantly in high-risk environments. Contact with an energized line, whether through direct contact or arc flash, can cause immediate death (Cadick et al. 2005). The transmission of a current through the human body affects the nervous, muscular, cardiovascular, and pulmonary systems. It can cause external damage such as burns and also internal tissue damage compromising organs and limbs (Gordon and Cartelli 2009; Spies and Trohman 2006). Furthermore, due to electrical ignition, falls, and fire, these damages can occur even when there is no direct contact with the electric source (Cadick et al. 2005).

Albert and Hallowell (2013) conducted the only notable research into TD safety. Their study evaluated the efficacy and cost of safety measures in TD operations based on the opinion of experts (Hallowell et al. 2011). The results showed that strict adherence to OSHA regulations and the employer's life-saving rules were perceived to be the most effective strategies to promote a safe environment (91% consensus). This was followed by de-energizing the lines (86%) and the use of insulated poles that prevent electric shock (81%). Despite the perceived effectiveness of de-energizing lines, the cost is prohibitive due to disruptions in service. The implication is that TD work must be performed on energized lines and that strict adherence to standard operating procedures and the use of personal protective equipment (PPE) is the only feasible method of controlling exposure. The result is a very dangerous work environment compounded by controls that are susceptible to human error. Unfortunately, as will be discussed, fatigue compromises cognitive and physical functions and ultimately causes human error. Thus, fatigue management is critically important for the TD sector.

3.3.3 The influence of fatigue on safety

Fatigue plays a significant role in many occupational injuries and fatalities, particularly in hazardous environments when concentration and skill are required to prevent contact with danger. Fatigue can be defined as a decreased ability to perform activities at the desired level due to lassitude or exhaustion of mental and/or physical strength (Gander et al. 2011; Hallowell 2010). When workers are fatigued, they experience compromised alertness, judgement, reaction time, mental acuity, physical strength, and the development of an uncooperative disposition (Gillberg and Åkerstedt 1994; Kajtna et al. 2011; van der Linden et al. 2003a; Lorist et al. 2005; Scott et al. 2006; Yaggie and Armstrong 2004). Such effects decrease a worker's ability to complete their work safely due to the increased rate of human error (Dembe et al. 2005). Thus, it is not surprising that many researchers include fatigue as a salient factor in most accident causation theories (Craig 1992; Czeisler et al. 1992; van der Linden et al. 2003a; Lorist et al. 2000, 2005; Scott et al. 2006; Yaggie and Armstrong 2004).

As described by Spurgeon et al. (1997) there are two primary reasons why fatigue compromises safety in an occupational environment. First, fatigue diminishes the ability of an individual to perceive and react to new information. Mental fatigue impairs the processing of such information, making it more difficult for an individual to understand incoming information and exercise judgement (Lorist et al. 2000; Reiner and Krupinski 2011). Second, fatigue diminishes the ability of an individual to accurately perceive and respond to risk, thereby clouding situational awareness and compromising decision making (Tixier et al. 2014).

3.3.4 Causes and consequences of occupational fatigue

Since the focus of this paper is on identifying specific causes and consequences of fatigue for TD workers, we have provided a brief review of the causes and consequences of occupational fatigue in the general literature. Since this is a very broad field of study, we cannot include a detailed description here. Rather, we refer the reader to Techera et al. (2016) for a comprehensive review of these factors.

Researchers have found that sleep deprivation (Åkerstedt 1990; Bliwise et al. 1992; Dawson and McCulloch 2005; Webb and Agnew Jr 1975; Zhang and Liu 2008), environmental conditions such as noise (Kjellberg et al. 1998; Krause et al. 1997; Landström and Löfstedt 1987), temperature (González-Alonso et al. 1999; Zivin and Neidell 2010),light (Park and Gotoh 1993), and vibration (Jiao et al. 2004; Landström and Löfstedt 1987), muscular exertion (Brown 1994; Grandjean 1979; Jason et al. 2010), overtime and long working hours (Beckers et al. 2008; Gander et al. 2011; van der Hulst and Geurts 2001; Meijman 1997; Park et al. 2001), incomplete recovery (Beurskens et al. 2000; Jason et al. 2010; Swaen et al. 2003), poor social environment (Bültmann et al. 2001; Hardy et al. 1997; Tepper 2000; Zapf and Gross 2001), heavy workload (Åkerstedt et al. 2002b; Boksem et al. 2008; Ribet and Derriennic 1999), and negative individual emotional predisposition (Ala-Mursula et al. 2005; Bültmann et al. 2001) are primary drivers for occupational fatigue. These causes are summarized in Table 9 together with their relative effect sizes(Techera et al. 2016). Also, the main consequences of fatigue in a work environment are presented in Table 10.

Table 9 Effect Size of causes of fatigue

Causes of fatigue	Cohen's d (95% C.I.)	p
Work Environment	2.83 (1.30 – 4.36)	0.000
Sleep Deprivation	1.22 (-0.86 – 3.29)	0.125
Mental Exertion	0.91 (0.47 – 1.34)	0.000
Overtime and Long Working Hours	0.49 (0.16 – 0.82)	0.002
Social Environment	0.39 (0.04 – 0.74)	0.015
Workload	0.25 (0.23 – 0.28)	0.000

Table 10 Effect Size of consequences of fatigue

Consequences of fatigue	Cohen's d (95% C.I.)	p
Cognitive Degradation	100 (0.91 – 1.09)	0.000
Physical Degradation	0.99 (0.25 – 1.73)	0.004
Bad Mood	0.95 (0.02 – 1.88)	0.023
Error and Injury	0.64 (-0.01 – 1.29)	0.052
Illnesses	0.33 (0.26 – 0.40)	0.000

3.4 Point of departure and contribution to knowledge

This study deviates from and adds to the body of knowledge through the first investigation of occupational fatigue in the TD sector and collection of data directly from workers. Most fatigue research focuses on fatigue in general or in laboratory settings rather than in the context of specific occupational environments. In general, TD workers are exposed to a different risk profile than most workers because they are regularly assigned to extended shifts and overtime, are exposed to the elements in often extreme weather conditions, are required to work at heights or in confined spaces, and they perform much of their work in remote locations that are far away from home. This work profile demands specific attention because the causes of fatigue may be different and the consequences of fatigue can be dire. Also, within the context of their work environment, TD workers must be able to self-diagnose fatigue and recognize fatigue in co-workers, especially when working in remote locations where access to resources is limited. Therefore, we aimed to identify the specific causes and consequences of worker fatigue for TD workers, the role of fatigue in past incidents in TD work, methods for self-diagnosing fatigue and recognizing fatigue in co-workers, and methods to prevent or mitigate fatigue in remote and often hostile conditions. As we present our results we link to the existing body of knowledge to ultimately draw a comparison between TD work and the general industry. Finally, we aim to investigate the role that demographics play in these salient aspects of fatigue management for the first time (e.g., how age relates to the causes of fatigue).

3.5 Research methods

Since there is a dearth of previous research into TD worker fatigue, we began with no assumptions. Consequently, we did not develop and test a hypothesis; rather, we performed an exploratory study and obtained data directly from a large population of TD workers in their field with open-ended interview questions.

3.5.1 Development of questionnaires

Despite the exploratory nature of this study, we aimed to obtain quantitative answers to allow for prioritization and statistical analyses. We used standardized survey interviews (SSI), which allow for comparison among interviewees and for the production of quantitative descriptive data(Fowler, Jr. and Mangione 1990). At the same time SSIs give the desired flexibility for examination and further clarification needed in an exploratory process (Fowler, Jr. and Mangione 1990). Two brief SSI questionnaires were developed, one for workers and one for their supervisors. We aimed to ensure that the questions were open-ended, clear, simple, and direct.

The questions are as follows:

Questions for TD workers:

1) What contributes to your fatigue?
2) How does fatigue affect your work performance?
3) How do you know when you or one of your coworkers is fatigued?
4) What do you do if you are fatigued?
5) What could you do differently in order to prevent fatigue?
6) Have you ever had an accident? If yes, were you fatigued at the time?

7) How fatigued do you feel on a daily basis from 1 to 10? —1 being not fatigued at all and 10 being extremely fatigued, to the point that you can't continue working.
8) How fatigued do you feel towards the end of the work week (from 1 to 10)?

Questions for TD supervisors:

1) How do you recognize when your workers are fatigued?
2) What do you do to help them when they are fatigued?
3) How does fatigue impact workers' performance?
4) What are the most difficult aspects of managing fatigue?
5) What do you think needs to change in order to help the workers not become fatigued?
6) How fatigued do you think the workers are on a daily basis from 1 to 10? —1 being not fatigued at all and 10 being extremely fatigued, to the point that they can't continue working.
7) How fatigued do you think the workers are towards the end of the work week (from 1 to 10)?

As one can see the two questionnaires are similar. Questions regarding the level of fatigue were purposely asked in the manner to allow for comparisons between the perspectives of supervisors and workers.

3.5.2 Respondent demographics

The sample population was comprised of 143 participants from the Northeastern United States, divided into 123 workers and 20 field supervisors. These participants belonged to one of the following categories: Underground operations, substation operations, or overhead operations. The demographics of the participants is described in Table 11.

Table 11 TD workers and supervisors' demographics

TD			Age		Experience	
		N	**μ (y/o)**	**σ (yrs)**	**μ (y/o)**	**σ (yrs)**
Underground	Workers,	77	41.5	11.0	14.4	11.8
	Supervisors	12	48.6	15.1	27.8	13.8
Substation	Workers,	33	40.1	13.2	14.5	12.8
	Supervisors	4	-	-	-	-
Overhead	Workers,	13	34.3	9.3	13.5	8.3
	Supervisors	4	48.5	8.3	28.0	9.3

Notation: (-)No demographic information was available for substation supervisors

The data were collected from workers in the summer months. During this time, 29% of the participants were working extended shifts (about 13hs a day) due to an emergency situation caused by abundant rain in the area. Additionally, during that period the weather was sunny with a mean temperature of 79^{o}F.

3.5.3 Data manipulation and statistical analysis:

Literal answers to each question were entered for every participant. During coding, some answers such as "loss of concentration", "distraction", and "loss of focus" were combined into one category with the name "loss of attention". Similarly, "high temperatures", "heat", "cold", and "low temperatures" were codified as "extreme temperatures." However, the original data were always preserved. Once the data were coded, the frequency of each answer was calculated.

When evaluating the causes and consequences of fatigue, a one-way Chi-square analysis for associations was performed in order to distinguish significant from non-significant relationships and responses. The Chi-square analysis requires independence of data. Consequently, for every question asked to a participant, we only considered the first answer for the Chi-square analysis. Often, participants gave several answers to a given question. For example, for the question: “what contributes to your fatigue?” most participants indicated several answers such as “lack of sleep”, “high temperatures”, and “heavy work”. In order to comply with independence, only the first answer of each participant was considered for the Chi-square analysis. Therefore, in the case of the presented example, only the answer “lack of sleep” would be considered for Chi-Square. The decision of choosing the first answer allows for the consideration of all participants because some of them gave only one answer. The other answers were preserved for future analyses.

For variables that showed to have a significant association in the Chi-square analysis, individual proportion tests were performed. Further statistical analyses were performed to test for significant differences among distinct demographic groups. For instance, all variables were tested for variation due to age and trade. When sample sizes of specific groups were too small for a Chi-square test, Correspondence Analyses (CA) were performed to visually identify any possible underlying association (Spencer 2013). The main purpose of a CA is to represent the complex nominal data presented in a contingency table in a plot (low dimensional space) were each point represents a variable or category (Spencer 2013). Variables with a similar distribution will appear close to each other in a 2D representation (Spencer 2013). This would indicate a possible association among such variables. Lastly, variables that showed similar behavior in the CA were merged and a two-way Chi-square test of these combined subgroups was performed.

3.6 Results and analysis

3.6.1 Results from TD workers:

The univariate results of the interviews with TD workers are summarized in Table 12. The results are specified for each major work type: underground utility work, substation work, and overhead line work. The variables included in Table 12 are those which were mentioned by at least 9% of the workers in each category. Bonferroni correction for multiple tests was applied when reporting significance. Table 13 summarizes the extent to which workers felt that fatigue had played a role in their past incidents (note that this assessment was not performed among substation workers due to an insufficient sample size). Lastly, Table 14 summarizes the self-reported levels of fatigue experienced weekly and daily for each work type.

Table 12 Overall results from electrical workers

Summary table	Underground	Substation	Overhead	Total
Causes of fatigue	n=76	n=33	n=13	n=122
Extreme Temperatures	63%*	82%*	31%	65%
Long Shifts	39%*	33%	62%	40%
Lack of Sleep	30%	52%	31%	36%
Heavy Manual Labor	24%	9%	22%	19%
Family Responsibilities	14%	-	-	-
PPE	14%	-	15%	-
Double Shifts	12%	6%	-	-
Excessive Workload	12%	9%	-	-
Consequences of fatigue	n=71	n=29	n=13	n=113
Loss of Attention	44%	69%*	15%	47%
Slow Down	52%*	17%	54%	43%
Rush up	17%	-	-	-
Mistakes	14%	-	8%	-
Forgetfulness	10%	-	-	-
Fatigue mitigation strategy	n=77	n=31	n=13	n=121
Take a Break	57%*	58%	46%	56%
Coffee	34%	52%*	23%	37%
Water	45%*	10%	31%	35%
Eat	17%	32%	8%	20%
Power Nap	18%	13%	31%	18%
Fresh Air	17%	3%	-	-
Energy Drinks	13%	6%	-	-
Slow Down	10%	35%	-	-
Fatigue identification	n=76	n=32	n=13	n=121
Body Language	28%*	31%	31%	29%
Slow Down	18%	56%*	23%	29%
Bad Language	18%	-	-	-
Vocalize it	22%	9%	8%	17%
Different Behavior	14%	3%	-	-
Loss of Attention	9%	28%	8%	14%
Bad Mood	13%	41%	-	-
Drowsy	11%	3%	-	-

Requested improvement	n=62	n=25	n=12	n=99
Better Break Policy	26%	20%	8%	22%
Hiring	26%	8%	8%	19%
Inclement weather clause	-	12%	33%	-
Receive Water	13%	-	17%	-

(*) Significant. Note: According to Bonferroni correction, significance varies from <0.025 for “Causes of fatigue” and “Fatigue mitigation strategies” to <0.05 for the remaining variables.

Table 13 Percentage of accidents attributed to fatigue by worker

Accidents and fatigue	Underground	Overhead
	n=68	n=12
No Accident	57%	17%
Accident not fatigue related	21%	50%
Accident fatigue related	22%	33%

Table 14 Self-reported level of fatigue

Self-reported level of fatigue (1-10) *	Underground			Substation			Overhead		
	Mean	Median	Mode	Mean	Median	Mode	Mean	Median	Mode
Daily	5.3	5.0	5.0	4.2	4.0	5.0	3.7	3.5	5.0
Weekly	7.3	8.0	8.0	5.7	5.5	3.0	5.3	5.5	7.0

(*) 1 means not tired at all; 10 means so tired that you must stop working

One-way Chi-square and proportion test results:

After considering the first answer to each question from every electrical worker, only the data obtained from underground workers and substation workers showed to be significant and the results are presented here.

Tables 15 and 16 present a one-way Chi-square analysis of the data obtained from underground and substation workers. The purpose of this analysis was to determine if the obtained results represent significant underlying associations or if such results could have been obtained by chance and chance alone. Once significantly different categories (different answers) were identified, a proportion test was performed between each pair of variables to find the probability of obtaining each specific difference. This final difference is described by a p-value, which is drawn from a binomial distribution.

Table 15 One-way Chi-square test and proportion test results for underground workers

Causes of fatigue	Categories: 9	χ^2 = 53.7	p-value: <0.000
	Expected Frequency: 8.4	**Proportion Test (sig. p-val.<0.025)**	
Answers (n= 76)	Actual Frequency	95% C.I.	p-value
Extreme Temperatures	19	12.0 – 27.6	0.001
Long Shifts	20	12.8 – 28.6	<0.000
Consequences of fatigue	Categories: 6	χ^2 = 45.6	p-value: <0.000
	Expected Frequency: 11.8	**Proportion Test (sig. p-val.<0.05)**	
Answers: (n=71)	Actual Frequency	95% C.I.	p-value
Slow Down	30	21.7 – 38.7	<0.000
Fatigue mitigation	Categories: 7	χ^2 = 35.9	p-value: <0.000
	Expected Frequency 11.0	**Proportion Test (sig. p-val.<0.025)**	
Answers (n=77)	Actual Frequency	95% C.I.	p-value
Take a Break	24	16.2 – 32.9	<0.000
Water	19	12.0 – 27.6	0.022
Fatigue identification	Categories: 6	χ^2 = 15.1	p-value: 0.009
	Expected Frequency: 12.7	**Proportion Test (sig. p-val.<0.05)**	
Answers (n=76)	Actual Frequency	95% C.I.	p-value
Body Language	21	13.7 – 29.7	0.023
Requested improvements	Categories: 4	χ^2 = 10.4	p-value: 0.017
	Expected Frequency: 15.5	**Proportion Test (sig. p-val.<0.05)**	
Answers (n=62)	Actual Frequency	95% C.I.	p-value
Receive Water	3	0.6 – 8.4	<0.000

Table 16 Chi-square test and proportion test results for substation workers

Causes of fatigue	Categories: 6	χ^2 = 18.8	p-value: <0.002
	Expected. F: 5.5	**Proportion Test (sig. p-val.<0.05)**	
Answers (n=33)	Frequency (1st answer)	95% C.I.	p-value
Extreme temperatures	13	7.6 – 19.1	0.004
Consequences of fatigue	Categories: 5	χ^2 = 26.7	p-value: <0.000
	Expected. F: 5.8	**Proportion Test (sig. p-val.<0.05)**	
Answers (n=29)	Frequency (1st answer)	95% C.I.	p-value
Loss of attention	17	11.3 – 22.2	<0.000
Fatigue mitigation	Categories: 6	χ^2 = 27.9	p-value: <0.000
	Expected. F: 5.2	**Proportion Test (sig. p-val.<0.05)**	
Answers: (n=31)	Frequency (1st answer)	95% C.I.	p-value
Coffee	15	9.3 – 20.7	<0.000

Fatigue identification	Categories: 5	$\chi^2 = 10.2$	p-value: 0.037
	Expected. F: 6.4	**Proportion Test (sig. p-val.<0.05)**	
Answers (n=32)	Frequency (1st answer)	95% C.I.	p-value
Slow down	12	6.8 – 18.0	0.033

<u>Analysis of Chi-square tests results</u>

Perceived causes of TD worker fatigue:

Three main causes of fatigue were identified among all TD workers: “extreme temperatures”, “long shifts”, and “lack of sleep”. These results confirm the importance of these variables in the development of fatigue as described by several previous authors (Beckers et al. 2008; Belenky et al. 2003; González-Alonso et al. 1999; van der Hulst and Geurts 2001; Lim and Dinges 2008; Van Dongen and Dinges 2005). Despite the fact that the results of this study indicate “extreme temperatures” as a main contributor to fatigue, very little research has been done regarding the influence of temperature in fatigue development. Consequently, future research should address this gap in knowledge.

Perceived consequences of fatigue among TD workers:

Two main consequences of fatigue were identified across all sub-trades: (1) loss of attention and (2) decreased productivity. Assuming that working slower affects productivity, then it is appropriate to associate fatigue with an overall decrease in productivity. Also, lack of attention induced by fatigue has been shown to compromise risk perception and decision making and increase human error, all of which can contribute to accidents at work (Folkard and Tucker 2003; Tixier et al. 2014). The perceived negative consequences identified here confirm some findings from previous studies in other industries. For example, a study in the oil and gas construction sector found that cognitive impairments, unsafe behavior; improper use of equipment, tools and

PPE, and even improper communication were outcomes of fatigue (n=321)(Chan 2011). Given the consistency in findings, it is likely that the negative outcomes of fatigue in TD work are the same as other industries while the margin for error is less with electrical work.

Methods to mitigate and manage TD worker fatigue:

In order to mitigate fatigue, workers take a break and drink water or coffee. It is important to mention that for this analysis, the frequency of the variable “take a break” was determined only by those answers that specifically mentioned “take a break”. Many other variables such as drink water, drink a coffee, or take a power nap, also imply to take a break. However, these later variables were considered as separate mitigation strategies. Despite the fact that power naps were the next most mentioned strategy to mitigate fatigue among workers, this procedure is currently not allowed by most employers. This situation may change in the future given the growing evidence that power naps increase both productivity and safety (Purnell et al. 2002; Rosekind et al. 1995; Sallinen et al. 1998).

Methods to identify fatigue in co-workers:

Identifying fatigue in co-workers is important to properly manage fatigue. Electrical TD work is typically performed by crews of 2 to 6 workers who usually work together for a long period of time. Consequently, TD workers are familiar with their coworkers and this allows them to identify subtler changes in behavior produced by fatigue. Not surprisingly, “body language” was found to be the most mentioned and significant (p-value: 0.023) way of recognizing a fatigued coworker. Besides this form of identifying fatigue among coworkers, interviewees also noted a slowing in work-pace as a sign of fatigue (p-value: 0.033). Not many researchers have investigated the way in which individuals identify fatigue among coworkers. However, these findings confirm suggestive results obtained by Lerman et al. (2012).

Suggested changes to better manage TD worker fatigue:

Even though the suggested fatigue mitigation methods were not found to be significant in a Chi-square analysis, the suggestions are useful as a starting point for future research and policy development. The most frequently mentioned suggestion were: (1) a better break policy that allows for more frequent breaks where power naps are allowed (suggested by 22% of interviewees); (2) increasing manpower (19%); (3) receiving water from the employer (10%); (4) an inclement weather clause that restricts the work to only emergency tasks during extremely hot or cold days (7 %). The perceptions were that suggested improvements would help mitigate the primary causes of TD worker fatigue (i.e., extreme temperatures, long shifts, and work load).

Correspondence analysis results and interpretation

Correspondence analysis was used to investigate the underlying associations among all variables, including demographics. That is, CA was used to investigate associations between causes of fatigue, consequences, identification strategies, and mitigation strategies, age, and trade. After performing CA some variables were consolidated and new two-way Chi-square analysis were performed. These analyses were complemented by individual proportion tests to evaluate significance of unique associations.

CA was used because it allowed for a visualization of the data structure, which enabled comparisons among demographic groups (Spencer 2013). For example, we hypothesized that the causes of fatigue are different for workers of varying ages or trades. Given a contingency table, CA compares the observed frequency of responses to the expected random frequency. When a significant deviation from the expected random frequencies is observed one can conclude that the association is significant. Furthermore, similar profiles help researchers to identify variables that behave similarly, which can be useful for dimension reduction (Greenacre 2007).

The concept of mass, inertia, and Chi-square distances are important in CA. The mass of a row in a contingency table refers to the total frequency of a row divided by the addition of all row frequencies. In the case of independent data (homogeneity), this number is equal to the sample size. The concept of inertia refers to a weighted Chi-square distance, which in the case of the inertia of a contingency table it is equal to the Chi-square statistic divided by the sample size. Lastly, Chi-square distances are a weighted Euclidean distance, where the weight corresponds to the column or row mass. Consequently, we can see a parallelism between the deviation of a specific frequency from the expected frequency and the Chi-square distance (Greenacre 2007).

Correspondence analysis allows for the graphical representation of variables and categories in a best-fitting plan where the Chi-square distances among variables and categories or between variables and categories are represented. There are 3 possible representations: (1) Asymmetrical Row Principal Normalization in which the row profiles are represented in their principal dimension; (2) Asymmetrical Column Principal Normalization in which the column profiles are represented in their principal dimension; and (3) Symmetrical Normalization in which both profiles are represented in their principal dimension. In these 3 cases, the principal dimensions are those which minimize the Chi-square distances of the individual profile elements to the average profile. Consequently, those points further away from the origin represent a frequency different from the expected frequency. Furthermore, two variables that appear close to each other manifest a similar behavior. Lastly, in an Asymmetric Row Principal Normalization, if a category is closer than the other categories to a specific variable, it is possible to deduce that the relative frequency of such a variable is highest for that category. For example, if a specific contingency table has hair color for rows and eye color for columns, row principal normalization will represent light color hair close to light color eyes and further away from darker color eyes (Greenacre 2007).

It is important to underline that asymmetric normalizations give us information regarding possible associations among variables or categories and between variables and categories for data sets with high dimensionality such as this. For example, by looking at an asymmetric normalization it is possible to consider the proximity of certain variables and the distances between variables and categories. On the other hand, symmetric normalizations only allow us to make inferences within variables or categories but not between them (Greenacre 2007).

Correspondence analysis for consequences of fatigue and trade:

From Figure 4 we can see that underground workers may be more prone to ‘slowing down’ when fatigued, compared to the other trades. This can be seen in Figure 4 because the graphical representation for “slow down” is closer to the graphical representation for underground workers than to the other trades. Likewise, the same graphic suggests that substation workers experience ‘lack of attention’ more than the other trades. Despite the low inertia represented by the raw principal normalization plot (28.4%), a new Chi-square test showed a that these associations were significant (χ^2 = 15.97, p-value = 0.003). This latter association may be explained by the fact that substation workers spend most of their time in one location (the substation) while underground and overhead workers are constantly changing from one location to another. Familiarity with the environment may reduce alertness and attention, especially under the effects of fatigue. This new hypothesis should be tested in future research. Figure 5 shows that some consequences of fatigue have similar profiles given their proximity in the graphical representation. However, these associations don't add value to the analysis already described and for that reason they are not explained.

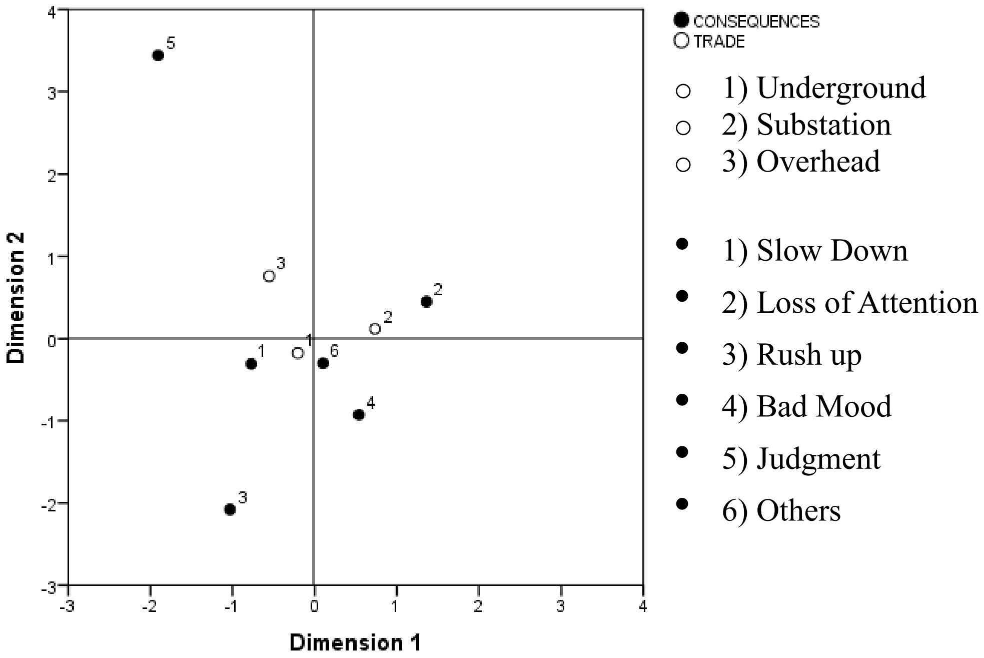

Figure 4 Row principal normalization of consequences of fatigue and trade

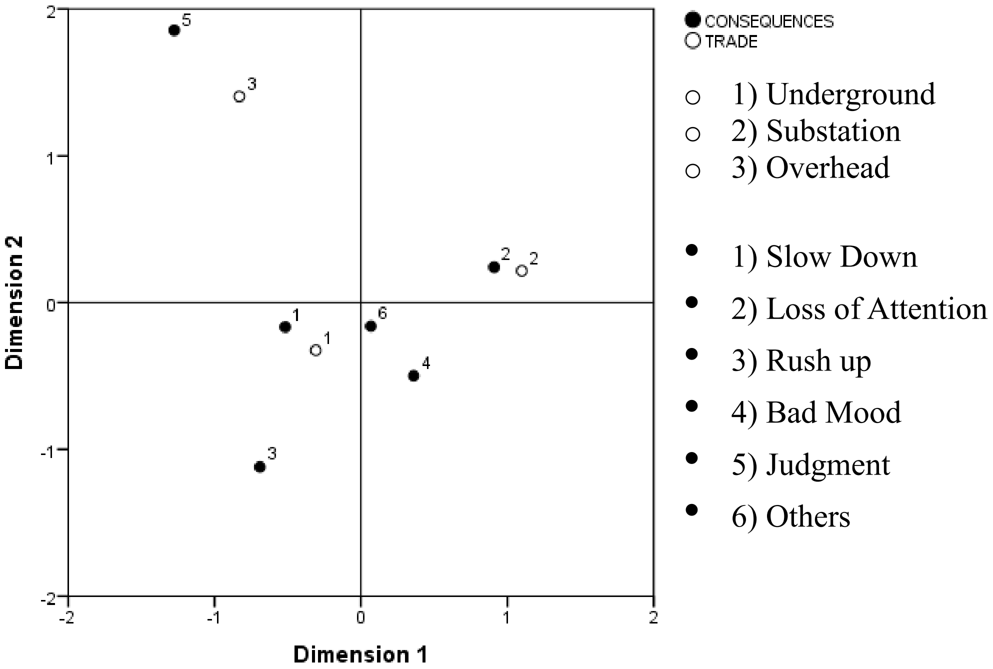

Figure 5 Symmetric normalization of consequences of fatigue and trade

Correspondence analysis for methods to identify fatigue and trade:

Figure 6 shows that underground workers identify fatigue among their coworkers by changes in body language, the use of foul language, and specific mention of being tired. From the same figure, it is possible to infer an association between substation workers and specific fatigue identification techniques. In this case, we can see that these workers mostly identify fatigue by noticing a slower pace of work and lower cooperation among their coworkers. All these associations are interpreted from the graphical proximity of certain fatigue identification techniques to specific trades. Similar to the previous case, the raw principal normalization represented only 17.5% of the total inertia. Nonetheless, these associations were confirmed as significant in a new Chi-square test ($\chi^2 = 13.64$, p-value = 0.009).

The associations among fatigue identification techniques described in the previous paragraph can be visually recognized in Figure 7 by the proximity of the graphical representation of specific fatigue identification techniques. For example, we see that identification techniques 1,2, and 3 are close to each other. This indicates that the column profiles of these variables may be similar. Consequently, under that assumption we can say that when workers identify fatigue by a change in body language they also identify fatigue by noticing the use of bad language and manifestations of how tired their workers are.

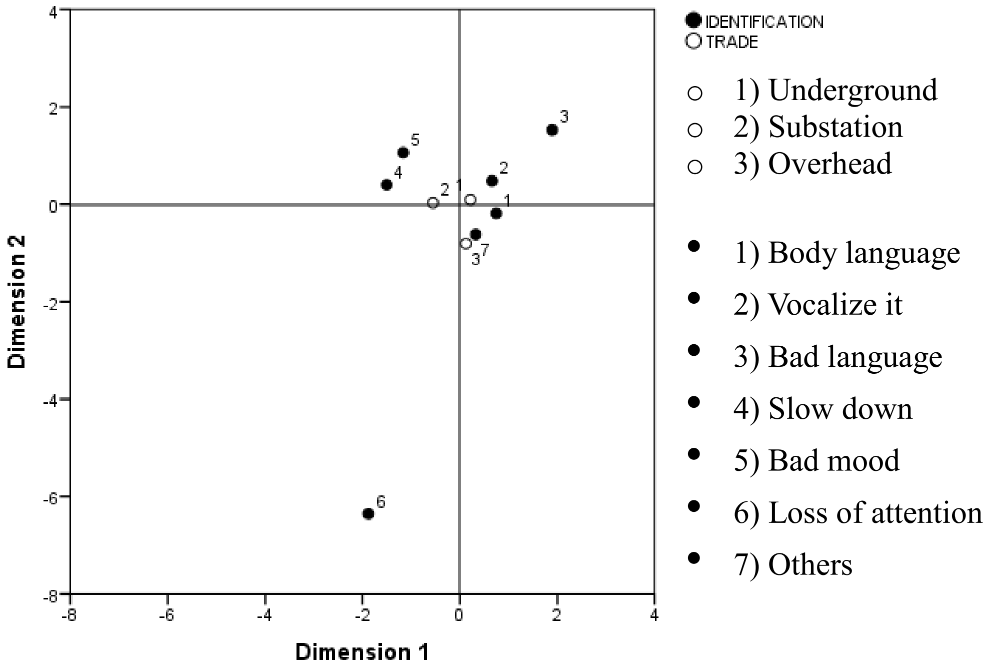

Figure 6 Row principal normalization for identification techniques and trades

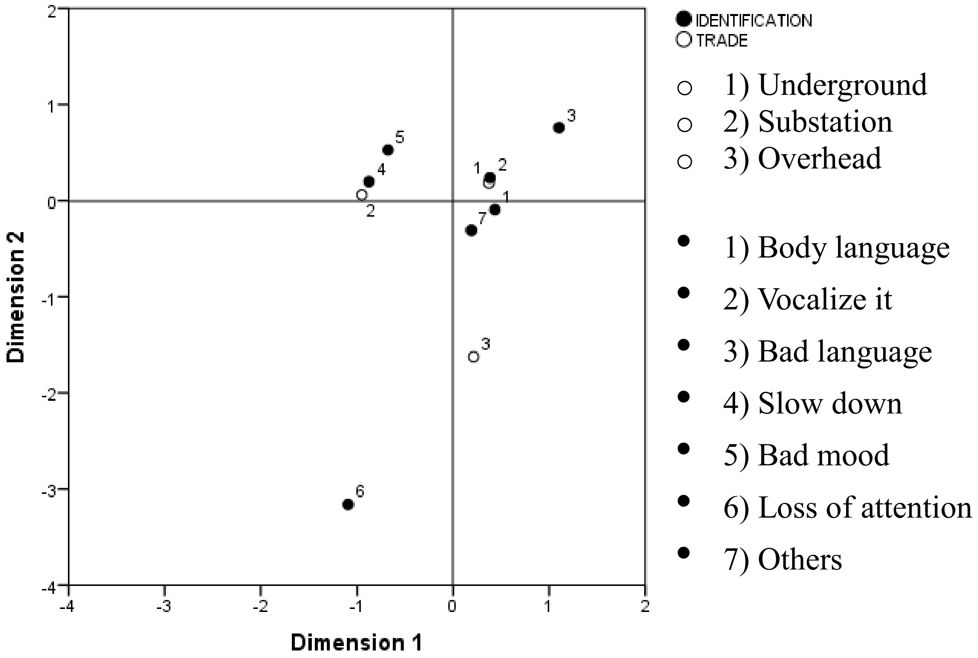

Figure 7 Symmetrical normalization for identification techniques and trades

3.6.2 Results from TD supervisors:

Given the small sample of supervisors (20), no statistically significant results were obtained from this group. However, the exploratory results obtained from this sample are presented because they are informative and interesting when compared with worker perceptions.

Fatigue identification

Most supervisors agree that when operators are fatigued they work slower, which is also the primary way in which supervisors identify fatigued workers. This is in stark contrast to how workers identify fatigue in their peers as described above. Supervisors did mention changes in mood and body language but to a lesser extent.

Action to help

According to supervisors, the most common action to help workers when they are fatigued is to give them a break. Unfortunately, certain situations like emergency work opportunities for breaks are practically limited. In such cases, supervisors try to assign additional workers to the current crew. When that strategy is not possible, supervisors will redistribute the workload among workers in order to avoid overexertion and provide water.

Consequences of fatigue at work

Supervisors felt that fatigue highly affects productivity and safety because workers are slower and lose attention, which yields safety incidents and rework.

Difficult aspects of managing fatigue

Supervisors mentioned that the biggest challenge of managing fatigue is balancing the need for completion of demanding tasks with a limited staff. Unlike other industries, TD workload fluctuates rapidly and supervisors are often under pressure to completing several tasks in emergency situations where public health and safety are at stake. In such situations, supervisors are aware that their staff will be fatigued; however, there are few options to change workload, hours, or number of workers.

Suggested improvements

Supervisors offered different potential improvements such as improving the current workload-stuffing imbalance by hiring more employees and increasing labor budgets. While the focus of fatigue improvements from the workers was on breaks and nutrition, supervisors focused more on staffing imbalance.

Table 17 presents a summary of the results obtained from the supervisors together with the percentage of supervisors that offered each answer. Although there were some differences in responses between workers and supervisors, Table 17 reveals that there is significant alignment on most topics. This suggests that supervisors are well connected with the work and the workers, which may stem from the fact that many supervisors were TD workers earlier in their careers.

Table 17 Summary of results from TD supervisors

Fatigue identification (n=20)		**Action to help (n=20)**	
Body language	50%	Give a break	75%
Slow down	50%	Balance workload	60%
Bad mood	20%	Give water	35%
Ask for breaks	15%	**Consequences of fatigue(n=12)**	
Requested improvement (n=12)		Slow down	80%
Hiring	40%		

3.7 Conclusion

Transmission and distribution power line managers, safety leaders, and union representatives describe the sector as one with a comparatively high fluctuation of workload. Unexpected events such as fires and inclement weather generate emergency work that requires intense and prolonged work for a limited number of workers. On the other hand, quieter times present the challenge of keeping the workforce active and vigilant. This fluctuation and inconsistency makes TD work particularly difficult to manage using a single stable system. Thus, fatigue management must be studied specifically in this industry, which has a different work profile that typical construction work.

Before this study, there was no research addressing fatigue for TD workers despite the fact that it is one of the most dangerous industry sectors. The objective of this study was to identify causes and consequences of fatigue, methods to identify fatigue in co-workers, and methods to mitigate and manage fatigue. Importantly, the data for this study came directly from workers and their field-level supervisors as to promote ecological validity and document the experiences directly from the workforce.

The study revealed several characteristics of TD line work that contribute significantly to fatigue. For example, extreme temperatures were identified as the principal contributors followed by extended shifts. These results are especially important because the link between temperature and fatigue has not been thoroughly studied in the past. We recommend future research in this area as it will help practitioners to better design fatigue risk management systems.

The consequences of fatigue were similar to those documented for other industries. For example, fatigue was perceived to have negative impacts to productivity and safety because of decreased vigilance and increased rates of human error. Experimental research is suggested to directly measure the impacts within the TD line work context. Surprisingly, there was no statistically significant difference in the perceived levels of fatigue, the causes of fatigue, or the consequences among different demographic groups. These causes and consequences largely were similar across workers, which is counter to previous research conducted in laboratory settings. This suggests either the laboratory experiments are not generalizable to the field or that worker perceptions of their own fatigue levels are skewed to be relatively consistent across demographic groups (e.g., old and young, new and experienced, etc.).

Although the results show that fatigue is perceived as a principle risk factor in their work that impacts both productivity and safety, there were no formal fatigue risk management systems in place. Furthermore, OSHA regulations do not emphasize the role that fatigue can play in safely working around high or low voltage electrical lines. This is seen by the authors as an extraordinary disconnect between research and practice that must be rectified. Improvements could be made by implementing a FRMS like those observed in aviation, transportation, oil and gas, and mining (Arnaldo et al. 2016; Chan 2011; Lerman et al. 2012; Marcus and Rosekind 2016). The findings from this study serve as a foundation for such FRMS because specific risk factors, impacts, and initial mitigation strategies have been identified and differentiated by specific TD trades. Previous research has shown that FRMSs must be designed for specific work and that they are not one-size-fits-all (Gander et al. 2011).

The authors offer some direct recommendations from this research. For example, the effects of extreme temperatures can be mitigated through practical means such as using blowers for underground work, supply water to workers on hot days, and providing regular breaks in warm, quiet environments on cold days. Also implementing a regular break policy, in which power naps are encouraged, will help to recover from physical and mental exertion. Work hours can be reduced by reorganizing shifts even when staffing is limited. Lastly, an education program can be implemented to help workers, supervisors, and their families to better understand what causes fatigue, identify fatigue in their peers, and understand how to obtain proper rest during and after work. These recommendations are based largely upon the risk factors identified and the ideas provided by the craft workers.

3.8 Acknowledgements

The present study was successful because of the collaboration and interest of safety leaders, union representatives, supervisors, and workers who provided open and candid responses and who accommodated the research team for in-person field visits.

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Chapter 4: Measuring and Predicting Fatigue in Construction Workers: An Empirical Field Study

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4.1 Abstract

The upsurge in commitment to safety from industry leaders and the implementation of better equipment and training have generated a 67% decline in recordable incident rates during the past two decades. Fatalities, however, have plateaued for the last decade and, in the past three years, have even increased. Current research indicates that human factors like fatigue play a major role in accident causation and fatality occurrence. To manage fatigue, it is essential to determine how fatigue can be objectively measured and predicted. The current body of knowledge suggests several potential predictors based upon laboratory experiments; however, no causal factors of fatigue have been validated in the context of construction work. The present study tested the hypothesis that a set of objective variables can predict variability in construction worker fatigue. A total of 252 US construction workers participated in the study. The results indicate that the amount of sleep and rest obtained in the past 24 h, the number and length of previous shifts, the temperature and level of noise at the worksite, and personal somatic characteristics can explain between 9% and 50% of fatigue variance. Future research should address the discovery of additional fatigue predictors that would allow for a more accurate prediction of fatigue.

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4.2 Introduction

It is not news that construction is one of the most hazardous industries (Sawacha et al. 1999). In 2015 the construction accounted for a fatality rate of 9.4 for every 100,000 full-time equivalent workers, nearly three-times greater than that of the overall working population (U.S. Bureau of Labor Statistics 2015). Accidents have shown to be caused by unsafe human acts and unsafe conditions (Kartam 1997).

Several decades of construction safety research have revealed that organizational and human factors, rather than technical failures, are the principal causes of accidents (Langford et al. 2000; Weick et al. 2008). Such research also classifies fatigue as a principal risk factor. In fact, Chan et al. (2011) carried out an exploratory analysis of the main safety risks in oil and gas construction, in which 78% of stakeholders (n=351) acknowledged fatigue as the main risk factor to accidents and the trigger to several other risks. Similarly, Hallowell (2010) also identified fatigue as a main concern in rapid renewal highway construction.

Fatigue can be defined as a decreased ability to perform activities at the desired level due to lassitude or exhaustion of mental or physical strength (Gander et al. 2011; Hallowell 2010). These are manifestations of the physiological deterioration that takes place under the effects of fatigue. For example, fatigue compromises the function of the prefrontal cortex thus affecting basic and complex cognitive functions like the ability to concentrate and assimilate new information, plan, communicate, and react to new stimuli (Angus and Heslegrave 1985; Harrison and Horne 1999, 2000a; Lorist et al. 2000; Van Dongen and Dinges 2005; Zhang and Liu 2008). Because of physiological degradation, the ability of an individual to work safely and efficiently can be severely compromised by fatigue.

To properly manage fatigue it is essential to detect early signs of onset among workers, thus allowing for a corrective intervention before unsafe levels have been reached (Dawson et al. 2014). The identification of fatigue predictors would enable meaningful ways of prioritizing management strategies. The results from past fatigue research suggests potential predictors such as the amount of sleep obtained, the length of the shift, and the physical or mental intensity of a job, and others. However, these potential factors, designated causal factors, have not been validated as predictive in an occupational setting as they are mainly based on laboratory results (Van Dongen 2004). To address this knowledge gap, the hypothesis that ***a set of objective variables predicts variability in fatigue*** was tested specifically with construction workers in high-risk tasks.

4.3 Background

4.3.1 Potential Predictors of Fatigue

Previous researchers have studied numerous variables that influence the onset of fatigue. While this study doesn’t address the many cognitive and physical ways in which these factors cause fatigue, a brief introduction to these variables is provided. For a detailed analysis of fatigue causing factors, together with their relative importance and impact, the reader should refer to Techera et al. (2016), who performed a recent meta-analysis of the causes and consequences of fatigue. The salient content from this previous study is abstracted here to provide context.

4.3.2 Sleep Deprivation

Among fatigue causal factors, sleep deprivation has been the most widely studied and several researchers affirm that it is the principal cause for fatigue (Belenky et al. 2003; Dawson and McCulloch 2005; Folkard and Tucker 2003; Lim and Dinges 2008; Van Dongen and Dinges 2005). In fact, Dawson and McCulloch (2005) proposed a model to determine fitness for duty based on previous sleep patterns. The prior sleep wake model (PSWM) indicates that if the time between waking up and the end of a worker's shift is longer than the amount of sleep obtained during the past 48hs, then such a worker presents a significantly high likelihood of causing a fatigue-related error. Furthermore, the same study concluded that a worker needs to obtain at least 5 h of sleep in the 24 h prior to work and 12 h of sleep in the 48 h before work to meet minimum requirements for fitness.

The PSWM was recently used in a longitudinal study with 347 train condcutors using the Fatigue Audit InterDyne (FAID) software developed by Dawson and Fletcher (2001). Although they obtained a strong positive correlation between violations of prescriptive thresholds (sleep deprivation) and fatigue levels, the methodological approach of the study is questionable because of construct validity. The FAID software used to measure fatigue only considers the shift schedule for the past 7 days. Consequently, the software delivers higher fatigue scores when a worker experiences shorter rest periods, and the correlation between rest period and sleep deprivation is obvious. Further, the factor of sleep deprivation is considered in isolation, although it well-documented that there are many, interconnected causal factors.

4.3.3 Incomplete Recovery

Incomplete recovery, understood as the inability to fully recover from a fatiguing episode, has been shown to contribute to fatigue accumulation (Beurskens et al. 2000; Jason et al. 2010; Swaen et al. 2003). Although related, incomplete recovery is typically considered independently of shift length because it is also strongly impacted by a worker’s personal life and rest habits (Dawson and McCulloch 2005; Gander et al. 2011). The link between fatigue and recovery time has traditionally been studied across shifts with different characteristics (i.e. split shifts, rotating shifts). It has yet to be validated as predictive.

4.3.4 Workload

Defined as high mental or physical demands at work, workload is another potentially obvious cause of fatigue important to consider in an industry setting. The degree to which workload contributes to fatigue depends on the extent to which a worker perceives the reward for completing a work-task in the demanded period of time as worth it (Boksem et al. 2008). The assessment of this effort to reward balance is usually assessed subjectively. Further, this factor includes the cognitive and physical demands, repetition, and schedule breaks (Gander et al. 2011; Hsiao and Simeonov 2001). Workload has typically been studied as an isolated proxy for fatigue but not as a predictor.

4.3.5 Overtime and Long Shifts

The time that a person spends at work exacerbates fatigue directly and indirectly. Long shifts and overtime are a direct fatigue stressor by limiting the available time for recovery (Gander et al. 2011). Additionally, overtime and long shifts expose the worker to other stressors, inherit to the work task, for additional time (Park et al. 2001; Dembe et al. 2005). The relationship between overtime or long shifts and fatigue are also indirectly related to fatigue through mediators such as sleep deprivation (Åkerstedt et al. 2002b).

4.3.6 Work Environment

It seems intuitive that work environmental factors, such as the level of noise, lighting, vibration, and temperature in the worksite can determine the type and intensity of workers' fatigue. However, despite the apparent obvious link, little research has been done to validate the impacts of such factors. Furthermore, most studies conducted were performed in a controlled environments rather than in the field where the true intensity of these factors is manifest (Jiao et al. 2004; Kjellberg et al. 1998; Krause et al. 1997; Landström and Löfstedt 1987; Park and Gotoh 1993; Zivin and Neidell 2010).

4.3.7 Mental Exertion

Mental exertion is conceptualized as sustained cognitive activity that requires extraordinary mental effort, mental exertion is a fatigue driver (Lorist et al. 2005). In laboratory settings, mental exertion has been shown to negatively impact the functioning of the pre-frontal cortex, which regulates executive functions. As the mental demand required for a task increases, so does the rate of onset of cognitive fatigue (Boksem et al. 2006, 2005; van der Linden et al. 2003a; van der Linden and Eling 2006; van der Linden et al. 2003b). For instance, Boksem et al. (2005) performed a laboratory experiment to assess the impact of mentally demanding activities on fatigue. In this experiment fatigue was measured as changes in brain activity (EEG) and by the subjective selfassessment of the participants. The results showed a strong correlation between time on task and fatigue increments.

4.3.8 Muscular Exterior

Fatigue can be caused by both mental and physical exertion. The latter often relates to the physical demands requirement of repetitive muscular effort or sustained muscular tension (Brown 1994; Christensen et al. 1995; Edwards and Lippold 1956; Grandjean 1979; Jason et al. 2010). Christensen et al. (1995) demonstrated that the frequency and power of electromyographic (EMG) signals decrease after dynamic or static muscular exertion, testifying of muscular fatigue. Consequently, muscular exertion can be considered as a predictor of fatigue and EMG signals present a possible scale to measure muscular fatigue. Thus, muscular exertion is yet another potential predictor of fatigue that may relate to other factors.

4.3.9 Social Work Environment

Most people spend between 25 and 40% of their time at work. Thus, the quality of the relationships with managers, co-workers, and subordinates becomes an important factor in the development of mental fatigue (Bültmann et al. 2001). For example, supervisors' abusive behavior were linked to emotional exhaustion in a subjective assessment among 249 employees in varied workplaces (Yagil 2006). Although difficult to measure objectively, this factor may be a predictor.

4.3.10 Personal Predisposition

It is important to consider individual differences while measuring fatigue. The source for such differences correspond to somatic or psychic characteristics of everyone, which can be temporal or permanent. For example, a somatic contributor to fatigue could be sleep apnea, which inhibits normal rest thus generating a fatigue debt that accumulates overtime (Chervin 2000). On the other hand, the negative or positive emotional state of an individual also plays a role in the development of mental fatigue (Bültmann et al. 2001). In general, the impact of personal predisposition on fatigue has been tested by comparing scores between questionnaires that measure personal characteristics (independent variables) and subjective fatigue scales (dependent variable).

The reviewed causal factors of fatigue all offer opportunities for prediction and objective measurement. In theory, objectifying and concurrently measuring these factors should produce the best predictive model based upon the current state of knowledge. Thus, we hypothesize that each of the reviewed factors offers some predictive power for fatigue. If so, a method could be created to objectively measure the potential for fatigue before work begins, thereby improving ability to manage and control its onset.

4.4 Fatigue measurement tools

In order to validate predictors, fatigue must be measured as a dependent (predictand) variable using state-of-the-art methods. There is a rich and extensive body of literature on fatigue measurement. However, given the complex physiological and psychosocial nature of fatigue, there is no consensus on how it should be measured. Consequently, researchers have relied on proxies for fatigue, often considering it as a product of its causes (e.g., workload) and effects (e.g., moving slowly). Such an approach assumes that the measurement of these variables determines the state of the underlying construct, which is problematic for scientific inquiry as fatigue itself cannot be measured. Thus, as a dependent variable, the prevailing subjective and objective methods of measuring symptoms of fatigue will be used.

There are two main ways of assessing fatigue: subjectively and objectively. The subjective assessment of fatigue is founded on the perception of the symptoms that people experience when they are fatigued. Such symptoms include sleepiness, lack of energy, and physical impairments among others. The apparent inability to measure these sub constructs directly resulted in their subjective assessments as the best means to measure fatigue. More recently, new technologies allowed for the direct assessment of specific physical variables that change under the effects of fatigue, such as neuronal activity or cardiorespiratory metrics. These technologies have enabled objective measures of fatigue.

4.4.1 Subjective fatigue measurement

Subjective instruments were initially developed in clinical settings to monitor patients with a terminal disease or who were undergoing long and aggressive medical treatment like chemotherapy. These patients experience acute fatigue for prolonged periods of time as a side effect of their condition (Piper et al. 1998; Shapiro et al. 2002; Smets et al. 1995; Taylor et al. 2000). Later, some of these scales were used to assess fatigue in healthy working populations, revealing some incompatibilities between clinical and industry settings. Consequently, additional scales were later developed specifically for healthy working individuals (Bültmann et al. 2000; Dainoff et al. 1981; Mota and Pimenta 2006).

Subjective fatigue assessment tools are self-administering questionnaires or scales that inquire about the manifestation or the intensity of specific fatigue consequences. For instance, assuming drowsiness as a consequence of fatigue, a subjective questionnaire may include a question related to the perception of drowsiness. The quality of these subjective instruments is largely determined by the ability of the subject to recognize and value the magnitude of his or her own drowsiness. Thus, the subjective nature of fatigue questionnaires yield scientific limitations because of reliability and construct validity.

Reliability or internal consistency refers to the degree to which different participants who experience the same level of fatigue will give the same answer to a specific question, thus allowing for comparisons across individuals (Santos 1999). This factor is determined by the inter-variable correlation across all elements of the questionnaire. Cronbach's alpha is the most common statistic to perform such an assessment (Cronbach 1951). This coefficient fluctuates between 0 and 1 and values equal or greater than 0.7 indicate good reliability (Nunnally 1978). An elevated alpha value indicates that all the items considered measure the same underlying construct.

Alternatively, construct validity is determined by compliance with convergent validity and discriminant validity. Convergent validity is the measure of the extent to which a questionnaire measures that which is intended to measure (Vries et al. 2003). The assessment of convergent validity relies on the comparison between the instrument being assessed, and an assumed perfect measure of the underlying construct. Specifically referring to fatigue, such perfect instrument doesn't exist. Therefore, the assessment of convergent validity is as good as the ability of the referent instrument to truly measure fatigue. Discriminant validity investigates the degree to which an instrument doesn't measure that which it is not intended to measure. Researchers usually perform this analysis by using groups with expected significant differences in fatigue.

Multiple studies address the characteristics of the available fatigue assessment tools. It is not in the scope of this study to reproduce such analyses; however, these past studies were considered when selecting the most reliable and valid subjective fatigue assessment tool for validation. A brief review of the salient subjective fatigue measurement tools is provided.

Need for Recovery Scale (NRS). The NRS is an instrument designed to measure fatigued caused by work shift (Van Veldhoven and Broersen 2003). It presents 11 dichotomous items to which a participant can answer "yes" or "no". The scores are then transformed to a 100-point scale that represents the final fatigue score of the individual. The internal consistency of the NRS was measured as 0.87, making use of the internal correlation coefficient (ICC), a comparable statistic to Cronbach's alpha. These two coefficients are based on the same measurement model and on the same definition of reliability (Bravo and Potvin 1991). Some of the items of this scale state: "I find it difficult to relax at the end of a working day" or "I cannot really show any interest in other people when I have just come home myself". According to the character of these questions, the NRS was designed to determine an overall level of fatigue that manifests regularly. Consequently, this scale does not comply with the requirements of the study. The researchers are interested in a tool able to assess subjective fatigue at a given point in time, rather than a period of time.

Fatigue Assessment Scale (FAS). FAS is a 10-item scale with 5 questions to measure physical fatigue and 5 items to measure mental fatigue. The FAS was administered to a sample of 1893 volunteers obtaining a Cronbach's Alpha of 0.87 . Similar to NRS, the FAS measures how a person usually feels rather than how a person feels at the time of the assessment. For example, one of the items states: "I have enough energy for everyday life" to which the responder chooses an option from (1) never, to (5) always. The scale has been validated among large samples in cross-comparisons with other fatigue measurement methods (Michielsen et al. 2004).

Swedish Occupational Fatigue Inventory (SOFI). The SOFI was developed from 95 verbal expressions such as: drowsy, sweaty, passive, and uninterested. In this scale, participants indicate to what extent they feel these sensations at a given point on a Likert scale. Initially, the questionnaire was tested on 705 individuals belonging to 16 different occupations (Åhsberg et al. 1997b). Factor analysis and stepwise analysis reduced the initial poll to 25 variables organized in 5 different factors. Such factors were named: lack of energy, physical exertion, physical discomfort, lack of motivation, and sleepiness (Åhsberg et al. 1997b). In its development, the SOFI showed strong reliability and the ability to discriminate across different occupations (Åhsberg et al. 1997b; Åhsberg 2000; Åhsberg et al. 2000b).

The discriminant and convergent validity of the SOFI was further explored among groups with expected differences in fatigue dimensions. In 1998 a group of 20 men and 20 women underwent 5 episodes of dynamic and static physical exertion (cycling and forward flexions) with a 20-minute break in between sessions. The participants filled out the SOFI and the Category Ratio Scale (CR-10) by Borg (1982) after every session. The results indicated high levels of both physical exertion and physical discomfort after dynamic and static work respectively, thus indicating good discriminant validity. Additionally, SOFI scores and CR-10 scores showed high Pearson product moment correlation, demonstrating convergent validity. The dimension “lack of energy” also scored high after both types of exercises. This suggests that the latter dimension measures an overall level of fatigue. The rest of dimensions presented significantly lower scores (Åhsberg and Gamberale 1998).

A similar protocol was followed to demonstrate discriminant validity for the remaining SOFI dimensions. This third study consisted on a proof-reading task (2x90 min) and a vigilant task (2x60 min) in which 20 men and 20 women took part. The results indicated significantly high scores for lack of motivation, sleepiness, and also lack of energy, thus demonstrating the overall construct validity of the scale (Åhsberg et al. 2000a).

More recently, the reliability and validity of the SOFI was reassessed on 597 workers, belonging to 5 occupations with different workloads. A revised questionnaire with 4 items per dimension sowed better psychometrics for the described sample. Based on this revised SOFI, new reliability coefficients were calculated. An overall Cronbach's alpha of 0.80 was found and the reliability for each dimension was as follows: Lack of energy (0.92), Lack of motivation (0.92), Sleepiness (0.89), Physical discomfort (0.92), and Physical exertion (0.87) (Åhsberg 2000). Since its development, the SOFI has been widely used among working populations and it has been translated into several languages, including Spanish (Åhsberg et al. 2000b; González Gutiérrez et al. 2005; Leung et al. 2004; Sultanian et al. 2014). The strong and robust validation of the tool and the fact that it measures fatigue at a single point in time made it ideal for the present study.

4.4.2 Objective fatigue measurement

Technological advances of the past few decades allowed for the development of tools that can measure fatigue as a latent variable (Dawson et al. 2014). Researchers from several fields have developed instruments to assess fatigue objectively based on the different observable variables that change with fatigue. For example, researchers in neurobehavioral science developed tools based on changes in cognitive ability, mood, and reaction time (RT) (Dinges et al. 1997). Performance in all these factors decreases under the effects of fatigue due to a decay in the central and peripheral nervous system (Balkin et al. 2004). Also, electroencephalography produced some products able to measure fatigue using frequency change in brain activity considering Theta (3.5-7Hz), Alpha (8-13Hz) and Beta (14-30Hz) waves' change under the effects of fatigue (Lal et al. 2003; Lal and Craig 2001; Okogbaa et al. 1994). Pupilometry, which measures visually-guided saccadic velocity (SV), initial pupil diameter (PD), pupillary constriction latency (CL), and amplitude of pupil constriction (CA) (Goldich et al. 2010); and oculometry, which measures the amplitude and frequency of eyelid movement, have also produced devices to assess fatigue (Wierwille et al. 1994). Lastly, devices that identify posture changes and/or head nodding have also shown to be able to alert of high levels of fatigue. Unfortunately these devices perceive fatigue usually when it is already too late to prevent a fatigue related accident (Hartley and Arnold 2001; May and Baldwin 2009).

Objective fatigue assessment tools can be classified according to their intent in three categories, (1) technologies that assess fitness for duty, (2) technologies that assess fatigue continuously, and (3) technologies embedded in machinery or vehicles. The first 2 types of technologies require interaction between the worker and the device, while the third type of technology is non-intrusive.

Every fatigue-measuring technology presents advantages and disadvantages. Those that assess fitness for duty require the worker to stop and dedicate time to the assessment; however, these assessments usually take less than 10 minutes. Conversely, technologies that measure fatigue continuously do not require workers to stop working for the assessment but require the participant to carry a device, which can be intrusive. The third type of technology is attractive because it doesnt require the worker to stop or to carry the device. However, these technologies only work in very controlled environments (i.e. in trucks with drivers) and even in those environments their performance is comparatively unreliable and inaccurate (Dawson et al. 2014). Since the goal of this study was to test the predictive validity of candidate indicators, fitness for duty methods of fatigue measurement that take place at specific times was preferred.

Fitness for duty technologies available in the market include: (1) The Psychomotor Vigilant Test (PVT), which measures RT as an indirect assessment of fatigue; (2) The Occupational Safety Performance Assessment Test (OSPAT), which is a computer based test that presents an unpredictable tracking task that measures RT, sustained attention, and hand-eye coordination; (3) The Online Continuous Performance Test (OCPT), which measures alertness and vigilance through RT during an online task that presents multiple visual stimulus; (4) The Eye Check, which assesses fatigue by measuring pupil diameter and constriction latency; (5) The Fitness Impairment Tester (FIT), which uses eye tracking (saccadic velocity) and pupilometry (pupil diameter, constriction amplitude, and latency) to assess fatigue; and (6) The Safety Scope, which measures pupillary reflex and eye movement parameters to determine the level of fatigue of an individual (Dawson et al. 2014). An exhaustive review of literature revealed spurious validity of most aforementioned technologies. Furthermore, many of these studies were found in the quasi-scientific commercial literature rather than in peer-reviewed journal articles. The extensive review carried out by Dawson et al. (2014) reveal that the PVT is the only technology with strong evidence of validation by independent researchers, laboratory studies, and field studies. Accordingly, it is considered by most researchers as the eminent method to objectively measure fatigue (Dinges and Powell 1985; Dorrian et al. 2005; Loh et al. 2004).

Traditionally the PVT was administered in a hand-held device known as PVT-192 (Ambulatory Monitoring, Inc., Ardsley, NY; Dinges & Powell, 1985). The principal challenge with this technology is its extremely high cost. Recently, a new software ,PC-PVT was developed to perform RT measures with the same functionality and reliability as the PVT-192 (Khitrov et al. 2013). Thus, the PC-PVT was the preferred objective method of measuring fatigue at single points in time in the field.

4.5 Point of departure

Although there is a strong body of knowledge related to the causal factors of fatigue, most previous studies were performed in a laboratory setting or in otherwise controlled environment. Construction, however, is dynamic, diverse, and transient and the predictive validity of these causal factors is unknown. The present study is the first to test the predictive validity of potential fatigue indicators in an uncontrolled occupational setting.

4.6 Methodology

The overarching procedure to test the principal hypothesis consisted of three distinct phases: (1) developing the experiment tools to assess potential predictors and measure fatigue; (2) collecting data from construction workers in the field, (3) statistical hypothesis testing using objective predictive statistics. These phases are described in detail below.

4.6.1 Research tools development and selection

Activity Questionnaire

Based on the causal factors of fatigue discussed in the literature review, an objective questionnaire was developed. Each of the causal factors was converted into an objective question, referred to as an activity variable. Collectively, these represented the activity questionnaire. Table 17 summarizes the causes, activity variables, and the corresponding questions. As one may note, variables were continuous or dichotomous, which is relevant for statistical testing. Additionally, demographic variables such as age, years of experience, position, and gender were included in the Activity Questionnaire. In total, 26 variables were collected using the questionnaire. These represented the independent predictor variables.

Table 18 Potential predictors of fatigue

Causes of fatigue	Activity Variables	Activity Questionnaire
Sleep Deprivation	Sleep 24h	How many hours did you sleep during the past 24hs?
	Sleep	How many hours do you usually sleep?
Incomplete Recovery	Rest in 24h	Besides sleeping, how many restful hours have you had in the past 24hs?
	Individuals	Do you have individual at home that require special attention?
	Time off	How many hours have you had off since your last shift?
	Start time	What is the start time of your shift today?
	Rotating	Do you have a rotating shift?
Workload	Consecutive shifts	How many previous consecutive shifts have you worked?
Overtime & Long Shifts	Overtime	How many hours do you work a week?
	Last shift	How long was your last shift?
Work Environment	Repetitive	Are you performing repetitive tasks at work?
	Vibration	Are you exposed to vibration while working?
	Noise	Are you exposed to loud noises at work?
	Light	Is the work environment well lit?
	Temperature	What is the approximate temperature in your work environment now?
Mental Exertion	Mental demand 1	Are you performing mentally demanding tasks at work?
Muscular Exertion	Physical demand 1	Are you performing physically demanding tasks at work?
Social Environment	Coworker	Do you have a good relationship with your coworkers?
	Supervisor	Do you have a good relationship with your supervisor?
Self-Predisposition	Caffeine	Did you drink caffeine today? If yes, how much?
	Condition 1	Do you have a condition that doesn’t allow you to rest well?
	Condition 2	Do you get fatigued more easily than your coworkers?

Fatigue Measurement Tools

Subjective measurement of fatigue:

The current body of knowledge identified the SOFI as the most valid method of subjectively measuring fatigue. The questionnaire includes 20 items such as: palpitations, worn out, lack of interest, and others that participants rate on a 0 to 6 Likert scale, where 0 refers to ‘not at all’ and 6 ‘to a very high degree’. The questionnaire is designed to produce higher scores when participants are fatigued. For example, the questionnaire states ‘lack of energy’ as an item for which a high answer (i.e. 6) would indicate ‘lack of energy to a very high degree.’ Because of space limitations, the entire SOFI scale is not presented here. However, it can be found in its entirety in (Åhsberg 2000).

Objective Measurement of Fatigue:

To objectively measure fatigue the PC-PVT was used. The implementation of the PC-PVT requires a laptop computer with 2 GB of memory RAM, Windows 7 as the operating system, and a gaming mouse with 1000hz response rate. To participate in a PC-PVT a participant sits in front of a laptop computer with their dominant hand on the mouse. Before starting, the screen shows an instructional message and when the participant clicks the mouse, the test starts. The participant observes a black screen and, suddenly, a stimulus appears in the form of a red four-digit millisecond counter that stops the count once the participant clicks the mouse. The counter displays the RT of the individual for 500 ms and then disappears. This sequence repeats at random intervals between 2 and 10 seconds. This test has been validated in a 5-min and a 10-min modality and the shorter modality was selected (Khitrov et al. 2013).

The PC-PVT stores the following relevant data: (1) time of the assessment; (2) number of minor lapses (RT> 500ms); (3) number of major lapses (RT>1000ms); (4) number of stimulus displayed; (4) minim RT; (5) maxim RT; (6) mean RT; and (7) median RT. The median RT was considered as the dependent variable and most accurate objective measure of fatigue. The mean can more easily be affected by lapses in RT, which are usually observed with the first stimulus due to the inexperience of the construction worker with the PC-PVT protocol.

4.6.2 Sample Characteristics and Data Collection

When selecting participants for this study, the researchers desired to focus on high-risk tasks where the impact of fatigue could be most severe. Among industry trades, electrical transmission and distribution (TD) workers are known to have a disproportionately high fatality rate. Specifically, the average TD worker's fatality rate has been 3 times greater than the construction industry average for the past 20 years (U.S. Bureau of Labor Statistics 2015). To add breadth to the study and demonstrate generalizability, general construction workers who represent several traditional trades, referred to here as GC workers, were also included but to a lesser extent.

The sample consisted of 252 construction workers from 6 different states across the US. This group included 200 TD workers (age: μ = 39.0 y/o, σ = 10.9 yrs.; years of experience: μ = 11.4 yrs.; σ = 9.3 yrs.) and 52 GC workers (age: μ = 35.7 y/o, σ = 11.0 yrs.; years of experience: μ = 7.1 yrs.; σ = 8.9 yrs.). Both groups were predominantly male: from TD workers, 193 men and 7 women; from GC workers, 50 men and 2 women; reflecting the actual demographic of the industry. TD workers included 'Lineman' (n=110), 'Control Room Operators' (n=59), 'Operators' (n=14), 'Foreman' (n=13), and 'Fuel Suppliers' (n=4). Lineman perform overhead, underground, or substation electrical work. Control Room Operators (CRO) are power plant workers who take care of the correct functioning of the power plant and divide their time between the control room and activities around the plant. Fuel Suppliers provide generators and equipment with the appropriate fuel for their continuous operation. Lastly, Operators control equipment and Foremen direct crews. These last two trades will be referred to as Electrical Operators (E. Operators) and Electrical Foreman (E. Foreman) to distinguish them from trades with the same name among GC workers. The group of GC workers was formed by ‘Carpenters’ (n=32), ‘Operators’ (n=7), ‘Laborers’ (n=6), ‘Foremen’ (n=3), ‘Electricians’ (n=2), and ‘Plumbers’ (n=2).

Data were collected at the beginning of each shift. Participants received an explanation of the purpose of this research project and the data collection process. After, participants gave their consent to participate in the study, completed the Activity Questionnaire, the SOFI, and took part in the PC-PVT. The data were then transcribed to computer files for their posterior analysis.

4.6.3 Data Analysis

Multiple Linear Regression was selected as the initial method of analysis to test the predictive validity of the activity variables. This method is generally used either to describe or to predict a relationship (Pedhazur 1997). Despite the continuous nature of the underlying construct (fatigue), it is important to ensure that the dependent variable used in the statistical analysis reflects continuity. The study analyzed two dependent variables (1) PVT median RT and (2) SOFI scores. The former dependent variable measures time, consequently it is a continuous variable; the latter is an aggregate of Likert scales with continuous properties. The way in which the SOFI was developed justifies the treatment of SOFI scores as continuous variables, and this is the way in which these scores have been treated by all other researchers (Åhsberg 2000; González Gutiérrez et al. 2005; Leung et al. 2004). Furthermore, the wide range of SOFI scores further justifies their treatment as a continuous variable. However, the authors took an extra measure of precaution and worked with the square root of the SOFI scores 'SQRT(SOFI)' which tested positive for normality, thus justifying its treatment as a continuous variable (Lubke and Muthén 2004).

According to Miller and Kunce (1973) a minimum of 10 data points per variable of interest may be sufficient to evaluate the predictive character of an independent variable. However, there is no hard rule regarding this number because it depends entirely on the characteristics of the data and the real correlation between the independent and dependent variables. In post-processing some variables were removed from the analysis (e.g., gender and experience) given their low to null variability.

The best model was selected after performing stepwise MLR (S) analysis, forward MLR (F) analysis, backwards MLR (B) analysis, and confirming the significance of the regression coefficients in a forced model. All statistical analyses were performed in SPSS Version 24. At the end of this process two separate validations were performed. First, the validation of the model's fitness was performed, which examined compliance with (1) Linearity, (2) Homoscedasticity, (3) Normality, and (4) Independence of the residuals (difference between predicted values and actual values). Second, a k-fold cross validation was performed to document the variability of the model when applied to a theoretically different population (Stone 1974). The k-fold cross validation consists of randomly dividing the data set in k equal and constant groups and design k new models using k-1 groups with a left-out group that changes every time. The results of this second validation will provide information about the variability of the model when applied to a different sample.

The analyses described above where applied to the overall sample and the TD and GC groups as described in Figure 1, for both dependent variables (PVT and SOFI). K-fold validation was applied to TD and GC groups separately as expected for a practical application of the model. Transformations of dependent variables and elimination of outliers were performed to comply with MLR validation requirements. The following section presents the results of such analyses.

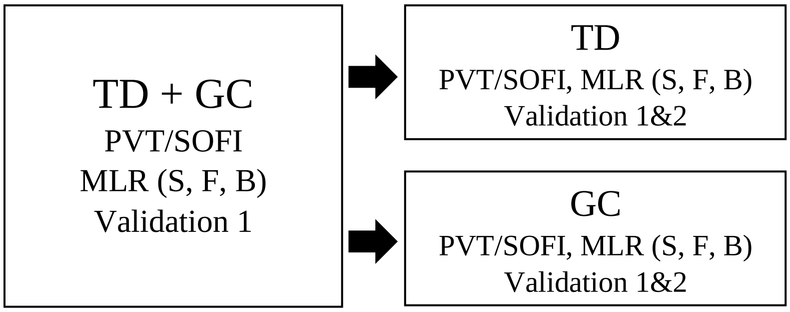

Figure 8 Statistical Analysis

4.7 Results and analysis

The results obtained from the MLR analyses and the k-fold validations are presented here by dependent variable. First, Table 19 shows the result for the MLR analyses with median RT values as the dependent variable. Second, Table 20 shows the results for the MLR models with SQRT (SOFI) as the dependent variable. A respective 95% and a 90% significance level for explained variability difference was applied to include and exclude a variable in any of the MLR methods used.

In the case of RT as the dependent variable, when working with data obtained from TD workers, a log-normal transformation of the PVT median values was applied to achieve normality of the residuals. Such a transformation was not necessary when analyzing the GC data. The cross validation for TD workers (n=200) consisted of a 10-fold cross validation with approximately 180 data strings per new sub model. A total of 7 data strings were not considered in the analysis due to missing values in the data. Similarly, a 4-fold validation with approximately 37 data strings for sub model was performed for GC worker's data.

Table 19 MLR and Validation results for PVT data

TD + GC workers			**TD workers**				**GC workers**			
D.V. Median RT, n=236			***D.V. Ln (Median RT), n=193***			***Validation μ (σ)***	***D.V. Median RT, n=47***			***Validation μ (σ)***
R^2	0.202		**R^2**	0.092		0.095 (0.015)	**R^2**	0.198		0.200 (0.024)
Adjusted R^2	0.185		**Adjusted R^2**	0.077		0.080 (0.016)	**Adjusted R^2**	0.161		0.151 (0.026)
Std. Error	37.456		**Std. Error**	0.137		0.145 (0.002)	**Std. Error**	35.285		35.330 (1.690)
Predictors	**B_i**	**Std. Error**	**Predictors**	**B_i**	**Std. Error**	***Validation μ (σ)***	**Predictors**	**B_i**	**Std. Error**	***Validation μ (σ)***
Intercept	303.664	16.481	Intercept	5.615	0.061	5.657 (0.017)	Intercept	258.366	25.812	259.592 (11.941)
TD worker	-29.607	6.467	Last Shift	-0.012	0.005	-0.016 (0.002)	Sleep 24 h	8.861	3.565	8.689 (1.446)
Last Shift	-2.744	1.316	Noise	0.060	0.027	0.058 (0.005)	Condition 1	-39.145	18.447	-38.680 (12.887)
Noise	13.091	7.388	Temperature	0.002	0.000	0.002 (0.000)				
Temperature	0.372	0.120								
Condition 2	19.200	7.132								

Note: D.V.: dependent variable; Std.: standard deviation

Table 20 MLR and Validation results for SOFI data

TD + GC workers			**TD workers**				**GC workers**			
D.V. SQRT(SOFI), n= 242			***D.V. SQRT(SOFI), n= 180***			***Validation μ (σ)***	***D.V. SQRT(SOFI), n= 42***			***Validation μ (σ)***
R^2	0.151		**R^2**	0.161		0.162 (0.015)	**R^2**	0.484		0.490 (0.060)
Adjusted R^2	0.137		**Adjusted R^2**	0.141		0.141 (0.015)	**Adjusted R^2**	0.458		0.454 (0.062)
Std. Error	1.972		**Std. Error**	1.201		1.201 (0.021)	**Std. Error**	0.928		0.925 (0.009)
Predictors	**B_i**	**Std. Error**	**Predictors**	**B_i**	**Std. Error**	***Validation μ (σ)***	**Predictors**	**B_i**	**Std. Error**	***Validation μ (σ)***
Intercept	9.076	0.951	Intercept	7.651	0418	7.651 (0.131)	Intercept	5.246	0.288	5.257 (0.055)
Age	-0.031	0.012	E. Operator	-0.998	0.348	-1.000 (0.060)	Consecutive Shift	0.449	0.081	0.442 (0.042)
Sleep 24 h	-0.317	0.081	Sleep 24 h	-0.180	0.056	-0.180 (0.017)	Condition 2	0.987	0.442	0.990 (0.265)
Supervisor	-1.761	0.676	Rest	-0.038	0.019	-0.038 (0.008)				
Condition 2	1.523	0.382	Condition 2	1.065	0.268	1.067 (0.088)				

Note: D.V.: dependent variable; Std.: standard deviation

From the general PVT model including TD and GC workers, TD workers appear as a predictor, indicating that there are differences in RT between the two groups of workers and that these should be treated as separate groups. Furthermore, the larger number of TD workers biased the overall model, because this model (TD + GC workers) shares most of the predictors with the model that considers only TD workers (*Last Shift, Noise, and Temperature)*.

Generally, the regression coefficients obtained in the models reflect the expected relationship between the predictors and the predicted variable. For instance, the coefficients for *Consecutive Shifts, Noise, Temperature, and Condition 2* (becoming fatigued more easily than coworkers) are positive in all models. This indicates that when considering each one of these variables at the time, if all the other variables in the model are constant, then an increase in any of these predictors would generate an increase in RT or SOFI scores, as expected. Likewise, the coefficient for *Supervisor* and most of those for *Sleep 24h* are negative. This shows that a good relationship with the supervisor and an increase in the amount of sleep obtained in the past 24h would contribute to a lower RT or SOFI scores.

Nonetheless, some of the results are unexpected. For example, the coefficients for *Last Shift* in two models resulted to be negative. This would indicate that the longer the previous shift of the workers, the faster RT or lower SOFI score they would obtain. A possible explanation for this could be that there is a slightly positive significant correlation between *Last Shift* and *Time Off* (Pearson's r = 0.171, p-value = 0.017). Consequently, one can infer that the longer the previous shift, the longer time off the workers had, thus allowing for more recovery. However, *Time off* was another variable in these MLR analyses and it was not found as a significant predictor. The full discovery of this matter will require additional research.

Similarly, the results obtained from the analyses among GC workers, considering median RT as a predictor, also suggest the need for further research with a bigger sample. In this case, the coefficients for both predictors show counterintuitive signs. The coefficient for *Sleep 24h* is positive, indicating that in general, the more a worker slept in the past 24h the slower RT observed. Likewise, the coefficient of *Condition 1* indicates that the few workers (n=4) that manifested to have a condition that didn't allow them to rest well, presented faster RT's than the rest. Figure 9, presents a Scatterplot matrix of the data showing that the counterintuitive relationship between the predictors and the criterion measured, as manifested in the regression analysis, is the true nature of the collected data.

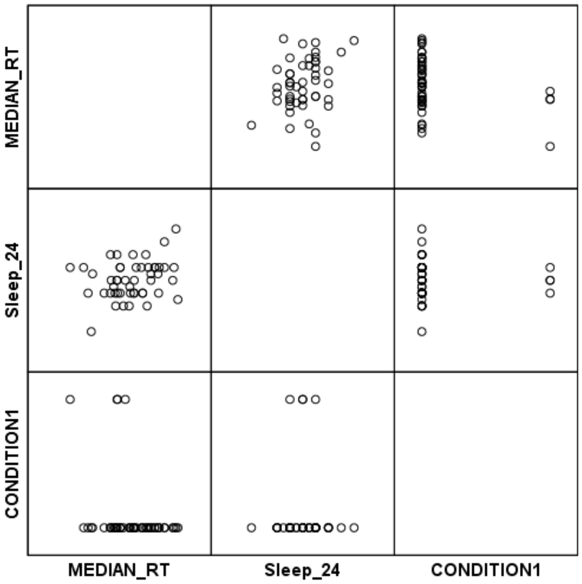

Figure 9. Scatterplot matrix of Median RT predictors for GC workers

To the extent to which fatigue can be measured by the PVT and SOFI, as justified by previous researchers, activity variables showed to be able to predict fatigue (Åhsberg 2000; Khitrov et al. 2013). However, the degree of predictability observed was low to medium. Overall, the predictive models explain 10% to 50% of the variability in the dependent variables. The models that predict RT median values, as measured by the PVT, showed a minimum explained variability of 9% and a maximum of 20%, with *Sleep 24h, Last Shift, Noise, Temperature, Condition 1, and Condition 2* as predictors. The 10-fold validation performed among TD workers with median RT as the dependent variable illustrates that in general, when applied to another theoretical sample, the model will perform as expected, showing the same level of predictivity. On the other hand, the models with SOFI scores as the dependent variable explain between 15% and 50% of variability, with: *Sleep 24h, Consecutive Shifts, Supervisor, and Condition 2* as predictors and the 4-fold cross validations indicates that the parameters of the model will be similar when applied to a new but comparable population. Thus, the predictors considered in this study are better at predicting SOFI scores than RT as measured by the PVT.

Overall, the models indicate an inability to predict between 80% and 90% of variability in RT and between 50% and 84% inability to explain variability in SOFI scores. It is unknown to the authors what specific variables could explain this variability and such a gap in knowledge should be addressed in future research. However, regarding RT, previous researchers showed that in addition to fatigue, age, sleep disorders, alcohol or stimulating substance consumption, and physical fitness, influence RT (Hultsch et al. 2002; Kosinski 2008; Powell et al. 1999). This study accounted for the effect of age, somatic disorders, and the ingestion of caffeine but not for physical fitness. On the other hand, SOFI scores represent 5 dimensions of fatigue (lack of energy, lack of motivation, sleepiness, physical discomfort, and physical exertion) and there might be a plethora of variables that influence each of these categories which were not included in the activity variables.

Furthermore, it is easy to see that SOFI and PVT models present 2 common predictors, *Sleep 24h* and *Condition 2,* and the rest of predictors differ between models. The PVT presents *Last Shift, Noise, Temperature, and Condition 1* as predictors*;* while SOFI presents *Consecutive Shifts* and *Supervisor,* as predictors. This indicates that PVT and SOFI measure different constructs and that none of them represent an exhaustive measure of fatigue by themselves. Furthermore, a correlation analysis revealed no significant correlation between PVT RT and SOFI scores (Pearson's r = 0.072, p-value = 0.254). The predictive model based on activity variables presented in this study was able to represent both constructs thus offering a more complete measure of fatigue. Table 21 represents a summary of causal factors, potential predictors, and actual predictors by dependent variable and trade.

Table 21 Predictors by fatigue measurement method and worker type

Causes of fatigue	**Predictors**	**PVT Predictors**	**SOFI Predictors**	**TD Predictors**	**GC Predictors**
Sleep Deprivation	Sleep 24h	X	X	X	X
Incomplete Recovery	Rest in 24h			X	
Workload	Consecutive shifts		X		X
Overtime & Long Shifts	Last shift	X		X	
Work Environment	Noise	X		X	
	Temperature	X		X	
Mental Exertion	Mental demand 1				
Muscular Exertion	Physical demand 1				
Social Environment	Supervisor		X		
Self-Predisposition	Condition 1	X			X
	Condition 2	X	X	X	X

The reader will notice that *physical* and *mental* demand didn't appear as significant in any model. The reason behind this is that such variables present almost null variability across participants; indicating that these variables are present and play an obvious role in the development of fatigue, but they are bad differentiators of fatigue.

Lastly, it is easy to see, from Table 21, that TD workers are more affected by work environmental factors compared to GC workers. Most TD workers, perform their work activities directly exposed to the elements all year around. For example, overhead lineman work on the pole exposed to sun radiation, wind, rain, or snow. On the other hand, underground lineman work in manholes which present a temperature approximately 10 ºF higher than outside, thus suffering the effects of high temperatures. GC workers, however, spend most of the time working inside newly constructed buildings once the infrastructure has been built. These differences may be the reason behind the different predictors between these trades.

All the MLR analyses performed were validated for linearity, normality, and homoscedasticity of the results. Furthermore, the data complies with independence of the residuals as there was no time pattern in the data collection process. Lastly, all models passed checks for outliers, leverage, and influence. In some cases, when specific data points compromised any of these statistics, these points were removed from the data as it is typically recommended in regression analysis.

Tables 22, 23, and 24 show the descriptive statistics of the predictors presented in the models and the dependent variables. Section 4.10 of this study presents an appendix with the descriptive statistics of all the activity variables considered.

Table 22 Descriptive statistics of continuous predictive variables

	Overall sample n = 249				TD workers n = 198				GC workers n = 51			
	Min	Max	$\bar{X}$	S	Min	Max	$\bar{X}$	S	Min	Max	$\bar{X}$	S
Sleep 24 (h)	3.0	14.0	7.0	1.6	3.5	14.0	7.0	1.6	3.0	11.0	7.0	1.4
Consecutive shifts	0.0	12.0	2.3	1.9	0.0	12.0	2.1	1.9	0.0	6.0	3.0	1.7
Last shift (h)	4.0	16.0	10.0	1.9	4.0	16.0	10.2	2.0	5.0	12.0	9.0	1.5
Temperature (F°)	17.0	110.0	60.5	20.9	17.0	110.0	59.9	22.4	42.0	80.0	63.0	11.6

Table 23 Frequencies of dichotomous predictive variables

	Overall sample		TD workers		GC workers	
	Yes	No	Yes	No	Yes	No
Noise	216	32	168	32	48	4
Supervisor	237	9	194	4	43	5
Condition1	34	214	30	170	4	44
Condition2	32	212	25	170	7	42

Table 24 descriptive statistics of dependent variables

	Overall sample n = 252				TD workers n = 200				GC workers n = 52			
	Min	Max	$\bar{X}$	S	Min	Max	$\bar{X}$	S	Min	Max	$\bar{X}$	S
Median RT	200	460	291	45	200	460	284	44	223	391	318	40
SOFI Score	0	76	22	18	0	71	21	17	0	76	27	20

4.7.1 Interactions

Possible interactions among all predictive variables where analyzed for every TD and GC model with median RT and the square root of SOFI scores as the dependent variables. Only 2 double interactions were found to be significant and these are presented in Table 25 and Table 26 respectively.

Table 25 Interaction's analysis for a PVT model among TD workers

D.V. Ln (Median RT), n=193		
R^2	0.150	
Adjusted R^2	0.132	
Std. Error	0.133	
Predictors	**B_i**	**Std. Error**
Intercept	5.593	0.024
Last Shift_C	-0.012	0.005
Noise	0.060	0.026
Temperature_C	0.002	0.000
Temp_Last Shift_C	-0.001	0.000

Notation: D.V. = dependent variable; _C = Centered; Temp_Last Shift = *Temperature* x *Last Shift*

Table 26 Interaction's analysis for a SOFI model among TD workers

D.V. L SQRT (SOFI), n=180		
R^2	0.192	
Adjusted R^2	0.169	
Std. Error	1.181	
Predictors	**B_i**	**Std. Error**
Intercept	7.590	0.412
E. Operator	-1.002	0.342
Sleep 24 h	-0.184	0.055
(Rest)	-0.017	0.020
Condition 2	1.883	0.409
Rest_Condition 2	-0.131	0.050

Notation: D.V. = dependent variable; ( ) = Not significant; Rest_Condition 2 = *Rest* x *Condition 2*

After centering the predictive variables of the PVT model, by subtracting the variable mean to each data point, no collinearity effect was detected. Table 25 indicates a significant interaction between *Temperature* and *Last Shift* that increases the explained variability to 15%. Regarding the SOFI model, the interaction between *Rest* and *Condition 2* also offers a greater level of explained variability at 19%. However, these interactions don't dramatically change the predictability of the previous models.

4.7.2 Limitations of the study

Despite minor limitations of this study, the authors recognize 3 main limitations. The first limitation refers to the initial selection of potential predictors. Such a selection was driven by previous research, therefore, only those variables recognized as causal factors of fatigue by other researchers where included in this study. The results indicate, that such variables are able to explain up to 50% of the variability in fatigue levels of the sample as measured by the SOFI and the PVT. Thus, indicating that there may be other predictors, not considered in this study, able to add explained variability to these models.

The second main limitation of this study refers to the extent to which the selected fatigue measurement tools can register all fatigue’s dimensions. In theory, the study accounts for an exhaustive measure of fatigue by measuring objective and subjective fatigue. However, it is possible that other fatigue measurement tools may be able to register other dimensions of fatigue not recognized by the SOFI or the PVT.

The third main limitation of this study refers to the volume of GC workers. When analyzing the results of such a group some unexpected results were found regarding the sign of the predictors. The use of a bigger sample would add more variability to the data and possibly correct biases. Thus, offering more valid results. An overall reflection of this study is presented in the following section.

4.8 Conclusion

The purpose of this study was to test the predictive validity of factors that have been found to cause fatigue in laboratory settings, by measuring fatigue in-situ, fatigue in a high-risk industry. Twenty-six variables representing nine fatigue causal factors were tested and the results revealed low to medium predictive power, suggesting that laboratory results do not necessarily translate to the field and that other factors not yet identified are likely at play.

This fact becomes evident while studying fatigue in physically active working conditions, such as those experienced in the construction industry. Laboratory results may apply more directly to those professions that require a level of activity similar to that experienced during laboratory experiments. In the case of construction workers, achieving such a similitude between laboratory conditions and the worksite is nearly impossible. Thus, questioning the external validity of laboratory studies relative to actual field conditions.

Nonetheless, the models presented in this study offer an alternative to predict fatigue from a few activity variables that is valid for the construction industry. Therefore, the researchers conclude that construction workers' fatigue can be predicted. Conversely, the authors sustain that such models are not ready for their implementation in the industry as fatigue predictive tools. The amount of error present in these models is still unacceptable for practical implementations. Therefore, future research should strengthen the predictivity of these models by discovering new predictors able to further explain fatigue variability.

The discovery that predictors vary by trades is a valuable contribution to the industry. Knowing that work environmental factors such as *noise* and *temperature* drive fatigue in TD workers can influence decision making regarding the management of fatigue in this sector. For instance, it will probably be more effective to buy ‘blowers’ to help underground workers cope with a hot day than prevent them from working an extra day. However, such affirmation should be studied in detail considering the characteristics of the work and job-site. This example is presented only to illustrate the principle. Interestingly, the predictors obtained for RT among TD workers coincide with those previously identified by TD workers as the main drivers of fatigue in an exploratory study conducted by Techera et al (2017).

Additionally, the identification of actual fatigue predictors in this study can help the industry implement Fatigue Risk Management System (FRMS). The multilayer system of defense suggested by FRMS offers a general tactic to manage fatigue and the protocol followed in this study should serve as a preliminary approach to craft a FRMS to a specific trade, thus increasing the likelihood of its success.

Even though most predictive variables where objective (i.e. *Sleep 24h* and *Consecutive Shifts*), these were better at forecasting subjective fatigue as measured by the SOFI than objective fatigue as measured by the PVT. Thus, further validating the correlation between objective fatigue causal factors and subjective levels of fatigue. The development of objective instruments to measure fatigue offers a very attractive approach to fatigue measurement because these instruments diminish the ability of an individual to manipulate the results. However, the results obtained in this study indicate that objective and subjective fatigue measurement tools identify different dimensions of fatigue and both should be considered to measure fatigue.

There is still no perfect or exhaustive method for measuring fatigue that is able to identify all dimensions of fatigue. Consequently, future research should present a multi-instrumental approach to fatigue measurement. Based on the results obtained in this study, a multidimensional approach as the one presented here with activity variables, has the potential to predict fatigue levels considering a wider range of fatigue dimensions than a specific instrument. Nonetheless, these models need further development and validation before serving as fatigue predictive tools.

The research community's understanding of sleep deprivation as a main driver of fatigue is reinforced by this study. However, this study emphasizes the importance of further investigating the impact of work environmental factors and social factors in the development of fatigue in the field. Such areas of research have not been widely studied and there is a dearth of research in these fields among construction workers.

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4.10 Appendix

Table 27 Descriptive statistics of continuous activity variables

	Overall sample n = 249				TD workers n = 198				GC workers n = 51			
	Min	Max	$\bar{X}$	S	Min	Max	$\bar{X}$	S	Min	Max	$\bar{X}$	S
Sleep 24 (h)	3.0	14.0	7.0	1.6	3.5	14.0	7.0	1.6	3.0	11.0	7.0	1.4
Sleep (h)	3.0	12.0	6.8	1.3	3.0	12.0	6.8	1.2	3.5	10.5	6.9	1.3
Rest (h)	0.0	20.0	4.4	4.5	0.0	20.0	4.7	4.9	0.0	11.0	3.0	2.3
Time off (h)	0.0	288.0	37.7	56.7	8.0	288.0	43.0	62.4	0.0	62.0	17.8	12.3
Consecutive shifts	0.0	12.0	2.3	1.9	0.0	12.0	2.1	1.9	0.0	6.0	3.0	1.7
Overtime (h)	0.0	44.0	7.1	8.4	0.0	44.0	7.4	9.0	0.0	20.0	6.1	5.3
Last shift (h)	4.0	16.0	10.0	1.9	4.0	16.0	10.2	2.0	5.0	12.0	9.0	1.5
Temperature (F°)	17.0	110.0	60.5	20.9	17.0	110.0	59.9	22.4	42.0	80.0	63.0	11.6

Table 28 Frequencies of dichotomous activity variables

	Overall sample		TD workers		GC workers	
	Yes	No	Yes	No	Yes	No
Individuals	128	124	100	100	28	24
Rotating	77	174	74	126	3	48
Repetitive	217	35	167	33	50	2
Vibration	183	63	147	52	36	11
Noise	216	32	168	32	48	4
Light	223	25	176	24	47	1
Mental	201	51	161	39	40	12
Physical	200	52	155	45	45	7
Coworkers	247	1	199	1	48	1
Supervisor	237	9	194	4	43	5
Caffeine	195	45	162	33	33	12
Condition1	34	214	30	170	4	44
Condition2	32	212	25	170	7	42

Chapter 5: Conclusion

The effort of researchers, industry leaders, and policy makers to make construction a safer environment has produced good fruits. A 67% reduction in recordable incident rates has been observed during the past 2 decades (U.S. Bureau of Labor Statistics 2015). However, the construction industry is still among the top most dangerous industries with a fatality rate nearly 3 times greater than the overall industry average. Furthermore, fatalities have plateaued for the last decade, and they have even increased in the past 3 years (U.S. Bureau of Labor Statistics 2015). Therefore, there is still much to do regarding safety in construction.

Safety becomes even more critical among sectors inside the construction industry such as Transmission and Distribution Electrical Workers (TD workers). These workers present fatality rates disproportionally high even compared to the overall construction industry. For instance, the average TD workers' fatality rate during the past 20 years is approximately 3 times that of the overall construction industry (U.S. Bureau of Labor Statistics 2015). These statistics situate TD workers among the 10 most dangerous jobs in the country.

Fortunately, past research sheds light on the way to accomplish a safer construction industry. Kartam (1997) demonstrated that accidents are caused either by unsafe human acts and/or an unsafe design that generates physical hazards. Additionally, Langford et al. (2000) and Weick et al. (2008) showed that organizational and human factors, rather than technical failures, are the principal causes of accidents.

A large body of literature shows the impact of fatigue on human error and accident causation (Craig 1992; James Yaggie 2010; van der Linden et al. 2003a; Lorist et al. 2000, 2005; Scott et al. 2006). Furthermore, some researchers have recognized the negative impact that fatigue has in the construction industry, identifying it as a main threat to safety and productivity (Chan 2011; Hallowell 2010). Nonetheless, such approaches study the impact of fatigue as a whole, based on the opinion of stakeholders and extrapolating results from studies conducted in other industries or in a laboratory setting. As of now, to the knowledge of the author, no study addresses the causes and consequences of fatigue in the construction industry.

Lastly, the current body of knowledge about fatigue is disorganized and disperse. The apparently fuzzy nature of the phenomenon, its multidimensional manifestation, and its commonality have contributed to the inexistence of a universal definition of fatigue. Consequently, a plethora of diverse fatigue measurement and management techniques exists with mostly little to no validation. Such conditions make the research of fatigue in the construction industry even more challenging. Several authors have identified a need for an organized body of knowledge that allows for a better understanding of fatigue causes and consequences in occupational settings (Reiner and Krupinski 2011).

5.1 Contributions

The research documents in this dissertation offer: (1) an organized framework to study occupational fatigue in the industry as a whole and, more importantly, in the construction industry; (2) new knowledge regarding fatigue causes, consequences, identification and management techniques for the construction industry. The contributions in knowledge here presented are of special importance to safety researchers, safety and industry leaders in the construction industry, and policy makers.

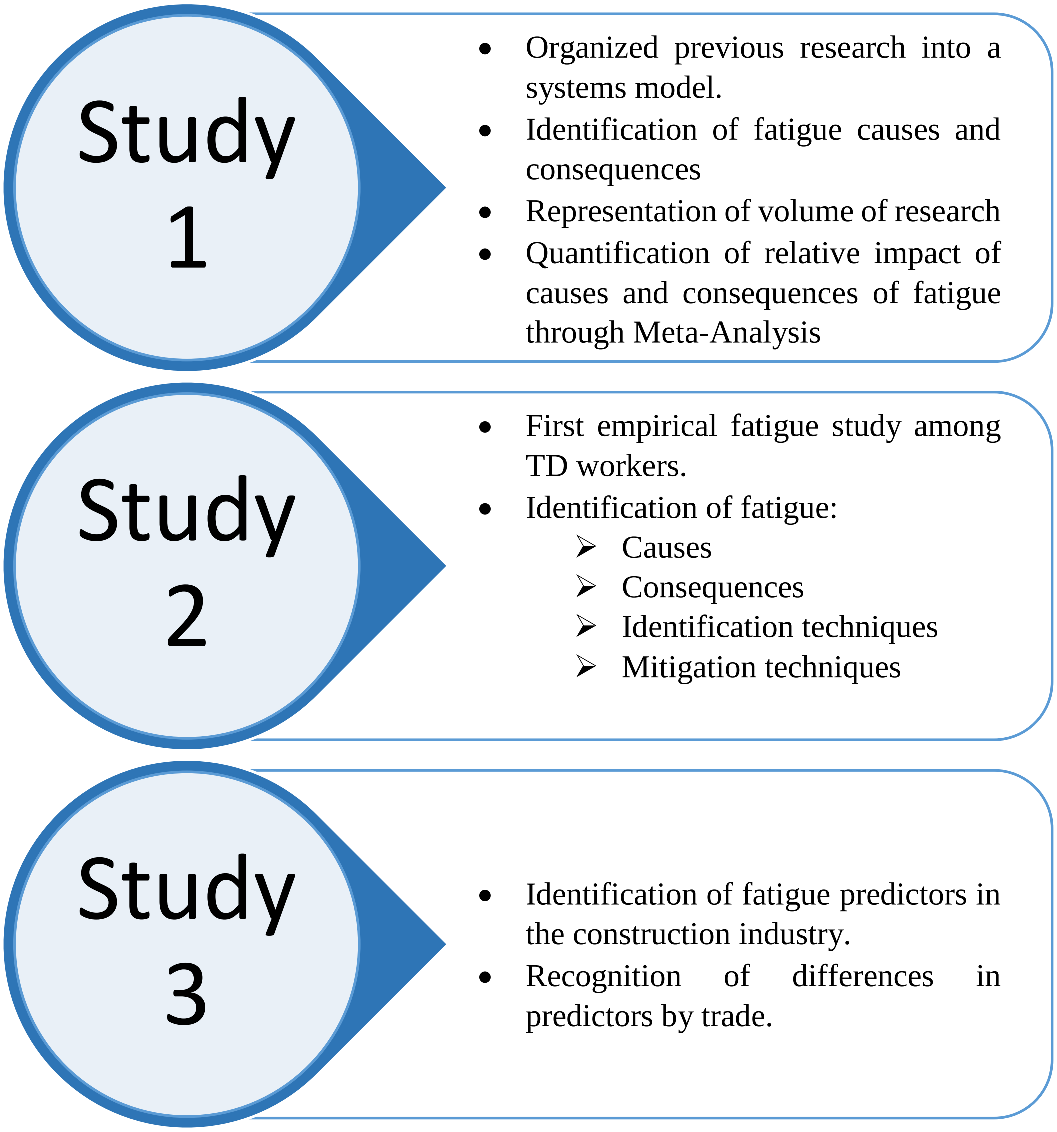
The first study presented in this dissertation formalizes the study of fatigue in working populations by organizing the disperse occupational fatigue literature and offering a clear overall understanding of the phenomenon and its dimensionality. The existing body of knowledge was organized in a single system's model allowing for an identification and easy visualization of the principal causes and consequences of occupational fatigue. Additionally, such a model illustrates the link between these factors and a specific dimension of fatigue, together with a representation of the volume of research performed for every link. This knowledge will help future researchers to identify where further investigation is needed in order to achieve a higher understanding of fatigue. Furthermore, now researchers and practitioners can access the principal causes and consequences of occupational fatigue through a single document without addressing the more than 120 studies contemplated in this work.

In the same study a meta-analysis was conducted to quantify the relative impact of fatigue causes and consequences. Such knowledge allows for comparisons among these factors helping the research community and the industry make sound decisions on resource allocations to further knowledge about specific fatigue causes and consequences or to decide on mitigation strategies.

The second study represents the first attempt to explore the presence and impact of fatigue causes and consequences among construction workers in the field. The data was collected directly from 143 TD workers thus providing excellent ecological validity. This fact is worth mentioning because past fatigue literature has addressed the issue from a more theoretical point rather than with actual empirical data. In addition to recognizing the specific causes and consequences of fatigue that affect TD workers, according to the opinion of the participants, this study also summarizes the strategies that construction workers use to identify and mitigate fatigue in the worksite. Furthermore, this study also offers recommendations on the first steps to manage fatigue in the TD sector based on empirical evidence. These results can be of great help to industry leaders and policy makers who look forward to an effective way of managing fatigue in the TD sector, which would potentially contribute to fewer accidents and higher productivity, among other benefits.

Lastly, the third study presented in this dissertation offers an even more relevant advancement in knowledge regarding fatigue management in the construction industry. To properly manage fatigue it is important to understand its causal factors and how to detect or predict fatigue impairments among workers (Dawson and McCulloch 2005). This study offers an empirical work, performed among 253 US construction workers belonging to 6 different states across the country. This diverse and populated sample adds strength to the obtained results.

This last study allows for the identification of fatigue predictive variables among two different types of construction workers: TD workers and GC workers. Furthermore, this study demonstrates (1) that fatigue predictors can vary across different trades and (2) that not one available instrument to measure fatigue is exhaustive. Consequently, when developing fatigue predictive models in working populations, there is a tradeoff between the predictors identified by instruments and the quality of the prediction. These results are especially important for safety researchers in the construction industry. Now researchers have an example of an approach to the development of a fatigue predictive model that they can apply to enhance the current models. Furthermore, the results presented in this study show that fatigue related results cannot be generalized across different construction trades. Figure 10 summarizes the contributions of this dissertation by study.


Study 1

- Organized previous research into a systems model.
- Identification of fatigue causes and consequences
- Representation of volume of research
- Quantification of relative impact of causes and consequences of fatigue through Meta-Analysis

Study 2

- First empirical fatigue study among TD workers.
- Identification of fatigue:
  - ➢ Causes
  - ➢ Consequences
  - ➢ Identification techniques
  - ➢ Mitigation techniques

Study 3

- Identification of fatigue predictors in the construction industry.
- Recognition of differences in predictors by trade.

Figure 10 Dissertation contributions

5.2 Suggestions for future research

The research performed throughout this dissertation informed the author of several opportunities for advancement in knowledge in this field of research. In the opinion of the author, the next steps in this field of research should encompass: (1) the empirical quantification of fatigue impact on accident causation; (2) the study of fatigue management among different construction trades;(3) measure the efficacy of Fatigue Risk Management Systems (FRMS).

5.2.1 Limitations of current data sets

Despite the rigorous methodology followed in the research processes here presented, the generalization of findings to a broader population will require further studies. The researcher is content with the large sample of TD workers that participated in these projects (n = 343). However, only 53 general construction workers took part in this research. Consequently, the author is confident in the generalization of most results to other TD workers in the US, given that the sample here considered was sufficient, diverse, and the data collection process was performed over the course of a whole year, thus allowing for the consideration of diverse weather. Furthermore, the samples considered were predominantly male while few participants were female. Therefore, these results, a priori, should not be generalized to a group of female construction workers.

There are additional limitations to the data related to the conditions in which data collection took place. Construction is a dynamic and fast paced environment in which workers have very limited time for interaction with researchers. Therefore, the circumstances in which data is collected vary from one worksite to another. However, these characteristics contributed to ecological validity. Furthermore, this same reasoning applies to all in-field studies in the construction industry.

5.2.2 Future research based on findings

The author has shown that additional fatigue predictors need to be identified to achieve higher levels of predictability. Given the lack of an exhaustive fatigue measurement tool, a multidimensional approach to fatigue measurement will give researchers the opportunity to identify new predictors of fatigue.

Along those lines, the author also showed that fatigue predictors vary across different trades, consequently, the multidimensional approach described above should be accompanied by the inclusion of several diverse trades because these may experience fatigue accumulation in different ways. This procedure will also help the discovery of new predictors. There are 2 other trades that should receive priority treatment: Roofers and Steel workers, which are among the 10 most dangerous jobs in the country. Interestingly, in the third study presented in this dissertation (Chapter 4), TD workers showed a significantly lower level of fatigue than GC workers. This was an unexpected result because the researcher would expect the opposite given the higher injury and fatality rate of TD workers compared to GC workers. Consequently, the implementation of the protocols here presented to different trades will shed light on the importance of fatigue in accident causation.

Additionally, the discovery of new predictors will also require the consideration of additional prospective predictors. It is the opinion of the author, that a possible way to develop a list of new potential predictors, would consist of conducting exploratory research such as that presented in the second study of this dissertation (Chapter 3). This pragmatic approach allows for open ended questions that would contribute with additional variables of interest, not foreseen by the researchers. At the same time these answers can be coded for rigorous statistical analyses.

5.2.3 Future research of fatigue in construction

Surprisingly, despite decades of occupational fatigue research, to the knowledge of the author, there are no longitudinal studies that directly investigate the impact of fatigue on injuries and fatalities. There is a need for longitudinal studies able to track fatigue levels and accident reports to empirically quantify the impact of fatigue in accident causation in the construction industry. The studies presented in this dissertation underline the importance of addressing this issue and even provide fatigue predictors in the construction industry that could be used to select the most appropriate measurement tools. However, none of these studies followed up on worker's performance, safety record, and fatigue levels overtime. Such information may or may not justify further research in this area in the construction industry.

Perhaps, for this reason, policy makers and industry leaders have not taken measures to directly manage fatigue other than shift length limitations. It is the opinion of the author that efforts to validate the impact of fatigue on accident causation and productivity loss should be accompanied by equal attempts to investigate the efficacy of FRMS in preventing accidents and improving productivity. This not only would allow for a more comprehensive approach to the formal study of fatigue in the construction industry, but this would also enable true experiments with control groups, thus allowing for direct comparison. It is in the best interest of industry leaders to sponsor the implementation of FRMS suited for the construction industry and longitudinal studies to quantify the impact of FRMS in accident reduction and productivity improvement. Then, a comparison between positive effects of fatigue management techniques and negative effects of fatigue in construction safety and productivity will be possible.

Additionally, recent studies indicate that the construction industry is experiencing a marked shortage of craft workers and this situation will become even more critical in the near future (Karimi et al. 2017). As a direct result, the workload for the available workforce increases and these workers are required to work longer and more frequent shifts. All of these factors contribute to the onset of fatigue. Thus, the author concludes that fatigue management, in the construction industry, will become even more relevant in the upcoming years. As it was shown in this dissertation, despite general fatigue causal factors such as sleep deprivation, there are specific causes of fatigue that vary across trades. Consequently, it becomes vital to determine these causes as early as possible to properly implement FRMS crafted to each trade, thus increasing the probability of success in fatigue management.

5.3 Personal Reflection

5.3.1 About research in the construction industry

It is my opinion, that in general, safety research in the construction industry has traditionally relied on a constructivist approached based on qualitative data obtained from experts or on the extrapolation of studies conducted in other populations such as students or other industries. Most current researchers are advocating for studies with strong ecological validity in which the data is obtained from the construction workers themselves. As a researcher, it is my responsibility and privilege to join this effort to further formalize research in construction safety by developing studies with strong ecological validity and a rigorous scientific approach.

Several improvements in ergonomics and working conditions have positively impacted safety in the construction industry. It is my opinion and that of other researchers that human factors play a major role in accident causation. The management of human factors requires an awareness of their influence on safety and a conscious personal effort to control them, if possible. Such a control over our human factors will require a change of behavior. I believe that education is the main avenue to overcome safety risks associated with human behavior. The personal conscious effort to modify our conduct may have an important impact in accident mitigation.

Finally, other human factors besides fatigue need to be considered to understand the impact that human factors have on safety in the construction industry. Some of those human factors include but are not limited to: emotions, stress, cultural differences, and personal biases. While conducting experiments to assess the impact of these human factors preliminary studies could be conducted in laboratory settings, however, these studies should also be validated in the field to ensure good ecological validity.

5.3.2 About the journey to become a Ph.D.

The path to the completion of this dissertation has been one of constant enthusiasm, challenges, and growth. I have felt a gradual internal change and now I can say that I am not the same individual that I was 3 years ago when I started this adventure. I have incorporated several skills that open a new world of opportunities. Humbly, I would like to express that such skills make me feel limitless. Not because consider myself better than anybody else, but because these skills have given me the opportunity to acquire knowledge in any area of my interest. I have developed the ability to: (1) critically see the world and recognize specific needs for additional knowledge in order to solve a specific problem or to gain a deeper understanding; (2) obtain, analyze, and synthesize the existing body of knowledge about a topic of interest to discover the many angles in which such a topic has already been observed and recognize those perspectives yet to be seen; (3) plan a scientific approach to the discovery of new knowledge; (4) execute such a plan; and (5) clearly present the obtained new knowledge for the benefit of my fellowmen. The development of these skills is my biggest takeaway in my journey to become a Ph.D. I happily recognize that I would have never been able to develop these skills without the constant and patient guidance of my advisor, Dr. Matthew R. Hallowell, to whom I am forever grateful.

The journey was full of challenging and rewarding tasks. Perhaps the most difficult task was the one of engaging industry members in my research. Each organization has its own interests and schedules and it is a difficult task to align interests and even more difficult to align schedules. However, the industry is full of professionals who want to make a difference in their companies, the industry, and the community. Thanks to those individuals, I was able to collect data from a significant number of construction workers which was very rewarding. This allowed for studies with excellent ecological validity and that is fulfilling because I know that the results of these studies have direct applicability to the industry. Additionally, one of the things that excites me the most about my research is that those advancements in knowledge that we obtain can potentially help save lives.

It is natural, in the process of learning, to look back and realize that some things could have been done better, not because I was not careful enough, but simply because I didn’t have the knowledge that I have now. In preparation to my comprehensive exam, I developed a research plan, a protocol for its implementation, and documents to collect data. All of these were carefully designed, however, mistakes still occurred. It is not relevant to mention the specific mistakes; however, it may be enriching to share what I learned from those mistakes. I learned that despite having a very good research plan, it is important to contemplate all the possible outcomes and plan on a course of action for each possible alternative. By so doing, the researcher will always be able to know what to do in order to achieve the desired objective despite changing circumstances.

Throughout my Ph.D. studies I learned some things that helped me complete my Ph.D. goals and may be of use to future students. First, I found it very helpful to spend enough time on a literature review of your topic of interest. In my case, my first study consisted in organizing the current body of knowledge about fatigue and for that reason I spent 6 months on a deep literature review and 6 more months working on a meta-analysis of such literature. After this, it was very clear what things were missing in the body of knowledge and where further research was needed. Probably most students will be able to reduce the amount of time if their field of interest possess a more organized body of literature. Second, once you have a tight plan to accomplish your research goals, present your plan to several people and learn from their feedback. I presented my plan to many professors, students, and industry professionals that were helping me at the time. The feedback that they provided was very enriching and allowed me to take better advantage of the data collection process. Lastly, I would advise any student to expect changes in their research plan, determine a plan of action for each foreseeable deviation from the plan and implement such a plan of action early. This will allow students to know exactly when to stop collecting data given their research objectives. These are simple tips but they helped me and they may help other students.

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Appendix A: IRB Protocol

TITLE: Study of the influence of fatigue on hazard recognition and development of a fatigue predictive tool

PROTOCOL VERSION DATE: 1st May 2016

VERSION: 1

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OBJECTIVES

The current study has two specific primary objectives:

First, we aim to develop a fatigue predictive tool. Some authors claim that the level of fatigue in an individual can be predicted based on the level of activity experienced during the past 24h-48h (Dawson and McCulloch, 2005). Previous research in the construction industry suggests that the amount of sleep obtained within such a period of time, the number of hours worked in the previous shift, the rest period between shifts, the type of shift, the intensity of the workload, the time on task, and the temperature are variables which could predict the level of fatigue in an subject (Techera et al. 2016). This hypothesis will be tested by comparison to an objective measure of fatigue. By so doing, a fatigue risk predictive tool will be created.

Second, we aim to study the influence of fatigue among the hazard recognition ability of individuals. We will test the hypothesis that fatigue diminishes the ability of an individual to recognize hazards. The data for this test will be obtained by asking individuals to recognize hazards present on a set of pictures, right after assessing their level of fatigue. The researchers expect to find a correlation between the level of fatigue in the individuals and their hazard recognition ability.

The findings of this research will have their application in the construction industry in general, and more specifically among Transmission and Distribution power line workers (TD workers).

BACKGROUND AND SIGNIFICANCE

In comparison to the average occupation, electrical TD construction, operation, and maintenance is nearly an order of magnitude more dangerous. According to the U.S. Bureau of Labor Statistics (2015) in 2014 there were a total of, 4,679 fatal work injuries, which equates to an all-industry fatality rate of 3.3 fatalities every 100,000 full-time equivalent workers (FEW). That same year, the construction industry showed a fatality rate of 9.4 every 100,000 FEW and electrical TD workers experience a rate of 19.2 fatalities every 100,000 FEW. The mean fatality rate for electrical TD workers for the past 20 years is 26.1 per 100,000 workers, over three times greater than the construction fatality rate and eight times greater than the all-industry average. These statistics set electrical TD operations among the 10 most deadly jobs in the country.

Fatigue plays a significant role in the causes of occupational injuries and fatalities, particularly in high-energy situations. When workers are fatigued, they experience compromised alertness, judgement, reaction time, mental acuity, physical strength, and the development of an uncooperative disposition (Gillberg and Åkerstedt 1994; Kajtna et al. 2011; van der Linden et al. 2003a; Lorist et al. 2005; Scott et al. 2006; Yaggie and Armstrong 2004). Such effects decrease a worker's ability to complete their work safely due to the increased rate of human error (Dembe et al. 2005). Currently, there are two ways of measuring fatigue, subjective questionnaires or devices that measure fatigue objectively. Subjective measures of fatigue are prone to easy manipulation. The majority of current technologies, that objectively measure fatigue, lack proper validation and are very costly (Dawson et al. 2014). These characteristics, diminish the applicability of these tools in the industry. The development of an objective fatigue risk predictive questionnaire will allow for a cheap and easy evaluation of the level of fatigue among individuals, thus alerting supervisors of a dangerous fatigue related situation and preventing accidents and fatalities.

Furthermore, a few studies suggest that fatigue diminishes the ability of an individual to perceive risk, therefore, subconsciously individuals assume higher risk than they would assume under a non-fatigued condition (Spurgeon et al. 1997; Tixier et al. 2014). However, none of these two past studies focused on hazard recognition with fatigue as the only treatment variable. For this reason, further research is needed to confirm these suggestions. The objective evaluation of the impact of fatigue among the hazard recognition ability of workers will represent and important and meaningful contribution to the current body of knowledge about fatigue and to the industry.

PRELIMINARY STUDIES

This study will be the first effort to create an objective fatigue risk predicting tool specifically designed for construction workers. Additionally, this study will confirm or deny the predicting character of the variables presented above in regards to fatigue, thus building upon the research developed by Dawson and McCulloch (2005).

Additionally, the current research is the first effort to address hazard recognition as a function of fatigue solely. The results of this study will either confirm or refute past research.

RESEARCH STUDY DESIGN

According to the research objectives, the study design is organized in the following way:

1) Fatigue risk predicting tool

According to the first objective of creating a fatigue risk predictive tool, the study is designed in 3 different sections which are, first Pilot Testing (PT), second "Instrument Development Phase (IDP), and third "Instrument Validation Phase" (IVP). The data collecting process will take approximately 9 months.

The point of departure consists of identifying variables that previous research theorize predicts fatigue. These variables have been previously studied separately; however, non-study has considered all variables together as predictors of fatigue. The current stage of the research process focuses on obtaining the regression parameters that will describe the predictive ability of each variable. To do that, the researchers will assess the state or value of each activity variable (the seven variables presented above) through an activity questionnaire, and analyze the relationship of those variables with a true measure of fatigue, which will be taken by a reaction time test (PC-PVT). These steps will be described in detail in the "Procedure" section of this document.

Sample size calculation:

In order to accomplish this first objective presented above, the researchers seek to determine the predictive validity of the variables presented above. The statistical method chosen to investigate the predictive validity is Multiple Linear Regression (MLR). This method is generally used either to describe or to predict a relationship (Gross 1973; Kerlinger and Pedhazur 1973; Pedhazur 1997). While using this method the minimum sample size varies depending on several factors such as the nature of each variable and the true correlation between independent variables and the dependent variable. Values as low as 10 data points per independent variable of interest have been shown to produce acceptable results (Miller and Kunce 1973). On the other hand some authors state that a minimum sample size of 30 data points per independent variable of interest are needed to obtain acceptable results (Pedhazur and Schmelkin 2013).

In this experiment, the sample size for the pilot test will be calculated based on the recommendation given by Miller and Kunce (1973) of 10 data points per variable of interest. For the second phase of this experiment (instrument development), we will base our initial decision of minimum sample size in the work produced by Knofczynski and Mundfrom (2007). These latter researchers utilized more than 23, 000,000 computed generated samples to calculate minimum sample sizes while using MLR for prediction. According to that study in order to guarantee that 95% of the correlation coefficients between the predictive variables and the dependent variable (fatigue) exceed 0.92 (good predicting level) and in order to be able to detect a squared population multiple correlation coefficient (ρ^2) equal or greater than 0.25 a ratio of approximately 30 data points per variable of interest should be obtained.

1.a) Pilot Testing:

This first data collection effort has two purposes. The first purpose is the one of ensuring the correct functioning of the research tools. These tools are: (1) activity questionnaire that inquiries about the participant's level of activity during the previous 24-48hs, a subjective fatigue questionnaire; (2) software that performs a reaction time test; and (3) a hazard recognition test based on pictures. The second purpose consist of acquiring enough data to more accurately calculate sample sizes needed for subsequent phases. The pilot testing phase is expected to last approximately 1 month where a sample of 70 graduate students from the University of Colorado at Boulder will voluntarily take part in the experiment. The sample size for this pilot test was calculated based on the fact that there are 7 principal variables of interest and using the method presented in the previous subsection. The reader will notice that the activity questionnaire presents more than 7 variables; the additional variables, besides the principal 7 variables, were included for exploratory purposes given the fact that they experience changes with fatigue, but our main focus is to determine the predictive ability of the 7 principal variables of interest. These variables are as follows: the amount of sleep obtained within the previous 24hs, the number of hours worked in the previous shift, the rest period between shifts, the type of shift, the intensity of the workload, the time on task, and the temperature.

During this phase, the level of activity during the 24-48hs previous to the testing time will be assessed, by the activity questionnaire, as well as the participant's level of fatigue (with the reaction time test) both objectively and subjectively (with a subjective fatigue questionnaire). A correlation will then be drawn between the level of activity of individuals and their level of fatigue. The results will give information for a more accurate sample calculation for the subsequent stages of data collection.

1.b) Instrument Development:

This second phase has the objective of collecting data among the population of interest which is construction workers (more specifically, electrical transmission and distribution (TD) line workers) in order to obtain the fatigue predictive variables and weights that fit this population.

In instrument development research the more participants the better. However, in reality the obtained sample size usually is far smaller than the desired sample size. The target sample size will be more accurately calculated after the pilot test; however, an approximate number of 300 construction workers will be established as the target population. This sample size was calculated on the basis that 30 data points per variable are needed to obtain good results from regression analyses and there are a total of 7 main variables plus 17 other possible fatigue predictive variables (30 X 7 = 210) (Knofczynski and Mundfrom 2007). An additional sample of 90 workers is considered which will allow for a stronger analysis or the possible inclusion of other 3 additional variables. These variables are presented in an objective activity questionnaire that will be described in the "Procedures" section of this document, however, the reader can refer to appendix A for such a questionnaire. The results' characteristics and the data analysis agree with those of the previous section.

1.c) Instrument Validation:

The main objective of this phase of the research project is validating a fatigue risk objective predictive tool developed in the previous step with a population of construction workers. This phase will be sub-divided between two stages which are (1) validation among TD workers and (2) validation among construction workers from a variety of trades to test generalizability.

The sample size calculated for this stage consists of at least the same number of participants that took part of the previous phase, per group where the questionnaire is to be validated. This indicates that the questionnaire will try to be validated among 300 TD workers and 300 construction workers in other sectors (e.g., concrete finishers, carpenters, plumbers). This validation procedure is expected to last about 5 months. The timeline will include: One month and a half to collect data among TD line workers; one month and a half to collect data among other construction workers; and one month for data review and analysis; and one month to coordinate visits with the different contractors.

By the end of this data collection effort, the researchers will have collected fatigue scores obtained by a new objective fatigue measurement/predictive tool and objective fatigue levels obtained with the PVT, which is the current gold standard to measure fatigue. The comparison among the fatigue scores and the true measure of fatigue will validate the researcher's tool.

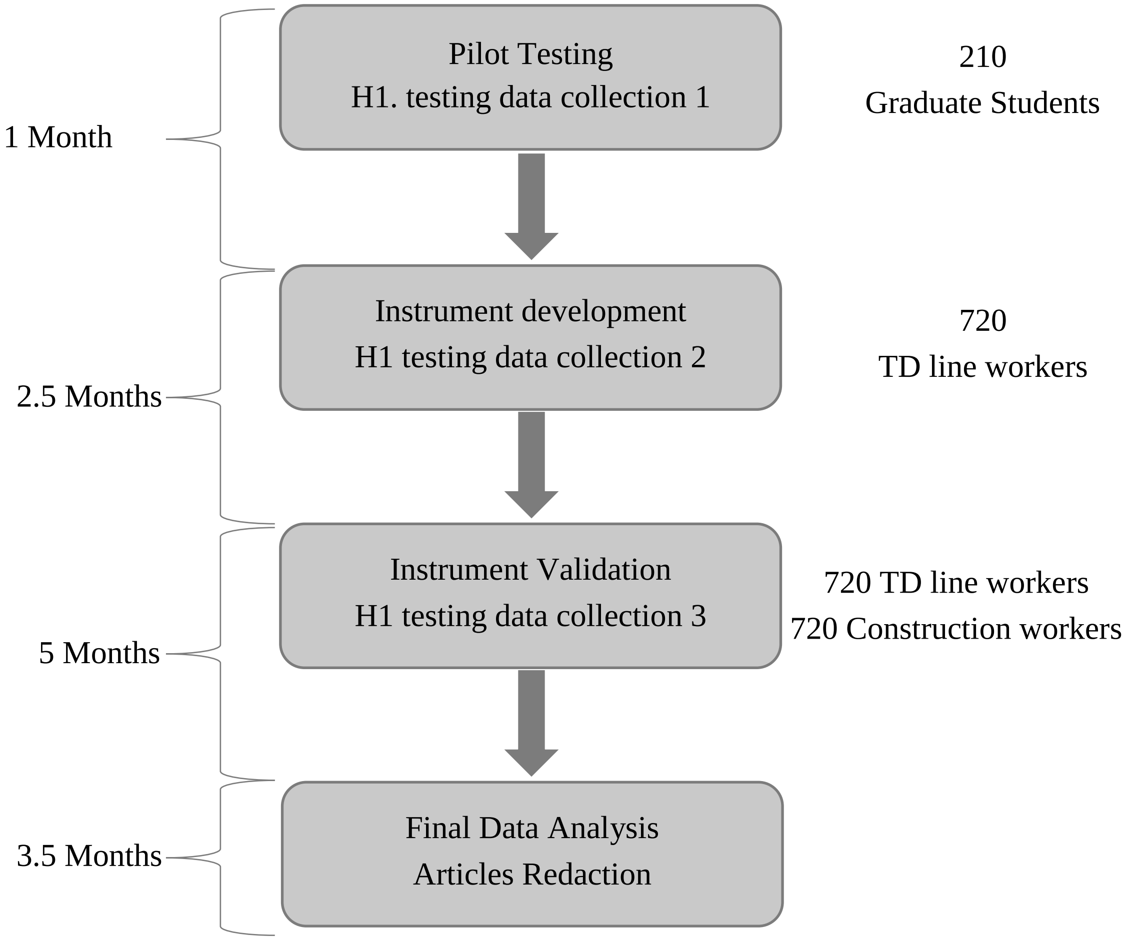
2) Hypothesis testing of the influence of fatigue on hazard recognition ability.

The main objective of this second phase of the research project consists of obtaining an answer for the following question: Does fatigue affect the hazard recognition ability of workers? To obtain such an answer, the researchers propose the alternative hypothesis that individuals will higher levels of fatigue have lower levels of hazard recognition.

This phase of the experiment will be incorporated to the stages 1.a, 1.b, and if needed 1.c. 70 graduate students and 900 construction workers will take part in this experiment. It is important to mention that the sample size needed to test this hypothesis is smaller than the sample size needed to develop a fatigue predictive tool because the experiment will involve fewer variables of interest (Brooks and Barcikowski 1995; Darlington 1990; Gross 1973; Pedhazur 1997). The total duration of this phase of the research project is expected to last approximately 9 months.

During this stage of the data collection process the hazard recognition ability of individuals will be measured and compared to their objective level of fatigue. A correlation between these two variables will be investigated. In order to measure hazard recognition ability a questionnaire with pictures will be presented to the participants. The pictures will be randomly pulled from a portfolio of pictures. Each picture contains a specific number of hazards identified by a panel of experts. Participants will be invited to recognize as many hazards as possible and the results from different participants with the same picture but different level of fatigue will be compared.

Research design flow chart:



FUNDING

None

ABOUT THE SUBJECTS

- A total of 970 subjects are expected to participate in the study. All these are volunteers older than 18 years of age which will voluntarily read and sign the consent form in order to take part in the study.
- From these volunteers, 70 are expected to be graduate students from the University of Colorado at Boulder, 600 are expected to be TD workers from the east coast of the United States, and the remaining 300 are expected to be construction workers from Colorado (U.S.).
- Besides these groups of participants, a panel of 5 members integrated by safety experts will be created to assist with stage 2 of the data collection process. This panel will consist of Professor Matthew R. Hallowell (co-author) and four graduate student experts in construction safety. More details about this panel of safety experts will be provided in the "Procedures" section of this document.

Subject Population(s)	*Number to be enrolled in each group*
Graduate Students	*70*
TD line workers	*600*
Construction workers	*300*
Safety Experts panel	*5*

- The researchers anticipate that approximately 70% of the planed number of volunteers will actually complete the experiment.
- Among the graduate students the researchers expect to find a slightly higher number of men participating in the pilot test due to the demographics of engineering students. We also expect to find a diverse group of ethnicities given the diversity of students in this campus.

  Among the TD workers sample the researchers expect to find a predominant white male population give the demographic characteristics of the TD workers in the east coast of the United States.

  Among the more general construction workers sample the researchers expect to find a predominant Hispanic male population due to the demographic characteristics of the industry.

- List the inclusion criteria - characteristics that must be met for individuals to be enrolled in study.
  - Older than 18 years old. Having a full proficiency in English. Graduate student or construction worker.
- List the exclusion criteria - characteristics that will exclude individuals from the study.
  - Younger than 18 years old. Non-English speaking individuals. Non graduate students or construction workers.

The objectives of this research project are directed to the construction industry and for this reason no minor or non-construction worker or graduate student will be considered for the study.

VULNERABLE POPULATIONS

- *What vulnerable populations will be considered for this study?*
  - None

- *Describe the additional safeguards that are included to protect their rights and welfare.*
  - N/A

- *How will coercion be avoided in this population?*
  - All participation in this research process will be voluntary and anonymous. The data collected will be dis-attached from any participant's personal identifier. No reward is offered to graduate students and construction workers will not receive any additional material compensation. In the same way, there is no sanction for not participating in the study for either group. Consequently the motivation to participate in this study is purely personal and has not external incentive or disincentive.

RECRUITMENT METHODS

- Graduate students in Engineering at CU Boulder will be recruited via email. The email will briefly explain the objective of the research and will ask for the voluntary participation in the experiment. The consent form will be attached to the email and those who desire to participate in the study will bring the consent form signed to the collecting data session. After that participants will receive an email with dates and times to take part of the experiment and these will enroll in one of those dates. The day previous to their testing an email will be sent to them to remind them of the coming testing session. No incentive or punishment are presented to the student in order to take part of the study. This guarantees the absence of undue-influence or coercion to force students to participate in this study.

- During the collecting data process you will interact with the principal investigator, Ulises Techera. This data collection procedure will take place at the conference room of the Civil, Environmental, and Architectural Engineering department of the Applied Sciences Engineering School, at the University of Colorado at Boulder (1111 Engineering Drive 428 UCB / ECCOT441, Boulder , CO. 80309-0428). The Pilot Testing phase of this research will take place during the month of May and June of 2016.

- TD line workers and construction workers will also be free to participate and in order to do so they must sign the consent agreement beforehand. The presentation of the research study and solicitation for participation will occur during a regular day of work. Once again, participants won't receive any material benefit or punishment for participating in the study. Consequently, their participation is entirely voluntary. Participants will be allowed by their supervisors to participate in the study or to continue working if that is what they prefer. It is in the best interest for the supervisor to have an operator continually working, however, no punishment will be given to any worker for their voluntary effort of participating in this study. Consequently, there is no undue-influence or coercion to participate in the study.

- During the collecting data process you will interact with the principal investigator, Ulises Techera. This data collection procedure will take place at the beginning of the shift, during the meeting with supervisors, at the company's facilities, and additionally in a quiet and spacious vehicle, parked near to where the operator will be working. The data collection process extends from June, 2016 to January, 2017.

List recruitment methods/materials and attach a copy of each in eRA

1. ***Email communication***
2. ***Personal invitation at the work site***

COMPENSATION

- For graduate students no compensation will be offered other than the personal satisfaction of contributing to a good cause.
- For construction workers (including TD workers) no monetary compensation will be offered other than maintaining their salary amount after performing the aforementioned tests.

CONSENT PROCESS

- Two different consent forms were created, one for graduate students which can be found in Appendix C, and another for construction workers which can be found in Appendix D.
- The group of graduate students will receive the consent form by email and they must sign the consent form before taking part in the study.
- The group of TD workers and the rest of construction workers will receive a briefing on the objectives of this research with a description of the experimental procedure and an explanation of their role as participants. Following the briefing, they will be invited to participate in the experiment and it will be indicated that no material reward or punishment will be given by participating in the study. Furthermore, it will be explained that the participation is entirely voluntary and the consent forms will be handed out. Those workers that decide to sign the consent form will be admitted for testing.

- All results will remain confidential and no results will be reported to employers or participants until all data have been aggregated. At no single point in the data gathering process identifiers will be collected (names, addresses, complete birth dates, etc.). The data will be completely anonymous and results will be presented as an aggregate, thus responses of any participant cannot be traced back to one particular individual.

PROCESS TO DOCUMENT CONSENT IN WRITING

- As mentioned above, consent will be obtained via 2 different documents depending on the characteristics of the sample. Volunteers participating in the Pilot Testing experiment will complete the consent form addressed to graduate students. On the other hand, construction workers will complete the consent form developed for construction workers.

- In every case consent forms must be delivered to the researcher in order for volunteers to take part in the experiment. Participants can abandon the experiment at any time.

PROCEDURES

Before describing procedures of the 3 different sections mentioned above it is convenient to go over the research tools that will be employed in such phases.

Research tools

The research tools that will be used to accomplish this first overall objective are: a questionnaire developed by the researchers (activity questionnaire), a subjective fatigue assessment questionnaire specifically designed to assess fatigue among a working population, and finally a device to objectively assess the level of fatigue of an individual.

The survey developed by the researchers is a self-administered questionnaire that presents 4 biographical questions (age, years of experience in the sector, position, and gender), 24 objective questions about the participant's level of activity during the previous 24-48hs, and 4 subjective questions. These questions inquire about the treatment variables which fatigue predictive ability wants to be determined. This questionnaire will be handed out to volunteers who will complete it in approximately 5 min. For more details on this questionnaire please refer to Appendix A.

The subjective assessment of fatigue will be performed by the Swedish Occupational Fatigue Inventory (SOFI-20) (Åhsberg et al. 1997), which is a self-administered questionnaire that has been widely used to assess fatigue among a working population (Åhsberg 2000; González Gutiérrez et al. 2005).

The questionnaire presents 20 questions rated on a Likert scale from 0 to 6. It inquires about 5 different dimensions of fatigue which have shown to behave differently depending on the type of job. The five dimensions mentioned before are: 1) Lack of energy; 2) Physical exertion; 3) Physical discomfort; 4) Lack of motivation; 5) Sleepiness. The internal consistency of this questionnaire was evaluated in a sample of 597 volunteers and the results showed an overall Cronbach's alpha of 0.80, indicated good internal consistency (Åhsberg 2000). For further information about the SOFI please refer to Appendix B.

The third and last tool used in this phase of the research project is a device developed to objectively obtain an indirect measure of fatigue, such a device is the Psychomotor Vigilance Test (PVT). The PVT is a reliable and validated technology that has been widely used in research during several decades to obtain an objective measure of fatigue. The PVT is a technology that assesses the Neuro-behavioral performance of an individual by measuring its reaction time to a stimulus. This method is considered the current gold standard to measure fatigue (Dinges and Powell 1985; Dorrian et al. 2005; Loh et al. 2004). The PVT-192 is the most commonly used and widely validated tool to objectively measure fatigue and it has been extensively validated in its 2 different modalities, a 5 minute version of the test (Ferguson et al. 2011; Lamond et al. 2005; Thorne et al. 2005), and a 10 minute version of the test (Balkin et al. 2004; Dinges et al. 1997; Dinges and Powell 1985; Dorrian et al. 2005, 2008; Pilcher et al. 2007; Van Dongen et al. 2003).

The PVT-192 (Ambulatory Monitoring, Inc., Ardsley, NY; Dinges & Powell, 1985), is the current "gold standard" to measure simple reaction time. The device consists of a hand held apparatus with a small screen (approximately 2" x 0.5") and two buttons at the bottom. The device shows a visual stimulus which consists of a four digit millisecond counter that stops the count once the participant presses a button. At that time, the reaction time remains on the screen for 500ms and then it disappears. These stimuli appear after a random interval of time denominated "Inter-stimulus Interval" (ISI), which varies between 2 seconds and 10 seconds. The device stores the data for each session, then, this data can be transferred to a PC for analysis. Some of the most common analyses of the data are: the number of lapses experienced by an individual (more than 500ms without response after a stimulus) and the average reaction time (Khitrov et al. 2013).

Recently, a new software "PC-PVT" was developed to perform simple reaction time measures among individuals. The principal objective of the developers of this software was to develop a PVT with the same reliability and functionality as the PVT-192 (Khitrov et al. 2013). The mentioned software has achieved these objectives offering a reliable, valid, more familiar and more economical way of measuring simple reaction time.

The PC-PVT is a software that requires Windows XP or a later version to run, Windows 7 being the preferred operating system (OS) for providing support for modern timing hardware. A PC is not specifically designed to measure reaction time. For this reason a PC presents 2 main sources of RT data degradation. One is a reduced accuracy in the measurement due to the multitasking nature of a PC, and second, is a systematic delay in response detection introduced by the hardware and /or by the software. Nonetheless, the PC-PVT, when in operation, raises its own priority level to have the OS dedicate as much of the central processing unit (CPU) time as possible to the PVT session (Khitrov et al. 2013) .

The PC-PVT test requires the PC-PVT software, a PC, and a mouse. The test can be administered in 2 different modalities of 5 minutes or 10 minutes. The test consists of sitting in front of a computer with one hand on the mouse and pressing a button on the mouse as soon as possible after receiving a stimulus. The screen will show a black background and the stimulus will appear as a 5 digit millisecond counter in red that stops the count when the individual presses the button. The RT remains on the screen for 500ms and then it disappears. The ISI is distributed randomly between 2 seconds and 10 seconds, as in the PVT-192. The software allows for the immediate storage of data by individual and by session in the PC right after a session finishes. This represents an important advantage in comparison to the PVT-192 which requires the transmission of the stored data in the device to a PC for statistical analysis with its consequent risks of corruption. The summary statistics of the PC-PVT currently display: number of lapses, mean RT, speed, mean of the fastest and lowest 10% of RTs and RT divergence (Rajaraman et al. 2012). The software even provides an interesting and useful feature which consists of individualized predicting algorithms capable of predicting reaction times for an individual up to 24hrs into the future. This feature can then be used after the first session when the software matches your performance to an empirical database to predict your future RTs. However, when an individual participates in multiple sessions the software refines the predictive algorithm by assigning higher weights to the participant's data and lower weights to the data coming from the empirical database, using a Bayesian approach (Khitrov et al. 2013).

The PC-PVT was validated in a wide range of PCs and laptops with different operating systems, screens, and mouses to contemplate the variety of devices used by researchers. The validation was against the PVT-192, using the RTBox as the true measure of delay. The RTBox, was developed at the University of Southern California (Los Angeles, CA; Li et al., 2010) and consists of a closed circuit capable of measuring the time between the onset of the stimulus and the response with sub-millisecond precision (0.1ms). The RTBox allowed for three different comparisons: 1) The RTBox against the PVT-192, 2) The RTBox against the PC-PVT with a standard mouse, and 3) The RTBox against the PC-PVT with a gaming mouse with a scanning frequency of 1000Hz. Each comparison took place in 5 different sessions of 5 minutes each where the RT varied from the fastest humanly possible (~ 160 ms) to ~ 2000 ms. The results indicated a delay for the PVT-192 characterized by a mean of 3.4ms and a SD = 0.8 ms. For the PC-PVT with a gaming mouse the mean = 7.8 ms with a SD = 1.0ms; and the PC-PVT with a standard mouse showed a delay characterized by a mean = 35.7 ms and a SD = 2.6ms. The delay found in the PC-PVT with a gaming mouse (mean = 7.8, SD = 1.0) constitutes an error of 3% assuming a mean RT of 240 ms with a SD = 29ms, which is common in fatigue research (Rupp et al. 2012). Consequently, the PC-PVT with a gaming mouse (1ms mouse response) has been proven to be valid and reliable for RT related research given its low margin of error (3%) which is comparable to the one presented by the PVT-192 (1%) and its almost negligible variability (1ms) compared to the intra-subject RT variability (~ 29ms) (Khitrov et al. 2013) . For this reason this research will utilize the 5minutes PC-PVT protocol, with an appropriate gaming mouse to measure reaction time, and in this way obtain an objective measure of fatigue.

In addition to the research tools presented above two additional tools will be employed during the data collection process. The first additional tool consists of the Objective Fatigue Predictive questionnaire that will be developed as part of this research process and later on validated as part of this research effort. The second research tool used in this experiment will appear during the second phase of this study. It consists of construction scenarios pictures which will display a specific number of hazards. More details on these two tools will be presented in the following subsections.

Name of instrument/tool/procedure	***Purpose (i.e. what data is being collected?***	***Time to Complete***
Objective activity questionnaire	*Objective past level of activity*	*5 minutes*
SOFI	*Subjective level of fatigue (score)*	*2 minutes*
PC-PVT	*Objective level of fatigue (RT)*	*5 minutes*
Objective fatigue risk predictive questionnaire	*Objective level of fatigue (score)*	*4 minutes*
Construction site pictures	*Present Hazards*	*12 minutes*

Now after describing the research tool we proceed with the description of each research phase to accomplish our first research objective of developing a fatigue risk objective predicting tool.

1) <u>Fatigue risk predicting tool</u>

1.a) *<u>Pilot Testing:</u>*

The procedure of the pilot testing experiment is as follows: Participants will be invited to take part in the experiment individually and after consenting by signing the consent form they will be given both a day and a time convenient to them to take part in the experiment. The experiment will be organized in groups of 10 volunteers. The 10 volunteers will start the testing protocol by receiving an overall explanation of the testing procedure and an introduction to the testing tools (approximate duration 3 min) where the anonymous character of the study will be described. Following the introduction, the participants will complete the self-administered questionnaire (Appendix A), which has a duration of approximately 5 minutes. Then, each participant will complete the self-administered subjective fatigue questionnaire SOFI which has an approximate duration of 2 minutes. Following this questionnaire, each participant will perform the 5 minute PC-PVT test and the data will be stored under a common identifier name that will appear on the other two previous questionnaires (non-participant related). At this point the testing procedure will have finished. The overall testing process will take approximately 20 minutes (considering 5 minutes for inter task delay). This protocol will take place every 2 days allowing time to recruit additional volunteers.

Once the data are collected, the researchers will have obtained answers to the objective fatigue questionnaire which consists of numerical values or Yes/No answers, subjective fatigue scores from the SOFI, and objective fatigue scores interpolated from the RT data (e.g. average RT or number of lapses). Regression techniques will be used to obtain weights that correlate the objective fatigue questionnaire answers to the objective fatigue scores obtained from the PC-PVT. The results from the SOFI will be used to compare fatigue scores with the objective PC-PVT results.

This pilot testing procedure will inform the researcher about the seemingly true number of predictive variables, the functionality of the research tools, and the statistical power obtained with the collected data. With this information, a more accurate minimum sample size for the next phases can be calculated.

1.b) Instrument Development:

Regarding the testing procedure in this phase of the experiment, it will follow the order described in the previous section utilizing the same tools and having the same duration. All workers will have the opportunity to freely decide if they want to take part in this experiment after a detailed explanation of the procedure and will be required to sign the consent form in order to participate. The researchers will have the opportunity to interact with groups of 10 to 20 workers at the beginning of the shift and smaller groups of workers throughout the working day. The researchers assume a capability of testing 10 individuals simultaneously due to the limited number of available laptops for this experiment (10 PC laptops). Given the situation, half of the worker groups will be assessed during the beginning of their shift and the other half will be assessed during the middle of their shift at their respective work locations. Companies participating in this research project will allow workers to spend the necessary time for testing away from their usual activities without receiving any salary reduction because of this procedure. Assuming that companies will allow the participation of only one of their shifts a day (20 workers) this second data collection effort will require approximately a month and a half (5 weeks of testing plus a week of travelling).

At the end of this second data collection cycle, the data will be analyzed by regression techniques in order to obtain the weights that correlate the answers to the fatigue objective questionnaire to the objective level of fatigue measured by the PC-PVT. Those variables that don't correlate to the results obtained by the PC-PVT will be discarded from the questionnaire and a new predictive objective activity questionnaire will be developed including only those variables that appear to have a predictive ability. After this, a fatigue scale that correlates to the PC-PVT results will be developed. Consequently, a fatigue risk predictive tool will have been developed which provides a score or level of fatigue as a result of the linear combination of the obtained weights and the inputted answers. A comparison amongst the predicted levels of fatigue by the new questionnaire, the PC-PVT scores and the SOFI will be performed in order to investigate the existence of a correlation between the SOFI scores and the PC-PVT scores or the SOFI and the new objective fatigue questionnaire scores. It is expected that this data analysis and the development of the new predictive questionnaire will take approximately one month.

1.c) Instrument validation:

The validation process consists of testing the fatigue risk level prediction ability of the created questionnaire. In order to accomplish this purpose participants will complete the questionnaire and then take the 5 minute PC-PVT testing protocol on two occasions: one right after completing the questionnaire and at a point in the last quarter of their shift (e.g., last 2 hours). This stage of the research process will require following up with every participant during their shift. The first testing procedure will take approximately 16 minutes. Because some questions on the initial survey will have the same answers (e.g., how many hours of restful time did you get between shifts?), the second test will take approximately 7 minutes.

If this last stage of the research process validates the objective fatigue risk predictive questionnaire a new reliable and valid tool to accurately predict fatigue among construction workers will have been created.

2) Hypothesis testing of the influence of fatigue on hazard recognition ability.

In order to test the hypothesis that fatigue affects hazard recognition a simple experiment is designed. The experiment starts by using pictures of construction sites where hazards have already been identified by an expert panel. A "hazard" is defined as anything that could injure, kill, or make a person sick. These hazards can be classified as Motion, Mechanical, Electrical, Pressure, Temperature, Chemical, Biological, Radiation, Sound, Gravity, or Motion (Albert et al. 2014)

Three pictures will be selected at random from a group of 6-9 pictures. Participants will receive each picture in a separate sheet, with the mentioned definition of hazard, and enough space to write down all the hazards that he or she can identify in the picture. The duration of this assessment is expected to be approximately 12 minutes. This assessment will take place right after administering the 5 min PC-PVT to the volunteer.

As a result of this phase, each picture will be evaluated by multiple participants who presented different levels of fatigue. With that data, a correlation analysis will be performed to test the alternative hypothesis that fatigue affects HR, with the null hypothesis that fatigue doesn't affect HR.

Visit #	***Procedures/Tools***	***Location***	***How much time the visit will take***
Pilot Test	• *Objective activity questionnaire* • *SOFI* • *PC-PVT* • *Construction site pictures*	*University of Colorado at Boulder*	*1 month*
Instrument Development	• *Objective activity questionnaire* • *SOFI*	*Power contractors from*	*1.5 months*

	• *PC-PVT* *Construction site pictures*	*the east coast of the U.S.*	
Instrument Validation	• *Objective fatigue risk predictive questionnaire* • *PC-PVT* • *Construction site pictures*	*Power contractors from the east coast of the U.S.* *Construction sites in Colorado*	*5 months*

SPECIMEN MANAGEMENT

- N/A

DATA MANAGEMENT

- According to the HRB-211 the data obtain in this research process presents a risk level of ____________

- All the data obtain during this research process will be initially delivered to the researchers in one of the following two ways: a) Hard copy or b) Computer file. The hard copy information will be obtained through the questionnaires administered to the participants (Activity questionnaire, SOFI, Objective fatigue predictor questionnaire, and the HR questionnaire). The computer files will be automatically saved in a computer folder after each PVT session. The name of the computer file (numeric codes) corresponding to a certain individual will be written on the hard copy questionnaires filled out by the same individual in order to link both types of data from the same participant. However, such a link or code has no identifying information that can trace the data back to such an individual.

- The hard copy data will be scanned and stored as encrypted and password protected files. At the end of each data collection day all computer files will be saved on 10 laptop computers and on a CUB server for remote access. In the laptop computers the data will be protected by a password. Only the principal researcher will have access to the storage files and the hard copy documents will be all shredded.

- Once the data collection period has finished the obtained data files will be transferred to 3 desktop computers.. The data storage in laptops will be deleted and the data storage in desktop computers will be password protected.

- It is very important to mention that none of the data collected is considered sensitive or identifiable data.

WITHDRAWAL OF PARTICIPANTS

- Each participant is free to withdraw at any time during the data collection process with no penalty. In case of withdrawal, the data obtained from that individual will be considered for analysis only if before withdrawing the volunteer was able to participate in all data collection processes (questionnaires and PC-PVT) at least once.

- There is no need for replacement in case of withdrawal.

RISKS TO PARTICIPANT

- Participation will always take place in a safe environment inside a familiar room (University or office workplace). Volunteers will have the opportunity to participate in a safe environment free from distractions and recognizable hazards. Additionally, none of the data acquisition procedures are invasive or present questions, states or images that could put the participant at mental or emotional risk.

MANAGEMENT OF RISKS

- No potential risk was identified in the previous step.

POTENTIAL BENEFITS

- ***Benefits to the Participants:*** There is no proven benefit from the participation in the data collection effort. However, presumably participants can benefit from the quiet time spent participating in the experiment which will potentially reduce their workload by diminishing the time that that participant will spend on their regular working activities. Additionally, participants can potentially benefit from the exposure to the knowledge that fatigue is a risk factor at work. This knowledge could influence the way that workers perform their activities during the day, hopefully helping them develop lower levels of fatigue and improve their safety.

- ***Benefits to the society/industry:*** As described before, fatigue has shown to be an important contributor to accident causation. The first objective of this study is to provide a way to predict high levels of fatigue before operators actually achieve those levels. This could be used to prevent fatigue related accidents or incidents. This could potentially decrease the current accidents and fatality rates of construction workers which are among the highest in the nation. The second objective of this study is to test the influence of fatigue on hazard recognition ability. The results of such a test will further inform the society/industry about the implications of fatigue in safety. This knowledge will empower the industry/society to better prevent accidents and fatalities.

PROVISIONS TO MONITOR THE DATA FOR THE SAFETY OF PARTICIPANTS

Participants, as mentioned above, will not be asked to disclose any personal information that would link the responses back to them. Furthermore, access to the dataset will limited to the key personnel (identified above). Each participant will be a random code number, however, the code number has no significance to participants' identity. All the data is stored in password-protected computers of the key-personnel related with this project.

There is no way the data collected can be traced back to an individual and his/her responses.

MEDICAL CARE AND COMPENSATION FOR INJURY

N/A

COST TO PARTICIPANTS

There is no cost to the volunteers participating in this study.

DRUG ADMINISTRATION

No drugs will be administered at any stage of this experiment.

INVESTIGATIONAL DEVICES

No investigational devices will be used at any stage of this experiment.

MULTI-SITE STUDIES

N/A

SHARING OF RESULTS WITH PARTICIPANTS

- After developing the fatigue risk predictive tool (questionnaire) an effort to pilot test its use in the industry will be organized by the collaborative parties (contractors). However, this effort won't directly depend on the researchers and therefore there are not current stated plans for this procedure.

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Appendix B: Consent Form

Title of research study: **Study of the influence of fatigue on hazard recognition, the influence of workload on fatigue, and development of a fatigue predictive tool.**

Investigator: ***Ulises Techera***

Why am I being invited to take part in a research study?

This research study focusses in the way that fatigue affects Transmission and Distribution power line workers and more generally construction workers. For this reason you are the most important factor of this research. Your opinion and experience matters the most in this research project.

What should I know about a research study?
Someone will explain this research study to you.
Whether or not you take part is up to you.
You can choose not to take part.
You can agree to take part and later change your mind.
Your decision will not be held against you.
You can ask all the questions you want before you decide.
Who can I talk to?

If you have questions, concerns, or complaints, or think the research has hurt you, talk to the research team at ulises.techerarocha@colorado.edu (Ulises Techera , principal investigator), matthew.hallowell@colorado.edu (Matthew R. Hallowell, Co-Investigator/Faculty Advisor), or at ray.littlejohn@colorado.edu (Ray Littlejohn, Co-Investigator).

This research has been reviewed and approved by an Institutional Review Board (“IRB”). You may talk to them at (303) 735-3702 or irbadmin@colorado.edu if:
Your questions, concerns, or complaints are not being answered by the research team.
You cannot reach the research team.
You want to talk to someone besides the research team.
You have questions about your rights as a research subject.
You want to get information or provide input about this research.
Why is this research being done?

The principal motivation behind this research project is the one of reducing injury and fatality rates for one of the most dangerous professions in the U.S. (Transmission and Distribution power

line workers) and for construction workers in general. The fatality rate of these professions are 8 and 3 times the average of the whole working population in the country. Fatigue has shown to be an important driver to accidents and for this reason it is the main focus of our research. After conducting this research experiments we will be able to understand how fatigue affects hazard recognition and we will have developed a tool to objectively predict the level of fatigue of individuals, which can be used to prevent fatigue related accidents.

How long will the research last?

We expect that you will be in this research study for ***about 30 minutes.***

How many people will be studied?

We expect about 480 people will be in this research study.

What happens if I say yes, I want to be in this research?

If you want to be part of this research you will participate in 2 data collection phases. Phase 1 will take approximately 30 minutes. Phase 2 will take approximately 7 minutes

During Phase 1 you will:

Complete the Activity Questionnaire (AQ) which is a survey with 28 simple questions about your level of activity. This will take approximately 5 minutes.

Complete the Swedish Occupational Fatigue Inventory (SOFI) which is a subjective fatigue questionnaire with 20 questions. This will take approximately 2 minutes.

Complete the PC-PVT which is a reaction time test that takes place on a laptop computer and last 5 minutes.

The Hazard Recognition Questionnaire (HRQ) which is a questionnaire with 3 pictures and 3 questions for each picture. You will have 9 minutes to complete this questionnaire.

During Phase 2 you will:

Complete the PC-PVT once again.

Complete the NASA-TLX which is a simple survey with 6 questions that will be used to assess the perceived workload of you activities. The completion of this questionnaire takes approximately 1 minute.

During the collecting data process you will interact with the principal investigator, Ulises Techera.

Phase 1 of the data collection procedure will take place at the beginning of the shift, during the safety meeting with supervisors, at the company's facilities. Phase 2 will take place in the work truck later on your shift.

Your participation is entirely voluntarily and no compensation will be offered in return.

No material reward or punishment will be given by participating or not in the study.

What happens if I do not want to be in this research?

You can leave the research at any time and it will not be held against you.

What happens if I say yes, but I change my mind later?

You can leave the research at any time it will not be held against you.

Will being in this study help me anyway?

We cannot promise any benefits to you or others from you taking part in this research. However, possible benefits include improving your awareness of the negative effects of fatigue in your life.

What happens to the information collected for the research?

Efforts will be made to limit the use and disclosure of your personal information, including research study and medical records, to people who have a need to review this information. We cannot promise complete secrecy. Organizations that may inspect and copy your information include the IRB and other representatives of this organization.

The hard copies of the questionnaires that you may fill out today will be scanned and then deleted. The computer files generated from this research will remain encrypted and password protected in a desktop computer located in the University of Colorado at Boulder. Only the key research personnel of this study will have access to those hard or soft files.

Signature Block for Capable Adult

Your signature documents your permission to take part in this research.

Signature of subject	Date
Printed name of subject	
Signature of person obtaining consent	Date
Ulises Techera	June 17th. 2016
Printed name of person obtaining consent	IRB Approval Date

Appendix C: Activity Questionnaire

INSTRUCTIONS: Please answer each question. If you have questions, answer the researcher.

AGE: ____
POSITION: ____
YEARS OF EXPERIENCE IN THIS SECTOR: ________________
GENDER: ____

Objective Questions:

1. How many hours did you sleep during the past 24hs? ___________
2. How many hours do you usually sleep between 2 shifts? ___________
3. Besides sleeping, how many restful hours have you had since your last shift? __________ (For example: the time you spend relaxing, watching TV, etc.)
4. Do you have individuals at home that require active care and attention? YES ☐ NO ☐
5. How long was your last shift? ___________
6. How many previous consecutive shifts have you worked? ___________
7. How many hours have you had off since your last shift? ___________
8. What is the start and end time of your shift today? START _________ END_________
9. If you are at work, how many hours have you been working during this shift? ___________
10. If you are at work, how frequent have your breaks been? (Example: every 2 hours)___________
11. On average how long was each break? ___________
12. How long is your usual shift? ___________
13. Do you have a rotating shift? YES ☐ NO ☐ If so, describe it. E.g. One week in the morning, one week in the afternoon, and one week at night, repeat. ____ ____ __________________________
14. How many hours do you usually work a week? ___________
15. Today, are you performing mentally demanding tasks at work? YES ☐ NO ☐

YES ☐ NO ☐

16. Today, are you performing physically demanding tasks at work?

17. Today, are you performing repetitive tasks at work? YES ☐ NO ☐

18. Today, are you exposed to loud noises while working? YES ☐ NO ☐

19. Today, are you exposed to vibration while working? YES ☐ NO ☐

20. What is the approximate temperature in your work environment now? __________

21. Is the work environment well lit? YES ☐ NO ☐

22. Did you ingest caffeine today? YES ☐ NO ☐ If YES, how much?
______________ YES ☐ NO ☐

23. Do you have a good relationship with your immediate supervisor?

24. Do you have a good relationship with your usual coworkers? YES ☐ NO ☐

25. Do you have a condition that doesn't allow you to rest well? YES ☐ NO ☐

Subjective Questions:

Not at all — To a great extent

1. How mentally demanding is your job?

Not at all									To a great extent
1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

2. How physically demanding is your job?

1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

3. How fatigued are you now?

1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

4. Do you get fatigued more easily than your coworkers? YES ☐ NO ☐

Appendix D: Swedish Occupational Fatigue Inventory

INSTRUCTIONS: Think about how you feel right now. **To what extent do the expressions below describe how you feel?** For every expression, answer spontaneously, and mark the number that corresponds to how you feel right now. The numbers vary between 0 (not at all) and 6 (to a very high degree).

	Not at all						**To a very high degree**
palpitations	0	1	2	3	4	5	6
lack of concern	0	1	2	3	4	5	6
worn out	0	1	2	3	4	5	6
tense muscles	0	1	2	3	4	5	6
falling asleep	0	1	2	3	4	5	6
numbness	0	1	2	3	4	5	6
sweaty	0	1	2	3	4	5	6
spent	0	1	2	3	4	5	6
drowsy	0	1	2	3	4	5	6
passive	0	1	2	3	4	5	6
stiff joints	0	1	2	3	4	5	6
indifferent	0	1	2	3	4	5	6
out of breath	0	1	2	3	4	5	6
yawning	0	1	2	3	4	5	6
drained	0	1	2	3	4	5	6
sleepy	0	1	2	3	4	5	6
overworked	0	1	2	3	4	5	6
aching	0	1	2	3	4	5	6
breathing heavily	0	1	2	3	4	5	6
uninterested	0	1	2	3	4	5	6

Adapted from:

© The Swedish Occupational Fatigue Inventory-20

Arbetslivsinstitutet, E. Åhsberg, F. Gamberale, A. Kjellberg, 1998