An engineering approach to personal protective equipment: An analysis of the PPE, non-compliance issues and the methodology to predict non-compliance

by

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DEDICATION

I dedicate this dissertation to:

My parents, Mr. Zeyad Mgaedeh and Mrs. Iftikhar Abdel-All, who have been a constant source of inspiration and support throughout my life. Although my dad passed away before I began my graduate program at Iowa State University, his words of encouragement and his unwavering belief in my abilities still echo in my mind, giving me the motivation and drive to pursue my dreams. His guidance has been invaluable in shaping the person I am today, and I owe him a debt of gratitude that I can never repay. My mother has been my rock, my confidant, and my everything in this world. She has worked tirelessly to raise us by herself and has always been there to lend a listening ear, push me toward my goals, and provide me with endless love and support. Her unwavering faith in me and her constant prayers have been instrumental in helping me achieve my dreams. Without her love and guidance, the present study would have remained a mere dream.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ABSTRACT

This dissertation focuses on Personal Protective Equipment (PPE) within the healthcare sector, particularly the emerging practice of double masking and compliance with its use.

The dissertation begins with a comprehensive literature review to map out the existing research on PPE, focusing on its adverse effects, double masking, and compliance. Extensive studies have shown that face masks negatively impact psychological, physiological, visual, motor, and cognitive functions, including changing breathing rates, raising blood pressure, and hindering communication. The review further revealed that these adverse effects, coupled with organizational issues, significantly drive PPE noncompliance in healthcare settings. The review also highlighted the emergent practice of double masking, recommended by healthcare organizations as a method to enhance protectiveness during the pandemic despite the potential for increased discomfort and non-compliance.

Consequently, the Second part of the dissertation presented an investigation into the impact of various mask configurations, including single and double masking, on human performance. This analysis demonstrated that wearing any form of face mask—be it a singular or doubled—resulted in higher errors during cognitive evaluation tests compared to a control scenario without a mask. Furthermore, this study highlighted that the practice of double masking significantly heightened the levels of perceived difficulty, discomfort, and anxiety among participants, mainly after they engaged in tasks requiring both motor and cognitive effort. This practice could lead to PPE non-compliance to relieve discomfort and increased thermal stress.

Therefore, the third study within this dissertation set out to define and measure non-compliance by creating a unique within-subject experimental simulation specific to a healthcare setting. A predictive model for non-compliance was constructed, identifying the key variables contributing to non-compliance called MPENC (Model of predicting personal protective equipment non-compliance). While PPE use and workload were significant predictors, the experience of discomfort and thermal burden emerged as the most critical factors in predicting non-compliance instances.

This work could be applied to healthcare organizations such as the CDC and OSHA as it provides insight into enhancing compliance with PPE by considering the contributing factors.

CHAPTER 1. GENERAL INTRODUCTION

Research Motivation

With the progress of this dissertation, the value of proving and having a prediction model of PPE compliance will become more apparent, considering different levels of protection and workloads. During the COVID-19 pandemic, Master's thesis, a machine that imitates human breathing by controlling temperature and relative humidity. We investigated the temperature and relative humidity levels accumulated inside various face masks while subjected to different workloads. Our findings revealed significant differences in temperature build-up among different face mask types that were consistent with earlier research. In addition, we conducted a survey among retail workers, showing that workload adversely affected the heat build-up inside the mask.

Furthermore, our findings indicated that wearing glasses while donning the mask significantly reduced vision ability. Also, a literature review showed the reasons behind the non-compliance of the PPE and investigated the effect of the different face mask types on physiological and comfort aspects. Previous studies did not examine or measure compliance in terms of the frequency of violations such as touching, adjusting, or removing the mask. They also did not express compliance regarding time spent wearing different Personal Protective Equipment (PPE) levels while subject to varying workload levels.

Consequently, there is a compelling drive to study the impact of different levels of PPE protection and workload on compliance. Furthermore, we are inspired to construct a predictive model for compliance.

Dissertation Organization

This dissertation follows the format of a journal article presenting five chapters. The organization of this dissertation is as follows: A general introduction is provided in Chapter 1, followed by a state-of-the-art literature review on personal protective equipment compliance, adverse effects, and strategy for selecting personal protective equipment in Chapter 2, which is presented in the format of a journal paper submitted to the *International Journal of Human Factors and Ergonomics*. The third chapter examines the impact of various varieties of face masks, in addition to double-face masks, on human performance, cognitive aspects, visual acuity, comfort, and anxiety. A method to measure and predict PPE compliance considering different conditions is presented in Chapter 4. The concluding chapter of this dissertation presents the general conclusions and suggestions for future research studies.

CHAPTER 2. A REVIEW OF PPE USAGE AND ITS IMPACT ON RISK AND PERFORMANCE

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Abstract

As stated by OSHA "use of personal protective equipment (PPE) – considered the last line of defense against worker injury and illness – is acceptable when controls higher in the hierarchy don't eliminate the hazard or are in development." Despite the importance of PPE to safety and protection, studies have shown that PPE has detrimental impacts on its users' psychological, physiological, visual, motor, and cognitive capacities. As a result, they are impairing the wearers' compliance with PPE. The effects of the impact of PPE vary depending on the type of PPE, level, and task. This article includes a detailed literature review of over 180 articles concerning the negative aspects of PPE. We present a comprehensive overview of the negative impact of PPE, compliance, and researchers' efforts to assign PPE better in order to identify the gap where we may minimize the negative effect of PPE and boost compliance. Thus, having a model or methodology that assists workers in assigning the proper PPE or assets and estimating the maximum time that a worker can comply before taking off the PPE will help protect the workers.

Keywords

Personal Protective Equipment, Compliance, Adverse Effect, Risk, Occupational Safety.

Introduction

PPE is “equipment worn to minimize exposure to hazards that cause serious workplace injuries and illnesses. These injuries and illnesses may result from contact with chemical, radiological, physical, electrical, mechanical, or other workplace hazards. Personal protective equipment may include items such as gloves, safety glasses and shoes, earplugs or muffs, hard hats, respirators, or coveralls, vests, and full body suits” as defined by Occupational Safety and Health Administration (OSHA) [1]. PPE had been used as a protective precaution for centuries and decades, even under other names, and was recently extended to the public in response to the COVID-19 pandemic. However, as practically anything has its benefits and drawbacks, research has demonstrated the detrimental impacts of PPE on its users, affecting their willingness to wear PPE for extended periods at work.

PPE is used in almost every field where other controls failed to prevent hazards, such as manufacturing, construction, oil and gas, healthcare, transportation, firefighting, food, etc. In 2021, the healthcare end-use segment dominated the market, followed by manufacturing and construction.

The PPE categories vary according to the body part to be protected, including hand and arm protection equipment, protective clothing, foot and leg protection equipment, respiratory protection equipment, and head, face, eye, and hearing protection.

In this work, we give a comprehensive literature analysis of papers on PPE in various domains, focusing on the impact of PPE on users and the most recent research on efforts to allocate PPE better. In addition to offering potential ideas, proposals, and insights for the future, the report includes these elements.

This paper has the following structure: Background, Issues that will explore compliance, and the adverse effects of PPE; the next part will cover human limitations and capabilities.

Section 5 will review the present efforts to select PPE, and Section 6 will give a general discussion. In section 7, the conclusion and future work are provided.

Background

PPE is the flip coin of the safety word, and it refers to all the meanings of protecting the wearer from hazards and the potential of transferring it to other individuals if it is attached to the wearer. PPE comes in a wide variety of kinds, but it is primarily classed by what it protects, such as protective clothing for the whole body, gloves for hands, respirators for breathing, and other forms of garments. PPE was utilized in wars before playing a significant role in the workplace. The historical discovery of gloves being used as protection for garden work, as documented in the eighth century B.C Greek poem called "Homers Odyssey" corresponded with the fact that humans have and always will respond to hazards by making a quick getaway or creating a physical barrier. In the medieval ages, gloves were a common trend that stood for the upper classes. However, when handling dangerous materials, masons must put on sheepskin gloves. The proliferation of diseases in the middle of the 18th century prompted doctors to examine patients while wearing gloves, some of which were made of sheep intestine, cotton, silk, or leather. After the severe hand inflammation of Dr. William's Halsted nurse, the first rubber gloves were introduced at Johns Hopkins Hospital in the 1890s. The development of the rubber vulcanization process by Charles Goodyear in the 1840s led to the introduction of rubber gloves.

Even though face masks have a wide range of designs, materials, and applications today, they have evolved and altered throughout history and worldwide. Face mask-like artifacts dating to the 6th century BC existed before the invention of the first face mask in the 16th century, and there are depictions of individuals covering their mouths with fabric on the doors of Persian tombs [2]. When serving the emperor a meal in the Yuan Dynasty of China in the 13th century, between 1279 and 1368, Marco Polo observed the servants covering their mouths and noses with silk scarves to prevent their breath from altering the flavor and aroma of the food [2]. A French doctor named Charles de Lorme created the first face mask coupled with a full uniform as a plague doctor costume during the last waves of the black death epidemic in the 16th century, which started in the early 1350s [3]. Johann Mikulicz, head of the surgery department at the University of Breslau (now Wroclaw, Poland), donned the first surgical mask in 1897 in response to experimental findings of the German bacteriologist Carl Flügge that the culturable bacteria carried by the respiratory droplets could cause infection [4], [5]. Following this, the mask quickly expanded and developed as surgeons began donning them within the operating room. Doctor Lien-teh Wu created the surgical mask that prevented the transmission of a user's breath droplet into a more durable cotton mask that filtered the inhaled air by adding multiple layers of cloth and tightly wrapping around the face (Figure 2.1), which was the first step toward the development of the respiratory mask between 1910 and 1911 in Northern China during the Manchurian plague [6]. In the 1930s, single-use, disposable paper masks began replacing washable and reusable masks [7]. A brand-new bubble surgical mask developed by 3M was produced in 1961; it was later employed as a dust mask because it failed to stop infections [6]. The first single-use N95 "dust" created by 3M was authorized in 1972. The N95 was primarily utilized in industries for decades until the 1990s when N95 standards were modified to match healthcare environments [6]. Before the Manchurian plague (1910–1911) and the influenza pandemic (1918–1919), the usage of the face mask was restricted to the operating room. After these epidemics, patients and medical staff began using them as a form of infection prevention.

Helmets were created as a direct outcome of conflict since safeguarding one's head during battle is the most important task, as the head is the processing hub. A leather or bronze helmet that dates back to 900 BC is the earliest known helmet (figure 2.2)[8]. During the 1730s, Jacobus Turck invented the first fire helmet made of leather. Later in 1836, Henry T. Gratacap created a modern-looking, leather-reinforced dome-shaped helmet with a front shied and a brim. Shipbuilders used tar-painted, reinforced helmets in the early 1800s to protect themselves from falling objects.

Another PPE that directly results from the battle is the protective coverall. The Japanese utilized leather-strapped iron plates for soldiers in the early fourth century. According to historical records, blacksmiths wore leather aprons, medieval knights wore armor, cowboys used leather chaps, and Eskimos wore parkas. With the industrial revolution and technological development, the concept of body armor translated into protective wear for different purposes of protection: biological, physical, and chemical hazards. However, the usage of medical apparel did not fully begin until the early 1900s. After that, medical personnel began donning it. In order to lessen eye strain and glare from white scrubs, light operating rooms, and wall colors, additional colors of scrubs weren't introduced until the 1960s.

Figure (2.3) depicted an ancient steel casing for Powell Johnson's 1880 "eye protector" patent for safety goggles [9]. The advancements made during World War Two facilitated the creation of impact-resistant or ballistic eye protection. The usage of safety eyewear in the industry didn't begin until the 1940s.

Figure 2.1. 16th century plague doctor uniform

Figure 2.2. Leather or metal helmet dating to the 9th century BCE

Figure 2.3. Metal casting of eye protection patent

Issues

Compliance

Construction-based industries such as masons, plumbers, and carpenters are often considered one of the world's most labor-intensive industries [10], [11]. This fact makes using PPE in these professions' paramount for the longevity of a career and even a life. The PPE of a hard hat, safety glasses, and other various pieces of equipment are used to combat the risks, including but not limited to falling objects, malfunction of tools or materials, and falling from varying heights [12]. In a survey conducted by Mansoura University in 2020, of approximately 348 workers in construction, only 59.4 percent use PPE while on the job, and the other 40.6 percent of workers do not use it for various reasons. Of the reasons given for not wanting to wear PPE, the biggest reason they did not want to wear PPE was due to discomfort, with over 78.2% claiming this, followed by a lack of knowledge at 73%, and poor fit and heating, both at 69% [12]. These workers were also asked if they had ever experienced an occupational accident, and of the 84.9% who said yes, they had, 65.2% reported they were not wearing PPE at the time. Of these injuries, 45.3% required some form of medical attention. [12] Many of these injuries could have been prevented just by using PPE, but can someone monitor the usage or compliance of PPE?

The detection and monitoring of PPE compliance can be done manually or automatically. There are two types of automatic monitoring: sensor-based and vision-based. The large number of workers in the industry that need to be tracked, the various PPE requirements based on different assigned jobs, the movement of workers from one department to another within the company, the presence of visitors or managers, supervisors on the site, and changes in the types of PPE are available, and the supplier is just a few of the challenges that come with manual monitoring [13]. Moreover, manual monitoring is costly, time-consuming, ineffective, and resource intensive [14].

The sensor-based strategy entails inserting a sensor into the PPE and, afterward, evaluating the signal. Such methods use radio frequency identification (RFID), ultrawideband (UWB), laser sensors, global positioning systems (GPS), and other wearable tracking devices. Tracking and locating essential materials and construction components frequently use RFID technology [15], [16], [17]. The chosen tracker component can be equipped with RFID tags. Tags come in three varieties: active, semi-passive, and passive tags. However, the antenna, transceiver, and transponder are the three major components of RFID that conduct the entire tracking operation. In the construction industry, there have recently been initiatives to use RFID technology to monitor employees' compliance with PPE. In order to verify that personnel is wearing the appropriate PPE at the gate before accessing the site, [18] used RFID tags on their PPE. In another study conducted by [19], in addition to detecting PPE compliance, RFID was utilized to locate and identify a worker's location in an authorized area and to alert them if they entered an unapproved workspace. Zigbee and RFID technologies were used by [20] for real-time detection of the right PPE worn by workers based on the regulations. Despite the promising outcomes, the RFID approach has some drawbacks, including the cost of purchasing sensors, the cost of installing them on each PPE, the cost of setting up the network, the inability to determine whether the worker is wearing the PPE or not, the suitability of the approach for controlled indoor environments, and its disadvantage in large-scale and congested sites [21].

UWB was employed to identify potential dangers from falling items or collisions with moving objects by putting tags on workers’ helmets and moving objects [18]. The system locates employees and moving items in real time determines the likelihood of an accident, and then generates a warning if there is a possible mishap. Also, detecting a collision of two moving constriction equipment was investigated [22]. Another research by [19] looked into whether it would be possible to use UWB to spot safety violations on construction sites. They investigated the illegal actions of stepping on a moving scaffold or on top or next to the top rung of a ladder. In each instance, a tag was attached to the worker's boot, the ladder, and the scaffold.

Researchers have proposed several ways to employ artificial intelligence (AI) to identify the presence of PPE because of the numerous difficulties management has in monitoring workers' compliance with PPE. Each effort utilized a different AI algorithm to detect various PPE types. Such algorithms, radiomics-based approach [23], vision-based motion detection [14], convolutional neural networks [24], YOLOv3 detector [25], [26] and transfer learning [26], fast R-CNN deep learning architecture [27], deep learning [28], low-power AI-enabled (object detection algorithm) cameras [29], Bayes rules [30], single shot multibox detector and MobileNetV2 [31], Histogram of Oriented Gradient and Circle Hough Transform [32], 2D pose estimation, MobileNetV2, Dense-and MobileNetV2 [33] and computer vision techniques [34].

Most of the AI-enabled approaches were extensively applied in the construction engineering area. For example, to detect safety helmets for preambulatory workers in a power substation [23], detect the hardhat in an indoor construction-like environment, indoor and outdoor dynamic construction environment, adverse lighting conditions in an indoor and outdoor environment [14], detect the presence of hardhat and the corresponding color [24], detect non-hardhat use considering the number of factors: visual range, weather, illumination, individual posture, and occlusions [35], detect the presence of hardhat and jacket with categorizing it as not safe, safe, no hardhat, no jacket [26], detect the presence of hard hat and if it worn properly [28], [36].

Other AI approaches not only detect the PPE, but also recognize the face to determine the worker’s identity, such as detecting a specific helmet and face recognition [37], detecting safety vests and distinguishing construction workers from pedestrians [38], detecting the presence of hardhat and the corresponding color, shirt, belt, glove, pant, and shoes present in construction site [25]. Moreover, some approaches alert either the management or the person regarding the noncompliance, such as detecting the hardhat and issuing a safety alarm correspondingly [39], detecting full compliance of PPE (helmet, mask, vest, glove) with a warning system to not full compliance under different conditions of light intensity and distance captured [27], detect if the worker’s need to wear a helmet and provide a warning when it is dangerous and required helmet [40]. Studies in various sectors have shown that when employees are aware they are being watched, their performance improves [41]. On the other side, research has indicated that electronic performance monitoring has a detrimental influence on human attitudes, such as work satisfaction and emotional commitment. [42], [43].

On the other hand, a monthly audit of PPE compliance using a standardized sheet was performed individually on each nurse working in the infusion area by a clinical nurse specialist at Dana-Farber Cancer Institute [44]. As a result, nurses' PPE compliance significantly increased and remained high in succeeding months. Performing surgeries during the early stages of the latest pandemic (COVID-19) was crucial and challenging. However, specific procedures cannot be postponed due to adverse effects, including the impact on cancer patients. Thus, the best action is to do surgeries while taking all PPE measures. The COVID-19-specific briefing and debriefing forms were utilized to audit PPE compliance, nevertheless, because of the difficulty that PPE imposed [45]. It had three parts: the second component and step 1, which were used to record every piece of protective equipment a healthcare professional had on them. The PPE that remained on at the end of the operation was documented in part 3. During COVID-19, a different strategy was used to check PPE compliance in healthcare facilities by creating PPE inspectors known as the "PPE police" [46]. The findings showed that compliance had increased from 56% to 89% during the inspection period, and the positive COVID-19 cases decreased from 31 cases/day to 5 cases/day.

The study [47] highlights the critical role of ergonomics in enhancing functionality and reducing the strain associated with medical tools. These ergonomic principles are equally applicable to the design of face masks. This application demonstrates the potential for extending ergonomic design concepts from medical instruments to personal protective equipment such as face masks, thereby improving both usability and comfort for the wearer. In addition, The [48] focuses on assessing the ergonomic risks associated with agricultural tasks, particularly through tools that evaluate lifting and posture in novice users. This approach can be paralleled in the context of face masks by examining the ergonomic considerations that influence their design, usability, and effectiveness, particularly for new or inexperienced users. The concept of training the nondominant hand to use a computer mouse and observing skill transfer to the dominant hand demonstrates that humans can adapt to new tools or methods and experience improvements even in untrained areas [49]. Similarly, wearing face masks can require adaptations in how individuals communicate or perceive social cues. People might develop heightened attentiveness to eyes and eyebrow movements for emotional and social cues, compensating for the covered lower face. This could enhance perceptual skills and non-verbal communication abilities even in contexts without wearing a mask.

Compliance of construction workers

There are two perspectives on PPE compliance among construction workers: the employees and the supervisors. Most of the studies were from workers’ perspectives. Various factors have been found to affect the use and compliance of PPE. According to [50], factors influencing PPE compliance among junior construction employees were separated into four categories: safety laws, junior staff attitude, site environment, and construction firm owners. Safety monitoring systems, company regulations, and policies are among the issues that need to be addressed to ensure that workers are protected from harm, as well as inadequate safety by laws and standards, lack of PPE training, and a lack of inclusion of safety practices in operative training. In conjunction with [51], management policy significantly impacted employees' compliance with PPE. It had been shown that the absence of incentives for compliance [52], [53], [54], and punishments for noncompliance [51], [53], [55], [56] affect the usage of PPE. Also, inadequate training on the proper use of PPE is a critical factor of compliance [51], [53], [57]. Management on-site supervision [52], [58], enforcement and reinforcement make the workers wear the PPE [53], [57], safety training [52], [58], and an inadequate safety performance review [57]. Indonesian cement workers and Nepalese welders' work experience was a factor in their adherence to PPE requirements [51], [59]. Another factor of inadequate PPE compliance is the discomfort [57], [60], [61] produced by PPE while working, which hinders job efficiency [52], [57], [62], [63] and thus affects the productivity where research by [64] showed that workers didn’t wear PPE to push the productivity. Poor fit is one of the discomfort aspects of PPE [57], [60], [61], such as the finding that the PPE does not fit feminine construction staff [65]. The extent to which risks are perceived to exist at the work site is another factor in determining whether or not PPE is used. [52], [61], [66]. Other startling aspects include not wearing PPE to compete and proving expertise in front of coworkers [52]. Because there is either insufficient PPE for all the employees or non-available, these workers choose not to wear their PPE while on the job [52], [57]. A recent study by [67] 2022 investigated the factors that contributed to the use or non-use of PPE from supervisors' perspectives. They found that there are 25 collective predictors of the use and non-use of PPE. However, only four significant characteristics independently predict the use of personal protective equipment (PPE): perception of risky circumstances' hazards, people equipped with safety training, supervision of site-specific safety measures, and the current status of employment.

Compliance of health care workers during infection disease

Literature showed that PPE compliance among healthcare workers (HCW) is low [68], [69], [70], [71], [72]. PPE compliance can be affected by various circumstances, including those at the individual and organizational levels. Studies revealed that improper PPE donning and doffing methods occurs in addition to noncompliance [73], [74], [75], [76], [77], [78]. Individual factors that are thought to influence compliance with preventative measures include perceived patient contact, knowledge of infectious organisms held by healthcare professionals, and risk assessments made with respect to those organisms [79]. Knowledge levels significantly varied among different HCW regarding the diseases found by [80].

Additional sinks [81], gloves, and gown dispensers made it easier for people to adhere to the protocols [82]. Research done by [83] to evaluate the influence of environmental factors on the compliance of doffing PPE found that it substantially impacts the safety of HCWs and patients. They categorized the design recommendations into equipment layouts and availability categories, such as color-coded zones, handrails, and safe spaces. Physical environment categories, such as smaller zones, should be considered for donning to minimize contamination and standardized communication aids. Insufficient supplies contribute to noncompliance with contact isolation precautions [82], [84], [85], [86], such as the accessibility of facial protection, which contributed to an increase in compliance [70]. Pressure on HCWs to comply with all contact precaution protocol measures in a timely manner is a further factor contributing to non-compliance [81], [82], [85], [87], [88], [89], [90], [91], [92]. The workload imposed on HCW made it difficult and challenging to adhere to some steps in the contact precautions such as hand hygiene [81], [85], [87], [88], [89], [90], [91], [92], [93], [94]. In addition, it had been discovered by [94] that the compliance of all components of the protocol declined when the contact isolation measures were raised. This was the case even though the precautions were essential for the safety of HCWs and patients. When healthcare workers believe that their companies place a high priority on their health and safety, they are more likely to comply with contact precautions [70], [95], [96].

Compliance during COVID-19 pandemic

When all other precautions fail to limit threats, PPE is the safety precaution that comes to the rescue [97]. The same is true during a respiratory pandemic; PPE is essential for shielding users from infections [98]. Therefore, healthcare professionals must wear the necessary PPE while doing their duties to safeguard their and others' lives. Self-administrative survey research that was undertaken in Egypt during the first wave of the COVID-19 pandemic revealed that 215 out of 404 participants (53.2%) did not comply with the PPE requirements [99]. It was discovered that receiving appropriate training on how to wear PPE properly, coming into contact with infectious patients, and engaging in procedures that carry a high risk of COVID-19 exposure are the factors that predict PPE compliance. In terms of compliance, gender, occupation, and work experience [100] were all factors that showed a significant difference [99]. Regarding PPE, findings showed that HCWs complied more with medical/surgical masks and disposable gloves. Although 88% of respondents believed that personal protective equipment (PPE) was effective against COVID-19, a study that was carried out in Qatar found that only 53% of survey respondents showed full compliance with the use of PPE when interacting with patients who had suspected or confirmed cases of COVID-19 [101]. Robust compliance was found to be predicted by high perceptions of the PPE's effectiveness [102], [103]. They showed that essential determinants of HCWs' complete compliance with PPE included age, nationality, health center region, field of employment, clinical experience, frequency of interaction with suspected or confirmed COVID-19 patients, and perceived efficacy of PPE [101]. During COVID-19, a number of studies they investigated compliance with personal protective equipment (PPE). Those studies found a noncompliance rate of 68.5% in Brazil, 54.9% in Congo, over 40% in Indonesia [104], but less than 20% in Germany and Ghana [100], [103], [105], [106], [107]. However, a study conducted by [45] found that the overall compliance of PPE was 96.3% during 183 surgeries of COVID-19-negative cancer patients. Due to the discomfort, reduced visibility, and frequent fogging it creates, they discovered lower compliance with the face shield. In a different type of study, researchers were concerned with adherence to the PPE donning and doffing procedure [108]. They discovered that 63.73 % consistently followed the donning and doffing process. As a unit and registered as senior, the emergency department adhered to the protocol best. Protective eyewear is the most frequently donned and doffed PPE wrongly, whereas gloves are consistently donned and doffed correctly in 90% and 93% of cases, respectively. Non-health care workers, such as nutritionists, pharmacists, pharmacy technicians, and radiologists, were the subject of another study [109]. The findings showed that challenges in utilizing PPE, lack of training and regular monitoring, and pain in donning PPE significantly impacted noncompliance with PPE requirements. Inappropriate PPE sizes, the design of the PPE and its complexity of usage, questions regarding the quality and efficacy of PPE, possible dangers when doffing, space arrangement between clean and contaminated areas, and discomfort with PPE use are examples of such obstacles [110].

There was a significant correlation between the number of PPE users per month, the duration of PPE use, smoking, BMI, and the occurrence of headaches (36.5%), breathing difficulties-palpation (25.1%), and dermatitis (20.3%) during the COVID-19 pandemic [111]. These results aligned with those of [112] during the SARS pandemic, which discovered for the first time that long-term use of an N95 respirator and a pre-existing headache are risk factors for headache development. A shorter wearing time is advised to prevent headaches since wearing an N95 respirator for longer than 4 hours is linked to headaches [112]. The results of [113] were consistent with [112] because combined PPE use (n95 respirators and goggles) for more than four hours is a substantial risk factor for de novo headache development in addition to a factor for headache diagnosis where 128 out of 158 developed de novo headache. 82.8% of the respondents reported a slight decrease in performance due to headache development [113]. Another research that looked at how de novo headaches formed while wearing various types of facemasks during the COVID-19 pandemic discovered that the filter mask (KN95 or FFP2) had a worse impact on occupational, familial, personal, and social aspects than the surgical mask [114]. 158 out of 306 people developed a headache during their study.

PPE adverse effect

The impact of various PPE kinds on human physiology has been well-researched and examined. Due to their importance for various occupations, face masks and respirators are among the most often researched PPE. Design fixation in the context of face masks refers to the phenomenon where designers or manufacturers persist in using a specific design approach or concept, even when it may not be the most effective or comfortable. This fixation can lead to adverse effects in face mask usage, impacting both functionality and user satisfaction [115]. Augmented Multisensory Interface Design (AMID) enhances user interaction with technology by engaging multiple sensory modalities. When considering the context of face masks, AMID can play a pivotal role in improving the functionality and user experience of masks, especially in mitigating some of the challenges posed by traditional mask designs [116], [117]. It had been found that the respiratory protective equipment had an effect on respiratory, breathing patterns, wave shape, anaerobic threshold [118], [119]. Alterations in one's heart rate, blood pressure, body temperature, rate of perspiration, and oxygen consumption are among the side effects of using a respirator. [120], [121], [122], [123], [124], [125]. Discomfort recorded by the subjects was mainly caused by the thermal stress burden [124], [126], [127], [128].

The effect of face masks on cognitive ability requires more research, as the majority of studies have found either no change or a little difference. They place greater emphasis on physical and physiological qualities than cognitive abilities. A study by [129] found that wearing face masks does not considerably influence university students' attention and executive functions, mental fatigue perception, reaction time, and time, and it can still be recommended during school lessons. On the other hand, [130] found that the use of surgical masks in physical education students produced a considerable increase in subjective stress perception, sympathetic modulation, cardiovascular response, and face and temple temperature while decreasing blood oxygen saturation. Eighty-one percent of 314 responding healthcare workers experienced cognitive impairment [131]. In another research [132], 5% of survey respondents experienced cognitive impairment. [133] found that 65 percent of respondents reported cognitive impairment when wearing PPE. This cognitive impairment may impact performance and threaten healthcare workers' and patients' health and safety. In a simulated healthcare setting, [134] found no changes in physiological strain, motor-cognitive function, or temperature discomfort between mask wearers and non-mask wearers. Additionally, 1999 research by Caretti et al. on the U.S. Army M40 respirator revealed no impact on mood or cognitive function when wearing the respirator and engaging in low-intensity activities [135]. The study of social cognition, which evaluates how humans interact with one another, has been recently studied, and it has been found that masks can significantly decrease social cognition and negatively harm others [136]. Additionally, it was shown that individuals wearing face masks had lower speech discrimination scores than those not wearing a facial PPE (fit-tested filtering facepiece code 3 mask and head visor) [137]. Likewise, when two photographs of the same person were shown, one with a mask on and the other without, wearing a surgical mask had an impact on how easily the faces could be recognized [138]. The error rate in tasks and cognitive abilities, including decision-making and problem-solving, was found to be affected by using full-face and negative-pressure respirators [139]. As a result of the PPE, decision-making was an issue for surgeons as well [140].

The visual element is one of the characteristics that may change when wearing PPE, according to the research [141] [140], [142], [143], [144], [145]. The visual effect of wearing a face mask can significantly influence human perception and performance, particularly in contexts where facial expressions and full visual cues are essential for communication and task execution. This connection is rooted in how masks obscure parts of the face, primarily the mouth and nose, which are vital for interpreting emotions and intentions [146], [147]. One hundred thirty-four surgeons from 26 nations who responded to the survey indicated that 63% of them had vision impairment and 54% had communication difficulties. As the face shields and goggles produce glares, adding respirators to the mix fogged them up.

Wearing PEE compromised psychomotor abilities and manual job performance in a long-term care environment [140]. The results of [140] were consistent with those of [122], which showed that respirators had an impact on psychomotor activities such as maintaining a steady work pace and performing motions that call for precise control to place items accurately. When comparing the assembly times for rifle and fault repair tasks, [148] found that the latter took 17% longer when respirators were used. Due to the importance of the physical and psychological stressors, a study of the interaction between them was conducted by [149].

According to [150], a review of the skin adverse events caused by personal protective equipment (PPE) found that three out of every four people could experience adverse skin events related to PPE and that, on average, skin-related PPE adverse events occurred in 75.13% of cases, with 57.71% of those cases involving face masks and 49.1% involving gloves and other personal hygiene products. Itching, acne, and contact dermatitis were the three most common skin reactions. The nasal bridge (67.22% of cases), the cheekbones (66.9% of cases), and the hands (62.6% of cases) were the anatomical parts that were damaged the most often. Wearing PPE for longer periods was the risk factor most connected with skin side effects [150], [151]. Healthcare workers had a higher rate of adverse skin events while using face masks, gloves, or poor hand hygiene than did non-HCWs. In a recent study conducted during the COVID-19 period, researchers discovered that 66 out of 137 survey respondents had 4 to 8 skin problems, and 62 out of 137 had 1 to 3 [151]. Concerning N95 masks, goggles, and face shields, 76.64% experienced nasal bridge scars, 70.07% reported skin soaking in perspiration from wearing latex gloves, and 71.53% reported excessive sweating and soaking from wearing protective clothes [151].

Double masking

Recently, during the COVID-19 pandemic, a new attitude of double masking emerged based on the recommendation by the CDC. Recent findings suggest that wearing double facemasks, specifically combining cotton and surgical masks, enhances protection against COVID-19 and its variants [152]. Research by Arumuru et al. and Sankhyan et al. has shown that a two-layer cotton mask over a knotted surgical mask significantly minimizes droplet leakage, and layering a cotton mask over a surgical one offers more protection than a single surgical mask with lower filtration efficiency [153], [154]. Although there is data supporting the efficiency of double masking in enhancing protection, it is important to note that double masking may have significant negative impacts on human performance, including psychological, physiological, visual, motor, and cognitive capacities. As a result, there may be an adverse effect on the non-compliance with PPE.

Human Limitations and Capabilities

It is generally recognized that heat has a variety of harmful consequences on the human body. In addition, there are elements that influence performance under heat [155]. When at rest, the human body emits about the same amount of heat as a light bulb that has a wattage of one hundred. That is acceptable if the ambient temperature is equal to or lower than the body temperature of 37°C (98.6°F). As the ambient temperature rose, the body began to cool itself by perspiring to prevent overheating. However, when it is very humid outside, sweating may be less efficient due to the saturation of the air. Thus, the body's core temperature will begin to rise, triggering protective measures to safeguard key systems. The blood flow to the skin will increase, causing an increase in heartbeats. As every 0.5°C rise in core body temperature, ten beats per minute are added to a regular person's heartbeat. Also, the muscle will slow down, causing fatigue, and nerves will misfire, causing headaches, nausea, or even vomiting. This was when heat exhaustion started. Organ failure, cell death, and cardiac arrest (heat stroke) all occur when internal body temperature rises to 40 degrees Celsius or above. However, many people will cease sweating and experience dry skin as a result. When internal inflammation increases, the kidneys are the first to fail. An expert on the effects of heat on the human body, Jason Kai Wei Lee of the Human Potential Translational Research Programme at the NUS Yong Loo Lin

School of Medicine in Singapore, has said, "When the kidneys are messed up, all the toxins that have built up cannot be excreted, and your body becomes toxic." Consequently, this will have deleterious effects on other biological systems and hasten the onset of degeneration. Researchers in [155] categorized the factors that affect humans’ performance in heat into controlled and uncontrolled factors. Uncontrolled factors are the level of acclimatization [156], [157], [158], degree of arousal [159], [160], [161], clothing worn [162], [163], [164], skill and training levels [165], [166], presence of other combined stressors [167], [168], [169], [170], [171], [172], [173], comfort [160], [174], [175], [176], [177], [178], [179], elevated core temperature [161], [166], [180], [181], [182], [183], [184], [185], [186], and physical work [166], [187], [188]. Controlled factors are thermal level, exposure duration, and task type. When the wet bulb globe temperature (WBGT) began between 30° and 33°C, it was discovered that performance under heat decreased for tasks requiring perceptual-motor abilities, such as tracking and vigilance tasks, regardless of the exposure time if it was less than 30 minutes or between 4 to 8 hours [155] which is coincided with the recommended exposure limits and recommended alert limits by NIOSH [189]. On the other hand, simple or mental tasks most likely exhibited little to no performance reduction due to heat.

Indoor environmental conditions, such as temperature, ventilation, indoor pollution sources, perceived indoor air quality, daylight, view, lighting levels, and quality, all contribute to and affect human performance. Several studies have investigated how these factors affect the efficiency of office workers and students. Despite differences in the best temperature for performance (at 21°C [190] (Figure 2.4), at 22.22°C [191], above 22.22°C [192], and at 17.22°C and 27.78°C [193], [194]), studies indicated the effect of temperature on performance. Factors including work environment, weather, clothes, and thermal comfort all play a role in these disparities.

The rate of ventilation has a similar effect on performance as does the temperature. However, there is not enough evidence to support the claim that performance improves along with increasing ventilation rate. Figure (2.5) was created to display the impact of the ventilation rate based on nine investigations [195]. Work type, external air quality, indoor pollutant emission rates, and other building attributes that affect indoor environmental quality are all factors that may significantly modify the effects of ventilation rate on productivity. The absence of air pollutants showed a significant increase in human performance in specific tasks, such as removing carpet increased the performance of typing, addition, and proofreading by 4% [196], [197], removing old personal computers with cathode ray tube (CRT) monitors decreased text typing errors 16% [198], removing of three-year-old linoleum flooring, shelves with books and paper, and three-month-old caulk sealant improved text typing [199], and reducing the volatile organic compounds improved various domain in decision making [200].

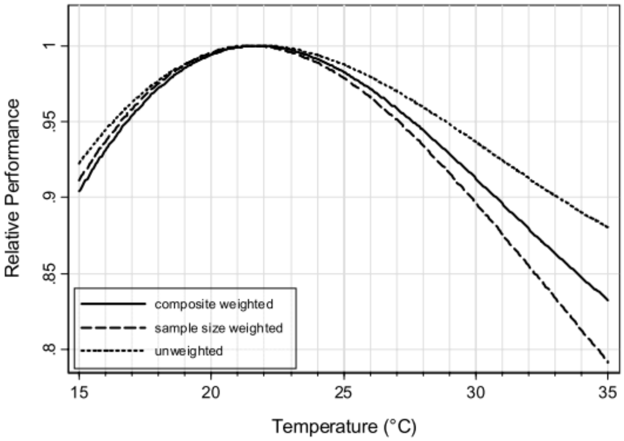

Figure 2.4. Relative performance across temperature increase

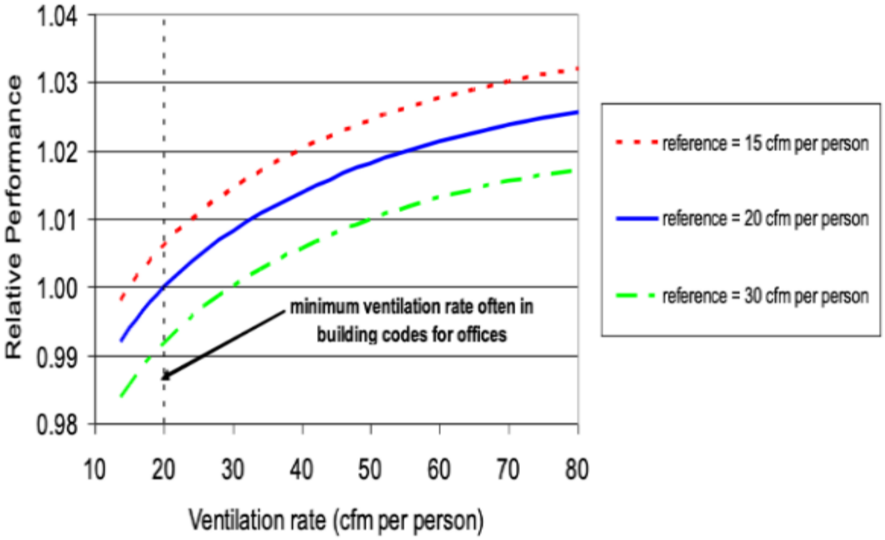

Figure 2.5. Relative performance under different ventilation rate

Strategy to Select Personal Protective Equipment

The instructions provided by the CDC for choosing PPE for healthcare workers may be summed up in three essential aspects: the type of anticipated exposure, the durability and appropriateness of the PPE for the task, and the fit [201]. NIOSH, in collaboration with the CDC's recommendations, produced a database that assists end users in making PPE selections [202]. Where the database is useful in determining the nature of the exposure, the patient's current medical condition, the appropriate PPE, and any applicable regulations. The database will then provide a list of potential personal protective equipment PPE options from which to choose. OSHA stated that cooperation between employees and employers is the best way to maintain safety and a healthy work environment, as shown in the table below [203].

Table 2.1. OSHA statement regarding PPE for the healthful work environment

Employers' responsibility	• Performing a "hazard assessment" of the workplace to identify and control physical and health hazards. Identifying and providing appropriate PPE for employees. • Training employees in the use and care of the PPE. • Maintaining PPE, including replacing worn or damaged PPE. • Periodically reviewing, updating and evaluating the effectiveness of the PPE program
Employees' responsibility	• Properly wear PPE • Attend training sessions on PPE • Care for, clean and maintain PPE • Inform a supervisor of the need to repair or replace PPE.

For infectious disease, [204] developed a risk-based strategy that helps HCW select appropriate PPE ensemble. They demonstrated their method for the activity of intubation for methicillin-resistant Staphylococcus aureus (MRSA) and severe acute respiratory syndrome coronavirus (SARS-CoV), which resulted in two distinct PPE ensembles. The strategy consisted of the following steps: (1) job hazard analysis (JHA), (2) infectious disease hazard analysis, (3) selection of PPE, and (4) evaluation of selected PPE. Step 2 consisted of the source of the pathogen, source strength, pathogen infectivity, severity of disease, and transmission route. In the fourth step of the process, PPE was assessed based on three categories: donning, doffing, and changing; usability; and fit for purpose. Questions that must be answered for each area were supplied. In another attempt to aid workers in selecting the appropriate PPE as it is defined, a complex process was proposed by [205] consisting of three main steps. The first step is to analyze the conditions of PPE use: metabolism, climate conditions, and job requirements. The second step is to consider the laws and standards followed in the workplace. The third step has three stages: initial PPE selection, preliminary trial, and finally, the field trial. In each stage, PPE was evaluated based on four criteria: performance, supplies, physical comfort, and psychological comfort. Where each criterion is broken down into sub-criteria. As a result, the criteria are exhaustive in terms of their conflicts and encompass all industry participants' concerns [205]. Using live components or working in an open installation necessitated the use of arc protection. The intensity of the risks varies depending on the energy of the arc. The BSD corporation created a user-friendly program called the BSD Arc Calculator. This software calculates the energy level in the shortest possible time and suggests the necessary degree of PPE protection [206]. The proper PPE vs. the most comfortable PPE has long been a debate. An argument was made by [207] on balancing PPE with a person's clothing's comfort, fit, and style. She said there are times when a full-body coverall isn't the best option because of the additional load of PPE on the worker's compliance, comfort, and functioning. She was referring to the fact that the full-body coverall can sometimes be cumbersome. Human psychological, physiological, cognitive, visual, and psychomotor abilities were studied and analyzed by [208], who examined the impact of several APFs. Different respirators were shown to have a negative impact on these skills, and the topic of discussion shifted to how to choose respirators that do their job while also allowing the users to function normally.

Discussion

In this review, a significant number of articles related to PPE in industrial and healthcare sectors were reviewed from human factors and ergonomic aspects to spotlight the shadow part of PPE with a primary focus on compliance, adverse effects, double masking, selection strategy, and human limitations and capabilities. Due to the abundance of research on the subject, this review did not focus on other characteristics of PPE, such as protectiveness and efficiency, besides the standards and regulations for controlling their application.

The review began with a brief overview of the history of personal PPE and the evidence gathered along the chronology of the beginning of its invention for human protection. Before being employed in the workplace, PPE was used for protection in war, such as helmets and coveralls, or in everyday life, such as gloves. Human nature inspired PPE since it was necessary for self-defense.

Compliance with PPE by workers in the industrial or healthcare sectors is the first PPE component to be reviewed. It can be seen from the literature that despite the hazards and risks that face the workers, compliance still occurs when they put their lives under threat. Monitoring worker compliance and the causes of compliance deficiency were discussed. The literature demonstrates that researchers exerted considerable effort in monitoring construction workers' adherence to wearing assigned and suitable PPE. The researchers used manual and automated (sensor-based and vision-based) approaches (to monitor compliance). Despite their limited success, both systems are costly and time-consuming to install and maintain. In addition, they expanded their attempts to apply AI to monitor PPE presence and face identification in construction zones using various techniques. However, these methods were not evaluated for use in the healthcare sector, nor were their efficacy studies conducted outside the construction sector. Approaches in the healthcare sector were often basic and time-consuming, such as paper-based monitoring by a nurse in a position of authority to verify employee compliance.

On the other hand, compliance issues with PPE were being probed in both sectors. Reasons may be classified according to the perspectives of management and employees. Both perspectives were described in depth above. Insufficient training, inadequate supervision, employees' experience, comfortability, improper fit, and the desire to compete and demonstrate skill are a few of these factors. Compliance in health care sectors differs in what needs to be complied with.

The adverse effect of PPE is the second component of the review. Extensive research was conducted on the impact of PPE on the wearers. The influence on the physiological, psychological, psychomotor, cognitive, visual, and skin aspects was investigated. In several fields of PPE use, their adverse effects and subsequent impacts on the wearers, such as noncompliance and performance, have been shown. There was a wealth of studies on this topic in the healthcare realm, especially on the effects of face masks. Despite the tremendous efforts in this field, additional study is required to integrate different forms of PPE in situations outside of healthcare. In addition, none of the examined studies in this context indicated or urged these effects to be mitigated.

The practice of wearing two masks simultaneously became a prominent fad during the COVID-19 epidemic. The researchers mainly focused on the efficacy of double masking. While the adverse impacts of wearing a single mask on numerous aspects of human health have been shown, the possible negative consequences of double masking have not been examined. This is crucial since it might lead to an increase in non-compliance.

Human limitations and capabilities are other aspects covered in this review. The purpose of this investigation was to show and assess that the performance and capabilities of people begin to deteriorate at a particular point after they have been subjected to a certain degree of external and environmental stimuli. While personal protective equipment (PPE) is believed to be a physical barrier to people, the findings of this section provide credence to the conclusions of the research about the impact of PPE on capacities.

The efforts in selecting the PPE are the last aspect reviewed. The PPE selection largely depends on the dangers found during the evaluation. This makes it particularly important that the

PPE be chosen with caution and reason. However, businesses should also consider the fit and comfort of PPE when picking suitable goods for each individual. PPE that fits properly and is pleasant to wear will increase employee compliance with PPE usage. Most protective equipment is available in numerous sizes, and care should be taken to pick the correct size for each worker. Despite these attempts, a clear and practical approach still needs to be developed, and the current methods need to be investigated and applied to a more extensive range of situations. In addition, the balance between safety and comfort remains unresolved, contributing to the decreased efficacy of more protective PPE due to comfort.

Conclusion and Future Work

This article is a review of current research that has been undertaken on personal protective equipment across various industries. The research conducted and evaluated for this article focuses on the effects of PPE on the individuals who wear it. The PPE was analyzed from a different perspective in this review. PPE Compliance, Personal Protective Equipment (PPE) Adverse Effects, Double Masking, Human Limitations and Capabilities, and Strategies to Choose Personal Protective Equipment were the primary categories used to classify the articles.

In the future, efforts must be made to find ways to cover the gap between the adverse effects of PPE, double masking, and compliance difficulties. As we observed from the evaluation, it is still challenging to allocate the appropriate PPE to each user because of the burden that PPE imposes. Therefore, there is an urgent need to make the experience of wearing PPE more effective and comfortable. This can be accomplished in several ways, including assigning PPE while maintaining a balance between safety and performance, developing efficient break schedules, or estimating the risk of wearing a particular PPE based on compliance and contamination.

In summary, workers may be exposed to low to high risks, necessitating protective measures. Elimination, substitution, engineering controls, administrative controls, and personal protective equipment are the five levels that comprise the hierarchy of controls that have traditionally been used to minimize or eliminate hazards in the workplace effectively. This hierarchy of controls was followed to control the hazards. Even though PPE is the final step in the hierarchy and is utilized when other controls fail to eliminate or decrease exposure to risks, PPE is crucial in protecting users in many industries. Because of the vital function that PPE has always played and continues to play, even when expanded to the public during pandemics, the area of PPE is rife with obstacles and gaps. These obstacles provide possibilities for merging efforts from several disciplines and fields to overcome the gaps experienced by PPE users. These challenges will be handled, and gaps will be bridged to provide consumers with more comfortable and safer PPE. It became necessary once PPE became a part of our lives in times of sickness and epidemics.

Disclosure Statement

The authors reported no potential conflict of interest.

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CHAPTER 3. THE IMPACT OF DIFFERENT MASK TYPES ON HUMAN PERFORMANCE: A STUDY ON SURGICAL, COTTON, AND DOUBLE MASKS FOR COVID-19 PROTECTION

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Abstract

Although vaccines prevent severe COVID-19 outcomes, mask-wearing is still recommended for transmission control, and considering the impact of mask choice on performance is crucial for different settings. With the increasing trend of double masking, this study aimed to investigate the effect of double masking on various aspects of human performance, including fine and gross motor skills and cognitive abilities. Fourteen participants participated in this study, engaging in distinct scenarios during four sessions: without a mask, with a cotton mask, with a surgical mask, and with both a cotton mask and a surgical mask, while undertaking varied tests measuring dexterity and cognitive abilities. Wearing single surgical, cotton, or combined masks led to more cognitive test errors than the no-mask control, indicating masks' impact on cognitive performance. Nevertheless, the research revealed that employing a double mask increased participants' perceptions of difficulty, discomfort, and anxiety after completing motor and cognitive tasks.

Keywords

COVID-19, double masking, fine motor task, visual task, cognitive task, surgical mask, cotton mask.

Introduction

Due to the ongoing evolution of COVID-19 variants since 2019, the Centers for Disease Control and Prevention (CDC) still recommends wearing face masks to reduce transmission [1]. Many studies have explored different aspects of face masks and their effects on people's daily lives and work. However, most of these studies have focused on a single type of face mask, such as surgical, N-95, or cloth masks. Only a few studies have investigated the impact of surgical masks on human cognitive abilities. In healthcare settings, Elisheva found that prolonged use of N95 and surgical masks during COVID-19 impaired cognition in some healthcare professionals [2]. Morris et al. found no differences in physiological strain, motor-cognitive performance, or thermal discomfort during facemask use in a simulated healthcare environment [3]. Kienbacher et al. showed that wearing FFP2 masks did not harm paramedics' dexterity performance [4]. Tornero-Aguilera and Clemente-Suárez found that surgical masks did not significantly affect university students' mental fatigue perception, reaction time, frequency, or heart rate variability during class [5]. However, another study by Tornero-Aguilera et al. showed that surgical masks increased stress perception, sympathetic modulation, cardiovascular response, and face temperature while decreasing blood oxygen saturation in physical education students [6]. Schlegtendal et al. found no significant differences in cognitive performance between pupils wearing surgical and FFP2 facemasks during regular school lessons [7]. The results of Schlegtendal et al. are consistent with the findings reported by Zimmerman et al., who explored three different types of respirators in their research conducted in 1991 [8]. However, it is crucial to highlight that Zimmerman et al. found a significant effect of wearing respirators compared to not on the performance of psychomotor tasks.

Mgaedeh et al. concluded that wearing facemasks could reduce retail workers' motion response [9]. Even though the cloth mask equipped with an exhalation valve has demonstrated the least temperature and humidity accumulation within the mask [10], it has been observed that individuals experience discomfort while wearing cloth masks. This discomfort can be attributed to factors such as breathability and the level of tightness against the face and head [11]. Furthermore, the act of wearing masks has been associated with an increase in anxiety levels and a decrease in work tolerability [12], [13]. A recent study on healthcare workers examined two sets of different PPE, varying in quantity and protection level. The findings indicated a significant impact on heart rate, energy expenditure, core body temperature, microclimate temperature, and humidity with increased levels of protection and number of PPE [14]. Regarding the body temperature ratings, the kind of face mask had a significant effect [15].

New research has indicated that using two facemasks instead of one can provide greater protection against COVID-19 and its more contagious variants [16]. Recent studies have examined using cotton materials for double masking combined with surgical masks to explore this further. For example, Arumuru et al. found that wearing a two-layer cotton mask over a surgical mask with a knot significantly reduced the leakage of droplets [17]. Similarly, Sankhyan et al. found that layering a cotton cloth mask over a surgical mask was more beneficial than wearing a single surgical mask, especially when the surgical mask had lower filtration efficiency [18].

To the best of the authors' knowledge, no research has examined how double masking may affect human psychomotor and cognitive. Therefore, this study has the potential to offer a more complete and reliable recommendation on the use of double masks that considers important human factors such as motor skills and cognitive abilities, in addition to health protection and reducing the spread of COVID-19.

The primary aim of this study is to examine how wearing different types of masks, including a single surgical mask, a cotton cloth mask, and a combination of a surgical mask and cotton cloth mask, can affect human performance in terms of fine and gross motor skills, visual abilities, and cognitive functions. The study's hypotheses are as follows:

I. The mask type would affect human fine and gross motor performance.

II. The mask type would affect human cognitive performance.

Methodology

Ethics statement

This study was approved by the Institutional Review Board (IRB) at Iowa State University. Upon arrival on the first day of the study, participants provided informed consent (Appendix: IRB approval memo).

Participants

A total of 14 individuals took part in the study, consisting of 11 males and 3 females, with an average age of 28.3 years and a standard deviation of 4.5. The eligibility criteria for participants involved being in a normal physical condition and not having any chronic respiratory illnesses, injuries, fatigue, or musculoskeletal disorders. Participants who reported having no allergies or skin irritations from surgical masks made of polypropylene or cotton and no current cognitive or visual impairments were included. However, individuals who did not meet these criteria were excluded from the study.

Independent and dependent variables

This study examined one independent variable: the type of facemask used. Four different levels of facemasks were considered, including no facemasks, a single surgical mask, a single cotton cloth mask, and a surgical mask combined with a cotton cloth mask. These three levels were compared to a control group that did not use face masks.

Five dependent variables were employed to evaluate the effects of various mask types on humans. These included fine motor dexterity, gross motor dexterity, cognitive performance, comfort level, and perceived anxiety associated with wearing the facemask.

The study used the Lafayette Purdue pegboard test (Model 32020A) to evaluate fine motor dexterity of fingertips and gross motor dexterity of fingers, hands, and arms [1]. The Purdue Pegboard Test was used to assess and record the total number of assemblies completed per minute. The board features two parallel rows of 25 holes each, totaling 50 pins. The participant was required to place as many pins as possible in the holes using the dominant hand, non-dominant hand, and both hands within 30 seconds in the first three subtests. The fourth subtest required the participant to alternate using both hands to assemble a pin, a washer, a collar, and another washer, completing as many assemblies as possible within one minute. A visual of the Purdue pegboard test set is displayed in Figure 3.1.

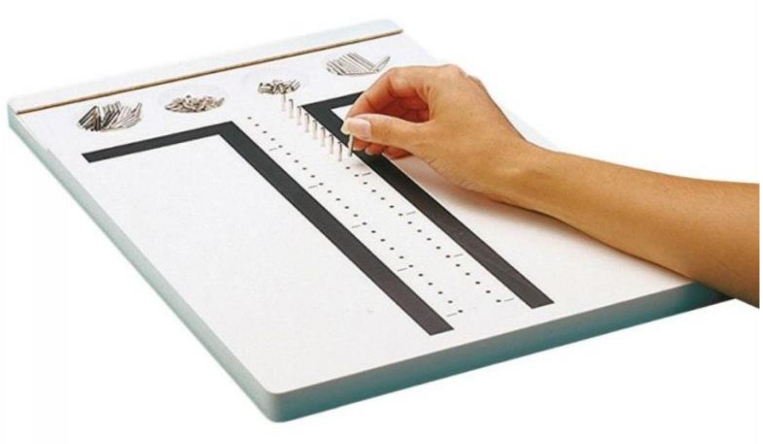

Figure 3.1. The Purdue pegboard test

The standardized Lafayette hand tool dexterity test is used to assess fine motor skills using ordinary mechanics tools [13] by recording the completion time in seconds. The test includes 12 bolts, four of each size, and a U-shaped apparatus with bolt heads inside the two uprights shown in Figure 3.2. The objective is to disassemble all the bolts using tools to loosen them first, then fingers to remove them, and then reassemble them on corresponding rows of the other upright with the heads of the bolts inside. The test requires tightening the bolts so they cannot be removed with the fingers.

Figure 3.2. The Hand Tool Dexterity Test

The Lafayette Minnesota dexterity test measured gross motor skills of the arm and hand using a folding board and sixty blocks [14]. The test includes two tasks: placing and turning. For the placing test, the participant fills the board's holes with disks using their dominant hand as fast as possible. In the turning test, the participant picks up a block, turns it, and returns it to its original position. The score is the total number of seconds taken to complete the task. Figure 3.3 illustrates the turning subtest's starting position and sequence of rows. The total completion time of two trials for the turning test was evaluated.

Figure 3.3. The Minnesota Dexterity Test

The Serial Sevens Test is a well-known method for measuring cognitive abilities by subtracting seven repeatedly from a four-digit starting number [15]. Participants were asked to subtract seven from the starting number 15 times, with time starting when the examiner announced the number and ending with the last subtraction. Errors are recorded for each miscalculation but not for correct answers.

The level of comfort provided by the facemask was evaluated using a Likert scale ranging from 1 to 5, where 1 indicated a very comfortable experience, and 5 indicated a highly uncomfortable experience. The level of anxiety induced by wearing a facemask was evaluated subjectively on a Likert scale ranging from 1 to 5, where 1 indicated low anxiety, and 5 indicated high anxiety. Task Perceived Difficulty Level was assessed subjectively on a Likert scale between 1 and 5. Where 1 is easy and 5 is highly difficult.

Experimental tasks and procedure

The study was performed in a laboratory at Iowa State University with an average temperature of 70°F, where participants were briefed and given questionnaires to determine their eligibility and demographic information. Participants then underwent training and performed three dexterity tests to determine their dexterity level. The experiment consisted of four sessions, in which participants were randomly assigned to wear different types of masks (single surgical mask, single cotton cloth mask, a surgical mask doubled with a cotton cloth mask, or no mask) and asked to perform the formerly stated tasks while wearing the assigned mask. They were also asked to rate each mask type's comfort, perceived difficulty, and anxiety level.

Statistical analysis

The statistical analysis in this study was conducted using the R Project for Statistical Computing Software, version 4.2.2. The Repeated Measures ANOVA technique was used to determine the effect of mask type on the different dependent variables. Their normality was checked to ensure that the dependent variables were approximately normally distributed. A significance level of 0.05 was set for all statistical analyses.

Results

The study's objective was to investigate the effect of no face mask, face mask type, and double masking on human fine motor, gross motor, and cognitive performance.

Fine motor dexterity

The study measured fine motor dexterity using two metrics: the total number of assemblies completed per minute and the time it took to complete the task in seconds. The statistical analysis showed that wearing a face mask statistically significantly affected the total number of assemblies per minute (with a p-value of 0.005). The obtained p-value indicated that one or more types of facemasks significantly impact the total number of parts assembled per minute. Thus, additional post-hoc analysis was performed using pairwise t-test comparison to determine which facemask had the most significant effect, as presented in Table 3.1. According to the pairwise t-test comparison shown in Table 3.1, the surgical mask was doubled with a cotton mask, and the control conditions were found to be significantly different from each other in terms of their effect on the total number of assemblies per minute.

Similarly, the single cotton mask and the control condition were also found to be significantly different from each other. The statistical analysis showed no significant effect of wearing a facemask on the completion time in seconds (p=0.585). This means the time to complete the dexterity tasks was not significantly different among the facemask types and the control condition.

Table 3.1. Pairwise comparisons using paired t-tests for fine motor dexterity

	Single Cotton mask	A surgical mask doubled with a cotton mask	No Mask
A surgical mask doubled with a cotton mask	1.00	-	-
No mask	0.025	0.044	-
Single Surgical mask	0.722	0.254	0.913

Gross motor dexterity

The repeated measures one-way ANOVA results showed no statistically significant effect of wearing different types of face masks on gross motor dexterity performance (p=0.217). This means that the choice of face mask did not significantly impact the gross motor dexterity tasks performed by the participants. The p-value of 0.217 suggests a 21.7% chance that the observed differences in gross motor dexterity performance between the face mask conditions could have occurred by chance alone. Therefore, based on these results, it can be concluded that the type of face mask worn does not affect gross motor dexterity performance.

The cognitive test

The repeated measured one-way ANOVA results on the cognitive test response variable (error) indicated a statistically significant effect of different face mask conditions (p=0.000614). This means that the type of face mask worn during the cognitive test significantly impacted the number of errors made by the participants. To determine which face mask condition produced the most significant change, post-hoc analysis using pairwise t-test comparison was conducted, and the results are presented in Table 3.2.

Table 3.2. Pairwise comparisons using paired t-tests for cognitive test

	Single Cotton mask	surgical mask doubled with a cotton mask	No Mask
surgical mask doubled with a cotton mask	0.811	-	-
No mask	0.046	0.014	-
Single Surgical mask	0.765	1.00	0.022

According to the pairwise t-test comparison shown in Table 3.2, the results suggest that the Surgical mask doubled with a cotton mask. The control conditions were significantly different from each other, indicating that wearing a combination of surgical and cotton masks or not wearing a mask at all resulted in significantly fewer errors compared to wearing a single surgical mask. The comparison also showed that the single cotton mask and the control condition were significantly different, indicating that wearing a single cotton mask or not wearing a mask at all resulted in significantly fewer errors compared to wearing no mask. Finally, the comparison showed that the single surgical mask and the control condition differed significantly, indicating that wearing a single surgical mask resulted in significantly more errors than not wearing a mask.

Subjective feedback analysis

Each participant completed all the tasks four times, once for each face mask condition. After each task, participants were asked to report their comfort level regarding the face mask they were wearing, their anxiety level, and how difficult they found the task to be while wearing the face mask. This was done in each of the four sessions.

A Likert scale is a commonly used rating scale that measures the degree of agreement or disagreement with a statement or question. In this case, the Likert scale was used to measure the level of comfort provided by the facemask. The scale ranged from 1 to 5, with 1 indicating a very comfortable experience and 5 indicating a highly uncomfortable experience. Participants were likely asked to rate their comfort level after each task performed with each face mask condition. The results of the ratings can be used to compare the comfort level provided by each type of facemask. According to the tables provided, the average uncomfortably rating was consistently higher for the Single surgical double with a single cotton mask condition across all tasks performed by the participants. This suggests that participants found this particular mask condition to be the least comfortable among all the conditions tested in the study. This information is important as it highlights the importance of considering not only the effectiveness of the mask but also its comfort level, as the discomfort can potentially lead to reduced compliance with wearing masks in real-world scenarios.

The level of anxiety induced by wearing a facemask was evaluated subjectively by the participants using a Likert scale. The scale ranged from 1 to 5, with 1 indicating low anxiety and five indicating high anxiety. Participants were asked to report their anxiety level after each task was completed with a different facemask condition. Based on the data collected and analyzed, the average anxiety rating was higher when participants wore a double mask after performing the Purdue dexterity tasks, turning dexterity tasks, and cognition tasks. However, the average anxiety rating was higher when wearing a single cotton mask while performing the hand tool dexterity task. This suggests that the type of task being performed and the type of mask being worn can have an impact on the level of anxiety experienced by the individual. It is important to note that these results are based on subjective self-report measures, and other factors may also contribute to the level of anxiety experienced by individuals wearing face masks.

Task Perceived Difficulty Level refers to the subjective perception of how difficult a task is for the participant. This was assessed on a Likert scale ranging from 1 to 5, where 1 indicated a very easy task, and 5 indicated a highly difficult task. As shown in the tables below, Participants reported higher difficulty perceptions for the single cotton mask while performing the Purdue dexterity and hand tool dexterity tasks. On the other hand, double masking caused higher difficulty perceptions of the task while performing the turning dexterity tasks and cognitive tasks. These results suggest that face masks may affect different types of tasks differently.

Table 3.3. Subjective feedback from participants after completing the Purdue dexterity tasks

	Difficulty	**Comfortability**	**Anxiety Level**
	Mean ± SD		
No mask	1.29 ± 0.59	1.07 ± 0.26	1.14 ± 0.35
Single Cotton	1.57 ± 0.62	1.71 ± 0.70	1.5 ± 0.63
Single Surgical	1.43 ± 0.62	1.5 ± 0.63	1.5 ± 0.63
Single surgical double with a single cotton	1.5 ± 0.73	2.14 ± 0.86	1.86 ± 1.12

Table 3.4. Subjective feedback from participants after completing the hand tool dexterity task

	Difficulty	**Comfortability**	**Anxiety Level**
	Mean ± SD		
No mask	1.57 ± 0.98	1.21 ± 0.41	1.29 ± 0.45
Single Cotton	2.07 ± 0.88	2.14 ± 0.74	2.07 ± 1.16
Single Surgical	1.76 ± 1.15	1.86 ± 1.06	2 ± 1.07
Single surgical double with a single cotton	1.93 ± 0.88	2.64 ± 0.81	1.86 ± 0.91

Table 3.5. Subjective feedback from participants after completing the turning dexterity tasks

	Difficulty	**Comfortability**	**Anxiety Level**
	Mean ± SD		
No mask	1.14 ± 0.35	1.14 ± 0.35	1.29 ± 0.45
Single Cotton	1.57 ± 0.62	2 ± 0.76	1.79 ± 0.77
Single Surgical	1.71 ± 0.96	2 ± 0.76	1.86 ± 0.91
Single surgical double with a single cotton	2.21 ± 1.08	2.14 ± 0.9	2.14 ± 1.12

Table 3.6. Subjective feedback from participants after completing the cognition task

	Difficulty	**Comfortability**	**Anxiety Level**
	Mean ± SD		
No mask	2.07 ± 1.49	1.79 ± 1.32	1.64 ± 0.97
Single Cotton	2.71 ± 1.16	2.29 ± 1.16	2.36 ± 1.11
Single Surgical	3.14 ± 1.19	1.93 ± 0.88	2.71 ± 1.33
Single surgical double with a single cotton	3.71 ± 0.88	2.86 ± 0.91	2.93 ± 1.53

Discussion

The hypothesis that different types of masks would affect human fine and gross motor performance was only partially rejected, as the only significant effect was observed with the cotton or surgical doubled with a cotton mask on the total number of assemblies per minute during Purdue's fine motor performance task. There was enough evidence not to reject the hypothesis that masks would affect cognitive performance. However, these findings suggest that individuals should be cautious when performing tasks that require facemasks and high working memory loads, such as those in STEM-related fields. Furthermore, individuals who work in jobs requiring fine motor skills, such as surgery, dentistry, jewelry making, data entry, and musical instrument repair and tuning, should also be cautious when wearing cloth or double masks.

Studies have shown that wearing face masks can increase facial skin temperature, impacting thermal sensations throughout the body and causing discomfort [23], emphasizing the need to understand this effect in order to assess the impact of different mask types on human performance. Studies have shown that wearing masks can increase skin temperature and affect the perception of thermal discomfort. Recent research has compared the effects of surgical and N95 masks on facial skin temperature and found that surgical masks produce less of an increase [24]. Studies have also examined the relationship between thermal stress, discomfort, and human performance and found that even mild stress can affect performance, with task characteristics being a key factor [25]. Cognitive load may affect Fine motor skills more than gross motor skills [26], which could explain the different effects of masks on the Purdue and Minnesota dexterity tests.

The effect of different face mask types on the completion time of the hand tool dexterity test is insignificant; this result is consistent with AlGhamri et al., results [27], despite increased discomfort and difficulty, according to the study's results. However, factors such as age, gender, hand size, and hand skin temperature may be more critical in determining hand tool dexterity scores [28]. To better understand the impact of mask type on performance, measuring the total number of errors and completion time during the hand tool dexterity task while wearing each mask type is recommended.

Wearing a single surgical, single cotton, or surgical mask doubled with a cotton facemask significantly increases the number of errors in the Serial Seven test and perceived difficulty, discomfort, and anxiety. These results conflict with recent studies on the effect of wearing facemasks on cognitive performance. According to [29], analyzing almost three million chess moves played by over 8500 individuals in eighteen countries before and during the COVID-19 pandemic shows that wearing a face mask can significantly decrease the average quality of player decisions, which could lead to a temporary impact on cognitive performance during a demanding mental task that requires a high working memory load. However, the decrease in cognitive performance can be attributed to the annoyance caused by the face masks rather than physiological factors like cerebral oxygenation. This is supported by the dramatic increase in reported perceived difficulty, discomfort, and anxiety by participants after completing the cognitive task while wearing facemasks compared to the control condition of not wearing a facemask. However, these findings contrast with other studies, such as those by [5] and [30], which reported no significant impact of wearing a surgical facemask on cognitive performance. Additionally, [31] found that wearing a non-woven fabric cloth facemask during warm-up could actually enhance cognitive function.

Limitations

To the best of the authors' knowledge, this is the first study that examined the effect of double masking. Thus, this study had several limitations.

First, this study was conducted over short periods, reflecting the immediate impact of double masking. Hence, comprehending the long-term effects of double masking and generalizing becomes complicated. Therefore, a longitudinal study is necessary to examine the potential adverse effect of double masking and the level of adherence and compliance among wearers.

Second, this study investigated cotton cloth masks and level 1 surgical masks. Further research is needed to include the many variants of cloth and surgical masks. In addition, further research may include other face mask types with combinations such as N95, KN95, and FFP 1.

Conclusion

To the best of the authors' knowledge, this study is the first to explore the influence of double masking on human psychomotor and cognitive performance and the first research to analyze how surgical and cotton masks impact human manual dexterity skills. The study showed that using a surgical mask along with a cotton mask can lead to higher levels of anxiety, discomfort, and difficulty during tasks. Wearing either a surgical mask or a surgical mask doubled with a cotton mask can notably impact human cognitive performance. This suggests that using face masks during mental tasks that require a high working memory load may compromise the quality of work and decision-making. Further research is needed to examine the total time required to complete cognitive tasks and the number of errors associated with wearing each type of mask.

Disclosure Statement

The authors reported no potential conflict of interest.

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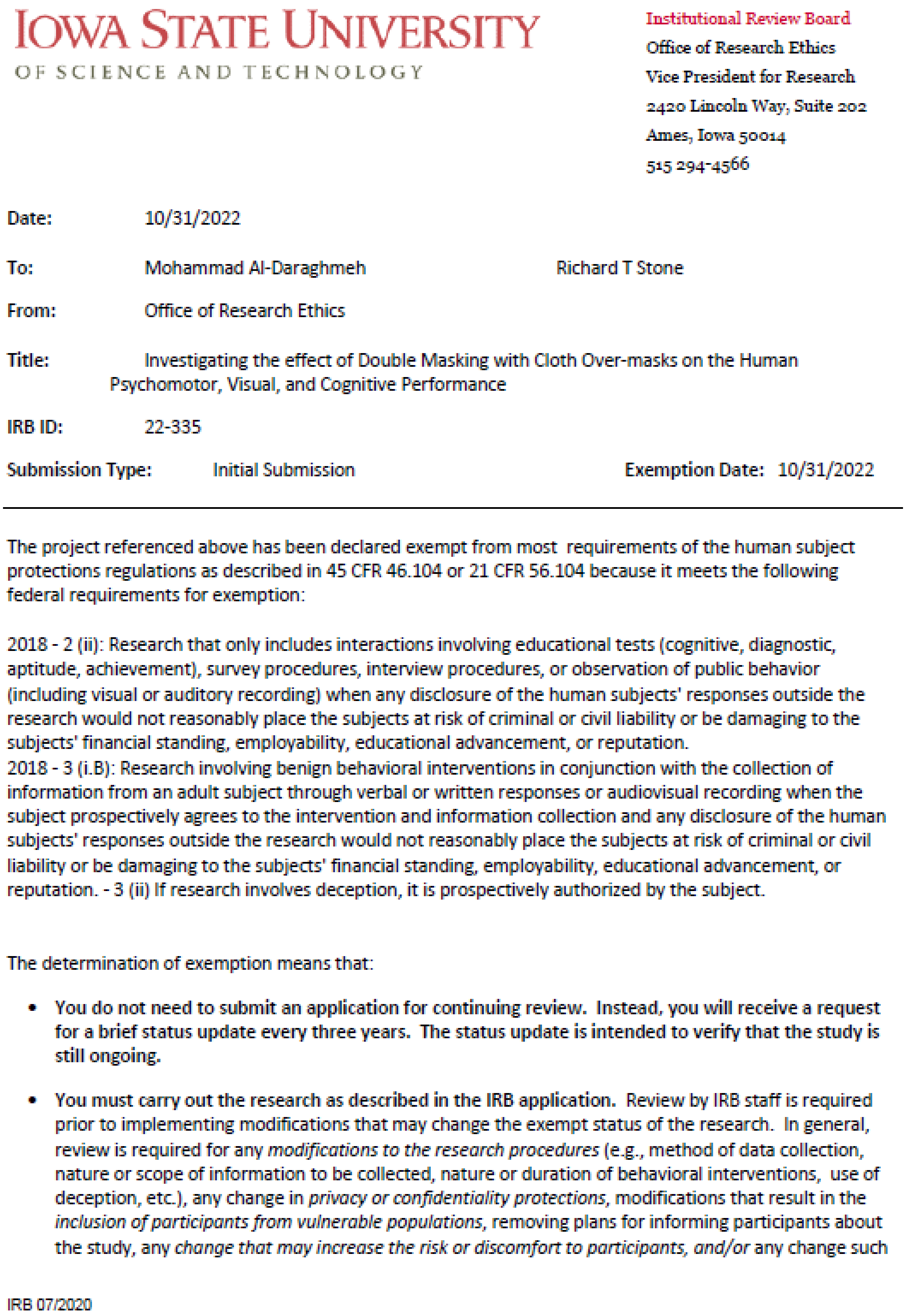
Appendix: IRB approval memo



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OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office of Research Ethics
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 10/31/2022

To: Mohammad Al-Daraghmeh Richard T Stone

From: Office of Research Ethics

Title: Investigating the effect of Double Masking with Cloth Over-masks on the Human Psychomotor, Visual, and Cognitive Performance

IRB ID: 22-335

Submission Type: Initial Submission **Exemption Date:** 10/31/2022

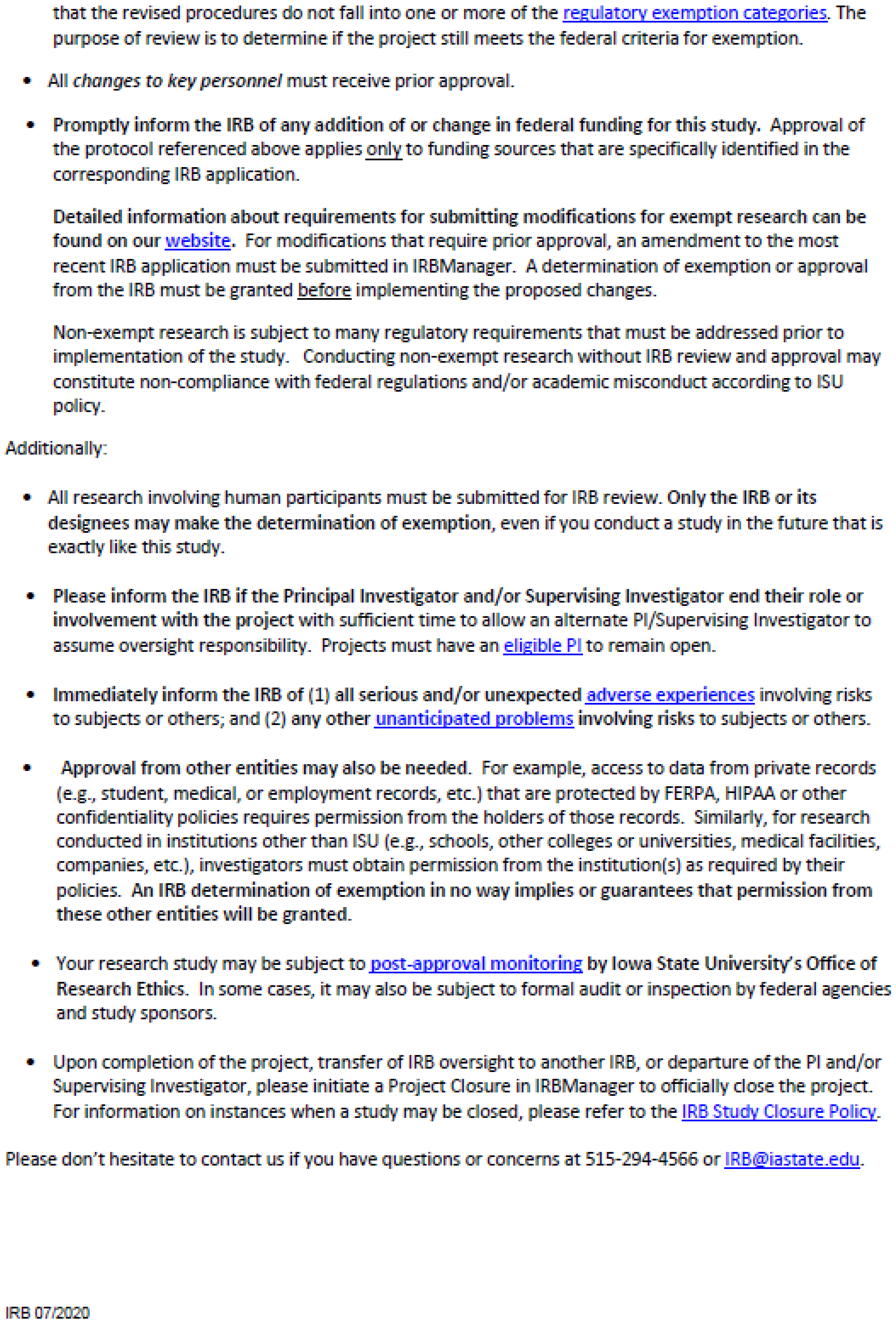
The project referenced above has been declared exempt from most requirements of the human subject protections regulations as described in 45 CFR 46.104 or 21 CFR 56.104 because it meets the following federal requirements for exemption:

2018 - 2 (ii): Research that only includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording) when any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation.
2018 - 3 (i.B): Research involving benign behavioral interventions in conjunction with the collection of information from an adult subject through verbal or written responses or audiovisual recording when the subject prospectively agrees to the intervention and information collection and any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation. - 3 (ii) If research involves deception, it is prospectively authorized by the subject.

The determination of exemption means that:

- **You do not need to submit an application for continuing review. Instead, you will receive a request for a brief status update every three years. The status update is intended to verify that the study is still ongoing.**
- **You must carry out the research as described in the IRB application.** Review by IRB staff is required prior to implementing modifications that may change the exempt status of the research. In general, review is required for any *modifications to the research procedures* (e.g., method of data collection, nature or scope of information to be collected, nature or duration of behavioral interventions, use of deception, etc.), any change in *privacy or confidentiality protections*, modifications that result in the *inclusion of participants from vulnerable populations*, removing plans for informing participants about the study, any *change that may increase the risk or discomfort to participants, and/or* any change such

IRB 07/2020



that the revised procedures do not fall into one or more of the regulatory exemption categories. The purpose of review is to determine if the project still meets the federal criteria for exemption.

- All *changes to key personnel* must receive prior approval.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.

  Detailed information about requirements for submitting modifications for exempt research can be found on our website. For modifications that require prior approval, an amendment to the most recent IRB application must be submitted in IRBManager. A determination of exemption or approval from the IRB must be granted before implementing the proposed changes.

  Non-exempt research is subject to many regulatory requirements that must be addressed prior to implementation of the study. Conducting non-exempt research without IRB review and approval may constitute non-compliance with federal regulations and/or academic misconduct according to ISU policy.

Additionally:

- All research involving human participants must be submitted for IRB review. **Only the IRB or its designees may make the determination of exemption**, even if you conduct a study in the future that is exactly like this study.
- **Please inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of (1) all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) any other unanticipated problems **involving risks to subjects or others.**
- **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **An IRB determination of exemption in no way implies or guarantees that permission from these other entities will be granted.**
- Your research study may be subject to post-approval monitoring **by Iowa State University's Office of Research Ethics.** In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.
- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure in IRBManager to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

IRB 07/2020

CHAPTER 4. MODEL OF PREDICTING PERSONAL PROTECTIVE EQUIPMENT NON-COMPLIANCE (MPENC)

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Abstract

Compliance poses a significant challenge in the application of Personal Protective Equipment (PPE), notably among healthcare workers (HCWs). Adherence to guidelines, particularly in refraining from touching or manipulating PPE, is vital for protecting those vulnerable to infectious disease exposure. A simulation study was carried out in which the combinations of PPE and workloads were varied. Volunteer students donned either an N95 or surgical mask, complemented by a face shield or goggles, and undertook various tasks under low or high workload conditions. Data on comfort levels, PPE impact evaluation, temperature, and relative humidity were gathered during and at the conclusion of the simulation. Sixteen volunteers participated in the study; fourteen participants were included in building the predictive model due to missing data. The predictive model included the itchy, tight, hot, humid, unfit, maximum comfort, maximum anxiety, maximum difficulty, fatigue, odor, salty, mode dew point, heating up slope, PPE, and workload. The Random Forest (RF) model demonstrated superior performance compared to Linear model regression and LASSO in terms of RMSE and MAE. This study not only sheds light on the factors affecting PPE compliance but also underscores the effectiveness of the Random Forest model in navigating the complexities of PPE use in healthcare settings, offering insights for future strategies to enhance compliance and protect healthcare workers and patients alike.

Keywords

Compliance, Workloads, Protection level, Face Mask, Temperature, Relative humidity

Introduction

While personal protective equipment (PPE) is considered the last line of defense in the hierarchy of controls for hazard prevention, it remains an essential tool for protecting workers when all other controls have been exhausted or are not feasible. Elimination, substitution, engineering controls, and administrative controls are all preferred over PPE because they can potentially eliminate or reduce hazards at the source. However, in some cases, such as when workers are exposed to airborne contaminants or infectious diseases, PPE may be the most effective means of protecting them. When selecting and using PPE, it is essential to ensure that the equipment is appropriate for the specific hazard and task, fits properly, and is used and maintained correctly. Failure to do so can result in inadequate protection and increase the risk of injury or illness.

Compliance with wearing PPE is one of the significant challenges faced by PPE users. Complying with PPE regulations entails verifying that the gear is being worn correctly, fits properly, and is suitable for the specific hazards encountered in the workplace. Additionally, it involves appropriately maintaining, storing, and disposing of the equipment. Ensuring compliance with PPE regulations is crucial in safeguarding the health and safety of employees, and violating these regulations can lead to severe injuries, illnesses, and even fatalities.

Several factors contribute to poor compliance with PPE use and can be categorized into organizational, individual, and work-related factors. Organizational factors such as management policy had the most significant impact on employees' compliance by the absence of incentives for compliance [2], [3], [4], punishments for noncompliance [3], [5], [6], [7], inadequate training on the proper use of PPE [3], [7], [8], enforcement and reinforcement make the [3], [8], [9], [10],

[11], safety training [2], [12], [13] and an inadequate safety performance review [8], [14], [15]. Individual factors include work experience [7], [16], [17], [18], [19] discomfort [8], [20], [21], Poor fit [8], [20], [21], compete and proving expertise in front of coworkers [2], workload imposed on workers [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], gender, occupations [17], [32], [18], and perceptions of the PPE's effectiveness [33], [34].

Research has shown that HCWs tend to have low compliance with PPE regulations [9], [35], [36], [37], [38], which is worrying because they are often exposed to infectious diseases and other hazards in the workplace. Targeted interventions and education to improve PPE compliance among HCWs could help lower the risk of workplace injuries and illnesses. Face masks and respirators are frequently researched types of PPE due to their critical function in protecting workers in various occupations. These devices are intended to protect against airborne hazards and infectious diseases, making their effectiveness in preventing illness transmission a significant focus of research. Wearing a face mask for extended periods can cause discomfort and have physiological, psychological, and cognitive effects, which can result in decreased mask-wearing compliance by the end of a shift [39], [40], [41], [42], [43], [44], [45], [46], [47], [48]. This can lead to a reduction in the effectiveness of face masks. The primary cause of discomfort experienced by subjects when wearing face masks was the thermal stress burden [49], [50]. In addition to heat build-up inside face masks, researchers have identified several other factors contributing to discomfort and tolerability issues for mask wearers. These include facial pressure or pain, skin irritation, difficulty breathing, and difficulty communicating [9], [51], [52]. These issues can make wearing masks for extended periods challenging, particularly in high-stress or high-intensity work environments. Different varieties of face masks, which offer differing degrees of protection, can also vary in terms of comfort and thermal stress, according to studies. N95 respirators, for example, have been found to be more uncomfortable and cumbersome to wear than surgical masks, presumably due to their tighter fit and increased respiration resistance [50], [53]. Depending on the material used and the number of layers, the degree of protection of cloth masks can differ. However, they are generally considered less cumbersome to wear than N95 respirators and surgical masks. When selecting a face mask for a particular situation, it is crucial to consider the trade-offs between protection and comfort, considering factors such as the level of risk, duration of use, workloads, and individual comfort and tolerance to reduce discomfort and promote compliance. The studies investigating the effects of different types of face masks on compliance and wear time did not reach a clear conclusion or measure as to which type of face mask is worn for a more extended period of time or with greater compliance by workers. Further research is needed in this area to understand better the factors that affect compliance and wear time for different types of face masks.

Consequently, this study aims to assess and measure the degree of compliance with various types of PPE ensembles in the context of the COVID-19 pandemic, taking into account different levels of protection and workloads. The study also aims to develop a prediction model for compliance based on the collected data. Also, temperature and relative humidity will be measured. We hypothesized that:

I. Increasing the level of protection will decrease PPE compliance
II. Increasing the workload will decrease PPE compliance
III. Higher temperatures will be built up while wearing a higher level of protection
IV. Higher temperatures will be built up under a high workload
V. No change in the relative humidity under different workloads or protection levels

Methodology

Design of experiment

Ethics statement

The study protocol was approved by the Institutional Review Board (IRB) at Iowa State University (23-220) (Approval memo found in Appendix 1), and the corresponding approval memorandum is available in Appendix 1. The participant signed the informed consent on the first day of the study.

Infection disease and PPE requirements

During the COVID-19 pandemic, personal protective equipment (PPE) has been crucial in protecting healthcare workers and others from infection. Face masks, respirators, mittens, hoods, and face barriers are examples of PPE. In healthcare contexts, PPE prevents virus transmission from patients to healthcare professionals and vice versa. PPE is also recommended in environments where physical distance cannot be maintained, such as public transportation and grocery stores. PPE is accompanied by guidelines and recommendations from health organizations and governments to ensure the appropriate use and disposal of PPE to reduce the possibility of infection. The information presented in Figure 4.1 provides guidelines by the CDC [54] for using personal protective equipment (PPE) when attending confirmed or suspected COVID-19 patients. The N95 face mask is preferred, although a surgical mask is considered acceptable. A face shield or goggles can be used to cover the face.

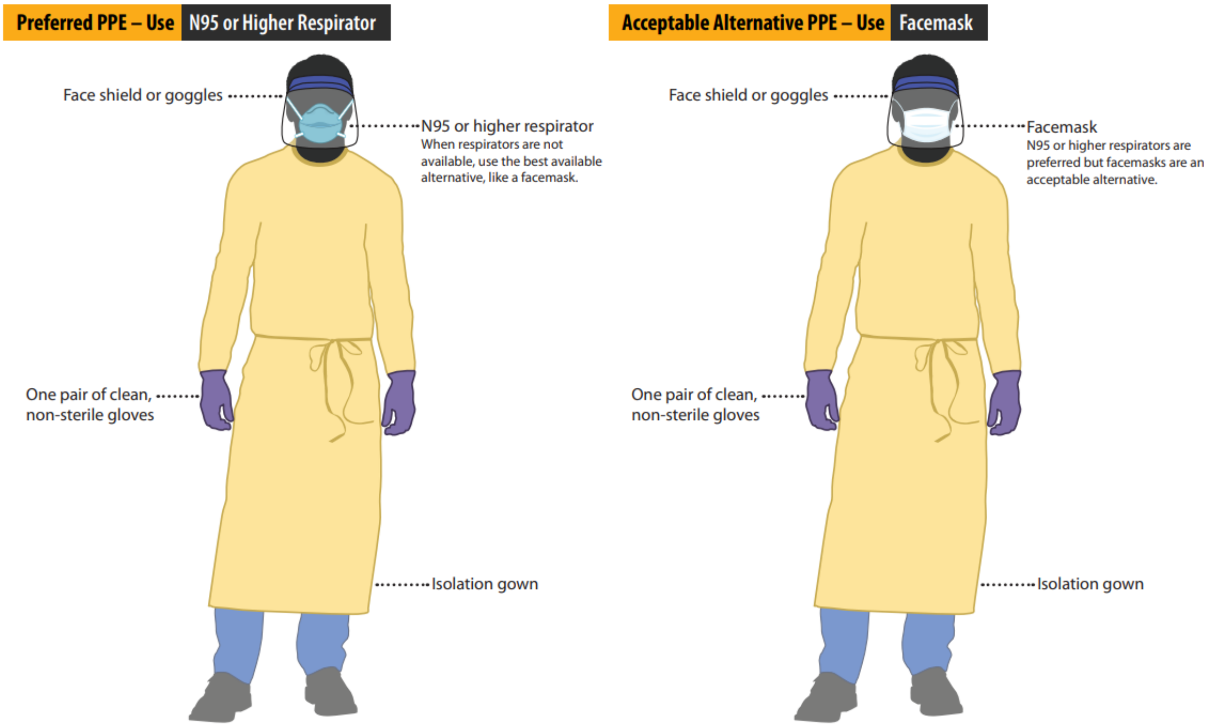


Figure 4.1. Preferred and Accepted PPE by the CDC when caring for suspected or confirmed patients with COVID-19

Participants

Participants were recruited from the Iowa State University campus using flyers and email. Participants were undergraduate and graduate student volunteers.

The inclusion criteria for participation in this study required individuals to be at least 18 years old and proficient in English.

Exclusion criteria included current cardiovascular or respiratory diseases (such as asthma, COPD, pulmonary fibrosis, pneumonia, and lung cancer), current injuries, fatigue, or musculoskeletal disorders (including Epicondylitis, Carpal tunnel syndrome, Repetitive strain injury (RSI), De Quervain's syndrome, Tendinitis of the shoulder, Biceps tendinitis, Tennis elbow, Golfer's elbow, Patellar Tendinitis, Achilles tendinitis, Tension neck syndrome, Lower back pain, etc., or individuals who are suffering from current cognitive disorders such as

Alzheimer's disease, Attention deficit disorder, Fronto-temporal dementia, and Epilepsy-related cognitive dysfunction).

Furthermore, individuals with allergies or skin irritations triggered by surgical masks (polypropylene), N95 masks, goggles, and face shields were excluded from the study. Pregnant individuals and those experiencing physical pain that may hinder focus or performance were also excluded from enrollment.

Individuals were encouraged to participate in the study if they maintained good health throughout the study sessions, displaying the absence of symptoms such as headache, nausea, dizziness, lightheadedness, or recent illness, and are not presently afflicted with contagious conditions including flu, hangover, pinkeye, or head lice.

Independent and dependent variables

For the purpose of the study, this investigation uses two independent variables that are distinct from one another (Table 4.2).

The first independent variable is the protection level of the PPE ensemble. Each ensemble has two PPE: a face mask and face covering. Each PPE had two levels of protection: level 1 and level 2; details are in Table 4.1.

The workload is the second independent variable, and it is broken down into two categories: low and high. The exercise consisted of walking on a treadmill at a speed of 1.34 m/s with no grade at the light (30 min) workload and with a 10% grade at the high (20 min) workload [55].

On the other hand, this investigation has four dependent variables: temperature, relative humidity, the count of times the face mask and face cover are touched (to adjust, modify, or else), and the comfortability of each ensemble.

Table 4.1. PPE ensemble

PPE level	**Face mask**	**Face cover**
Level 1	Surgical mask	Face shield
Level 2	N95	Goggle

Table 4.2. Factors, levels, and treatment combination yields (Yij)

Workload, j →	**Low**	**High**
Protection Level, i ↓	**1**	**2**
1 Surgical mask – Face shield	Y11	Y12
2 Surgical mask – Goggle	Y21	Y22
3 N95 – Face shield	Y31	Y32
4 N95 – Goggle	Y41	Y42

Apparatus

In our investigation, to augment the authenticity of the simulation and replicate the actual conditions encountered in emergency procedures and everyday healthcare activities requiring proximate healthcare worker-patient interaction, we employed two specialized medical simulation devices: an IV access hand mannequin (Figure 4.2) and an intubation mannequin (Figure 4.3).

The IV arm, constructed from premium plastic and latex materials, ensures the reliability of this IV practice kit. It comes with an adjustable metal infusion stand for added convenience. Modeled closely after a human arm, this phlebotomy kit offers a highly realistic simulation.

Featuring two venous vessels with an accurate vein system and several puncture sites, it provides an ideal setup for practicing venipuncture techniques.

The intubation manikin is crafted to mimic the anatomical structure of the human body, featuring lifelike textures, consistent skin tone, and a realistic appearance. Successful intubation is indicated by lung expansion, accompanied by a light display and sound. Incorrect insertion into the esophagus triggers an alarm and light due to stomach inflation. Additionally, compressing the teeth activates a light-based warning. The manikin also allows for observation of pupil size differences between the normal side and the side with dilated pupils.

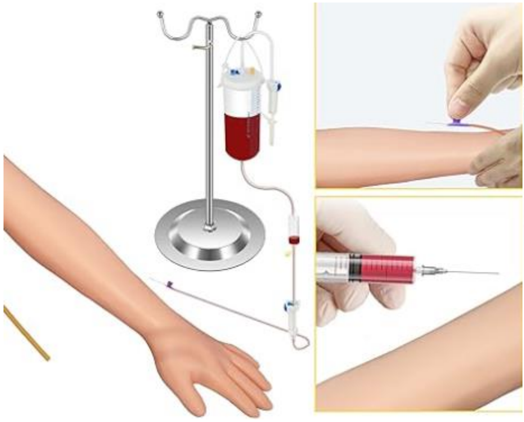


Figure 4.2. IV practice arm [59].

Figure 4.3. Intubation mannequin [60].

In this research, the face masks investigated included N95 masks, specifically focusing on the 3M 1860 (Cup) model and Level 1 surgical masks. Additionally, the study assessed the effectiveness of Clear Plastic Face Shields and Anti-Fog Protective Safety Goggles as types of face covers.

Experimental tasks and procedure

Participants visited the laboratory on nine distinct occasions spanning three weeks. One day was allocated for training, while the remaining visits corresponded to each experimental condition. The scheduling of participant sessions was designed to allow for adequate recovery periods and minimize the potential for carryover effects.

On the first day of the study, participants underwent a comprehensive session wherein the study protocol and objectives were elucidated. Following this, participants signed the consent form and completed a demographic survey. Subsequently, participants were familiarized with two simulated tasks, intubation and IV access, which they would be performing. The participants viewed a demonstration video detailing the intubation process, which was elucidated by the research team, and a hands-on demonstration on a manikin conducted by the research personnel. Subsequently, each participant engaged in ten intubation attempts, with the duration of each attempt and any errors incurred being meticulously recorded. This was succeeded by an instructional session on IV access, which included a video presentation and a detailed explanation by the research staff, culminating in a practical demonstration on a manikin hand. Finally, participants attempted IV access for twenty-five minutes, during which all errors were documented.

For the rest of the eight days, the session started with providing the participants with the PPE ensemble and sensor to stick inside the face mask. During this, the research staff started the sensor to begin logging data. The participants then provided their baseline comfort, difficulty, and anxiety.

Then, the participant went through a simulation session for one hour and a half or one hour and 20 minutes. The participants were asked to watch a video for 10 minutes, then walk on the treadmill (low, high), which ended with intubation and IV access procedures (counterbalance). After each task, the participants were asked to rate their comfort, difficulty, and anxiety. In addition, participants were given a break of two minutes between tasks.

Before and after each task was performed, the research team visually checked the face mask fitting. The total time for the experiment while wearing a face mask was 90 minutes for a low workload and 80 minutes for a high workload.

The study was video recorded for counting analysis and time estimation (take off the mask, touch it, modify it, etc.).

Data analysis

Data set

The data set that was included in model development is described below.

- PPE levels: four levels of PPE were included in the models, presented in table (4.1).
- Workload: The data set included two workloads (low and high) for each PPE level.
- Sensor components: for each PPE level and workload, temperature, relative humidity, and dew point. In addition, heat index and heating up slope were calculated and added to this category. (temperature; 3 components, humidity; 2 components, dew point; 2 components, heat index; 2 components).
- Sensation of discomfort: Participants were requested to assess their experiences of nine different discomfort sensations: humidity, heat, breathing resistance, itchiness, tightness, saltiness, feeling unfit, odor, and fatigue.
- PPE Impact Assessments: Participants were requested to evaluate their comfort, difficulty, and anxiety following each task to demonstrate the influence of PPE on

their ease, task difficulty, and task-related anxiety. These attributes comprise six components, encompassing average and maximum values for comfort, difficulty, and anxiety.

- Non-compliance: Non-compliance is measured by the number of instances of interaction between the PPE and the wearer.

Table 4.3. Summary statistics of non-compliance data. The non-compliance is a count.

Summary Statistics[*]	**Value**
Total number of subjects	14
Mean non-compliance	18.69
Standard deviation of non-compliance	15.11
Standard error mean of non-compliance	1.43
25th percentile of non-compliance	9
Median	14.5
75th percentile of non-compliance	23.75
Minimum non-compliance	0
Maximum non-compliance	86
PPE levels	4
Workload components	2
Number of sensation of discomfort	9
PPE Impact Assessments	6
Number of sensor components	9
Numbe**r** of observations	112

***before modeling**

Data preprocessing

Data preprocessing was conducted to ensure the data is meaningful and in a useful and efficient format for fitting machine learning models.

One-hot encoding. In this study, there is one categorical variable, which is the PPE level. Categorical variables were one-hot encoded. In the one-hot encoding method, each distinct category within a categorical variable is transformed into a distinct binary attribute within a newly formed column. Consequently, within every observation, a binary indicator of 1 is allocated to the attribute correlating with its original categorization, with all remaining attributes receiving a binary value of 0. This approach engenders the creation of a novel binary attribute for each potential category, thereby enhancing the precision of modeling and predictive analysis.

Z-score normalization. Given the wide variety of sensor data (encompassing temperature, relative humidity, dew point, heat index, and statistical measures such as average, standard deviation, maximum, minimum, mode, and median), it is critical to mitigate bias stemming from individual features. To this end, the z-score normalization method (Equation 1) was employed to standardize the values of all sensor-related variables. This normalization process rescales the variables to fit a standard normal distribution. This technique serves a dual purpose: it not only reduces bias but also enhances the numerical robustness of the model and expedites the training process. The formula rescales each variable to have a mean of 0 and a standard deviation of 1.

$$S_{i,j} = \frac{s_{i,j} - \overline{s_j}}{\sigma_j} \qquad (1)$$

Where:

$S_{i,j}$: the standardized value of the *i*th observation of the *j*th sensor variable,

$s_{i,j}$: the original value of the *i*th observation of the *j*th sensor variable,

$\overline{s_j}$: mean of the *j*th sensor variable,

σ_j: the standard deviation of the *j*th sensor variable,

j ranges from 1 to K, where K represents the total number of sensor variables, which in this case is 1008 (9 variables * 112 time periods).

Added features. New features were added to the data set. First, the heating-up slope was calculated and added to the data to represent the trend in the temperature data in the first few minutes after donning the PPE, which was not presented by the average, SD, mode, median, or maximum. The second feature is the heat index, calculated from temperature and relative humidity. Heat index, often called the "apparent temperature," is how hot it feels to the human body.

Missing values. In the data set, there was only one row of missing values related to one subject where the sensor failed to collect the corresponding data. The SimpleImputer class offers fundamental techniques for filling in missing values. It allows for replacing missing values with either a specified constant or by utilizing the statistics (mean, median, or mode) of each column where the missing values occur. In our study, missing values were imputed using the statistical method of mean.

Feature selection. Given the limited number of data points and the extensive array of input variables or predictors, it is crucial to employ feature selection to prevent overfitting and construct machine learning models that can generalize well. A two-step approach was adopted to identify the most vital and decisive features for predicting the target variable: initially, feature selection was conducted based on domain knowledge, followed by permutation feature selection using random forest.

Multicollinearity

The variance inflation factor (VIF) approach was employed to detect the degree of multicollinearity in a set of regression variables. Multicollinearity manifests when a regression model's independent variables display significant correlations, thereby potentially diminishing the statistical relevance of an individual independent variable. In scenarios where no predictors are correlated, the VIF values will uniformly be 1. VIF values greater than five are often considered multicollinear and may need further investigation or removal from the model. VIF is calculated using the following formula:

$$VIF_j = \frac{1}{1-R_J^2} \qquad (2)$$

b_j: estimated regression coefficient,

R_j^2: the R^2-value obtained by regressing the jth predictor on the remaining predictors,

VIF_j: the factor by which the variance of b_j is "inflated" by the existence of correlation among the predictor variables in the model.

Model development

This study employed linear regression, LASSO regression, and Random Forest to predict non-compliance.

Linear regression. Linear regression is a statistical and machine learning technique designed to predict a measurable outcome using one or more predictors based on the assumption of a linear relationship between the predictors (independent variables) and the response (dependent variable). It presupposes normal distribution of variables, absence of multicollinearity, and homoscedasticity (constant variance of error terms). This method is favored across various domains for predictive analysis, elucidating variable relationships, and trend identification, owing to its straightforwardness, ease of interpretation, and robust theoretical framework supporting it.

LASSO regression. LASSO regression, standing for Least Absolute Shrinkage and Selection Operator, is a linear regression method that incorporates regularization to prevent overfitting and simplify models, especially when dealing with data characterized by many features. This technique introduces an L1 penalty to the linear regression loss function, aiming to shrink some coefficients towards zero. Such regularization constrains coefficient estimates towards zero and facilitates in-built feature selection by excluding certain variables altogether, effectively setting their coefficients to zero. The strength of the L1 penalty, governed by the alpha parameter in sklearn’s Lasso function, plays a pivotal role in the model's complexity and interpretability; a higher alpha generally results in more coefficients being reduced to zero. In our research, we experimented with a spectrum of alpha values spanning [0.0, 10.01, 0.01]. Our findings indicated that setting alpha to 10 yielded the most favorable outcome.

Random forest. RF is an ensemble learning algorithm in machine learning that enhances prediction accuracy by combining the outcomes of multiple decision trees through a technique known as bagging. Bagging involves creating numerous subsets of the dataset through random sampling with replacement, allowing each tree to learn from a different data subset. This process is repeated multiple times, with the final prediction being an average of all tree predictions. This dual focus on reducing prediction bias and variance establishes the random forest as a robust and effective machine-learning algorithm. Our study identified that utilizing 150 trees within the RF model optimized prediction accuracy. Notably, further increasing the number of trees did not enhance accuracy and instead significantly extended training time. Additionally, our investigation into tree depth revealed that a maximum depth of 15 was ideal for achieving precise predictions. Adjusting tree depth profoundly affected accuracy, where increasing depth risked overfitting, and decreasing depth led to reduced accuracy.

Optimizing the hyperparameters of machine learning models and identifying the most effective models with the optimal settings of these parameters are essential for achieving superior prediction accuracy.

Hyperparameter settings leading to the highest performance on the validation set were chosen, and the associated model was then assessed on the test set to evaluate its capacity for generalization. Table 4.4 presents the hyperparameters tested and the optimal estimates achieved for the predictive models.

Table 4.4. Hyperparameters of the machine learning models employed to predict Non-compliance.

Method	**Hyperparameter**	**Best Parameter**
LR	-	-
LASSO	α (alpha)	10
RF	Maximum depth	15
	Number of estimators	150
	Min- sample split	2
	Min-sample-leaf	4

Performance metrics

In this study, the performance of our prediction models was evaluated using two widely used metrics: MAE and RMSE. Both metrics measure our models' accuracy and the deviation from the actual values. MAE measures the mean of the absolute difference between the predicted values and the actual values of the target variable (Equation 3). RMSE is the square root of the average of the squares of all errors (Equation 4). RMSE and MAE allowed us to assess the accuracy of the models and compare their performance relative to one another. Together, these metrics provide estimates of the error (RMSE, MAE).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \qquad (3)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \qquad (4)$$

Where:

n: the total number of data points,

y_i: the true value of the *i*th data point,

$\hat{y}_i$: the predicted value of the *i*th data point.

Results

Participants

Table 4.5. Participants' characteristic

Characteristic	**Values**
Participants (total)	14
Age (years)	
Mean	31.07
SD	7.16
Height (cm)	
Mean	177.71
SD	5.13
Weight (kg)	
Mean	88.69
SD	26.23
Gender (%)	
Male	92.86%
Female	7.14%
Other	0
Prefer not to respond	0
Hand dominating side (%)	
Right side	100
Left side	0
Both	0
Class standing (%)	
Freshman	0
Sophomore	0
Junior	0
Senior	14.3
Masters/Doctoral	85.7
Professional Student	0
Continuing Education Student	0
Non-degree seeking	0

Note: SD = Standard deviation

In this study, sixteen individuals volunteered to participate. However, data from two participants were omitted from the analysis due to incomplete data, which was attributed to their inability to attend all nine sessions and their failure to complete the treadmill walking task at the designated time and speed.

The analysis comprised a total of 14 participants, predominantly male. The average age of the participants was 31.07 years, with a standard deviation (SD) of 7.16 years. Regarding physical characteristics, the mean height was 177.71 cm (SD = 5.13 cm), and the average weight was 88.69 kg (SD = 26.23 kg). All participants identified their hand dominance as right-sided, with no individuals reporting left-sided or ambidextrous hand dominance. The characteristics of the participants are detailed in Table 4.5.

Initial screening (ANOVA model)

An initial evaluation was conducted to assess the impact of PPE, workload, and their combined effect on non-compliance. The normality of the non-compliance data was evaluated and did not meet the criteria (Figure 4.4). Consequently, the data was transformed to achieve normality. After transformation, the non-compliance data conformed to the normal distribution, as evidenced by a p-value > 0.05.

The findings indicated that the individual differences among subjects (as a random effect) did not have a significant impact on the log-transformed non-compliance (log(noncompliance+1)), as detailed in Table 4.7. Moreover, PPE, workload, and interaction effects were statistically non-significant, with all p-values > 0.05 (table 4.8).

Figure 4.5 represented the interaction plots of the workload and PPE. Based on the graphs, it shown that there are no significant effects of workload on non-compliance. Also, the PPE showed that it had no effect on non-compliance. However, it is shown that there is an interaction between N95-Faceshield and surgical mask-Face shield with the same interaction while wearing goggles.

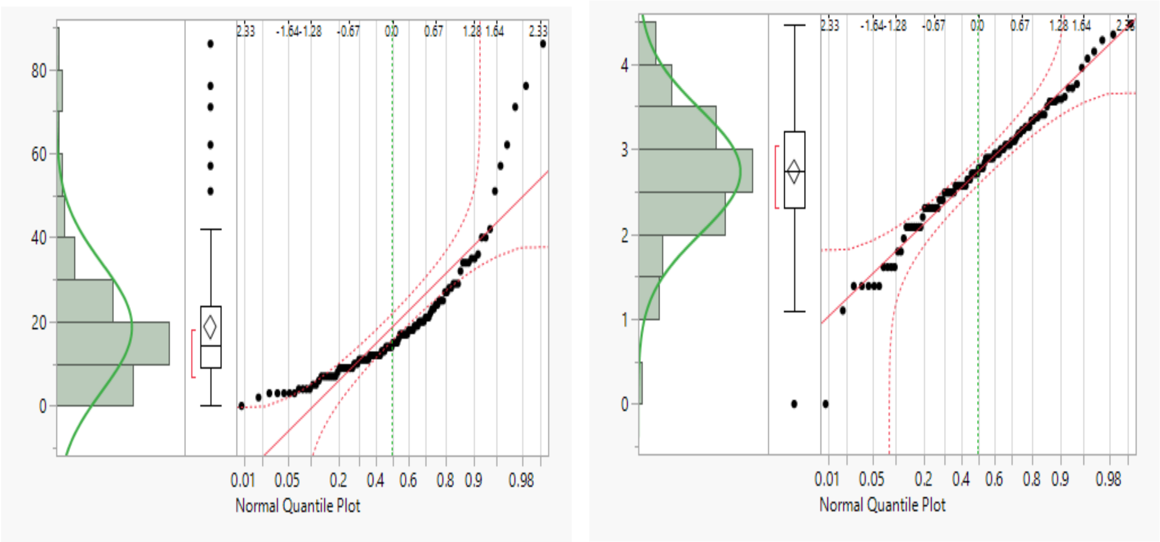


Figure 4.4. Normality check for Non-compliance (right) and log(Non-compliance+1) (left)

Table 4.6. Random effect predictions

Term	BLUP	Std Error	DFDen	t Ratio	Prob>|t|
subject	-0.016232	0.01291	2.491	-1.26	.3136

Table 4.7. REML variance component estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
subject	0.0008687	0.0004301	0.0009938	-0.001518	0.002378	.6651	0.087
Residual		0.4951741	0.0690008	0.3835537	0.6640263		99.913
Total		0.4956042	0.0689701	0.3840074	0.6643281		100.000

Table 4.8. Fixed effect tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
PPE	3	3	103	1.6078	.1921
workload	1	1	103	2.7833	.0983
PPE*workload	3	3	103	0.8172	.4872

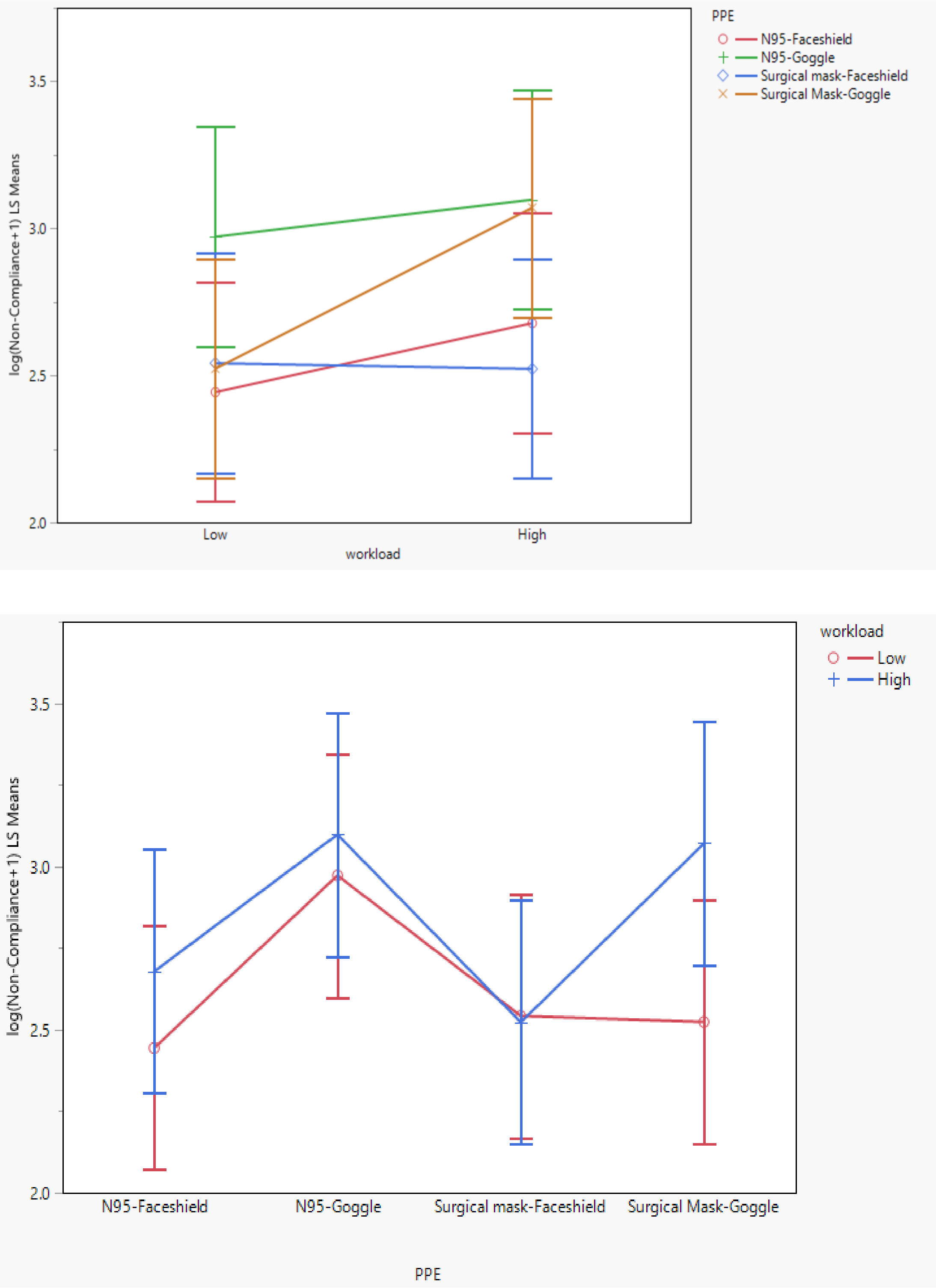


Figure 4.5. Least Square Mean Plots by Workload (Top) and by PPE (Down)

The effect of PPE, workload, and their combined influence on temperature was evaluated to examine our hypothesis. The normality of the temperature data was analyzed and found to comply with the required criteria, as depicted in Figure 4.6.

The findings indicated that the individual differences among subjects (as a random effect) did not significantly impact the temperature as detailed in Table 4.9. Moreover, workload and interaction effects of PPE and workload were statistically non-significant, with all p-values > 0.05 (table 4.10). PPE significantly impacted temperature accumulation inside various face masks, with a p-value < 0.05 indicating statistical significance.

Figure 4.7 represented the interaction plots of the workload and PPE. Based on the graphs, it shown that there are significant effects of PPE on temperature. Also, the workload showed that it does not affect temperature. Table 4.11 illustrates that there is a significant difference in temperature accumulation when wearing an N95 mask compared to a surgical mask, regardless of whether it is combined with a face shield or goggles, for both low and high workloads.

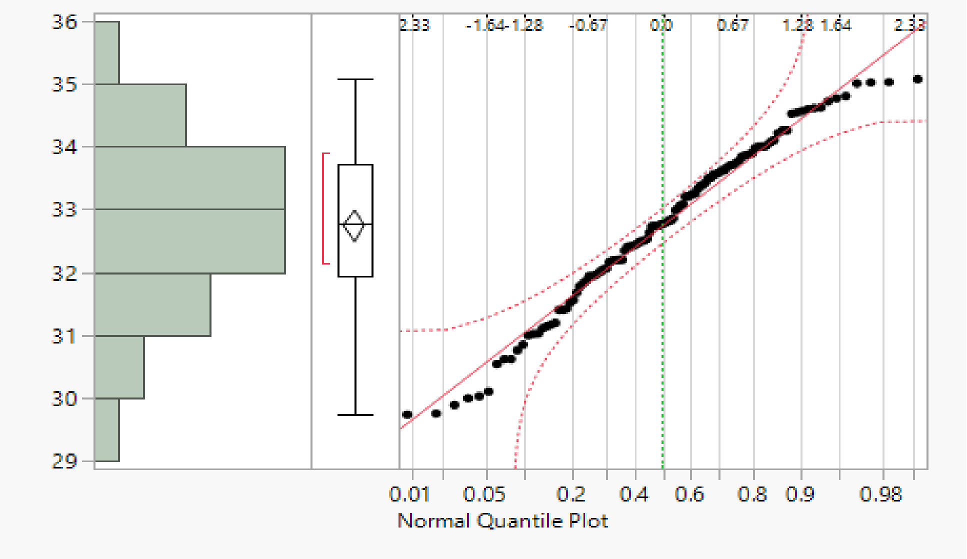


Figure 4.6. Histograms, boxplot, and Normal quantile plot of temperature

Table 4.9. REML variance component estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
subject	0.0289241	0.0168189	0.0242373	-0.030685	0.0643232	.4877	2.811
Residual		0.581482	0.0810275	0.4504064	0.7797649		97.189
Total		0.5983009	0.0845322	0.4618963	0.805852		100.000

Table 4.10. Fixed effect tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
PPE	3	3	103	28.9912	**<.0001***
workload	1	1	103	1.6020	0.2085
PPE*workload	3	3	103	0.1957	0.8991

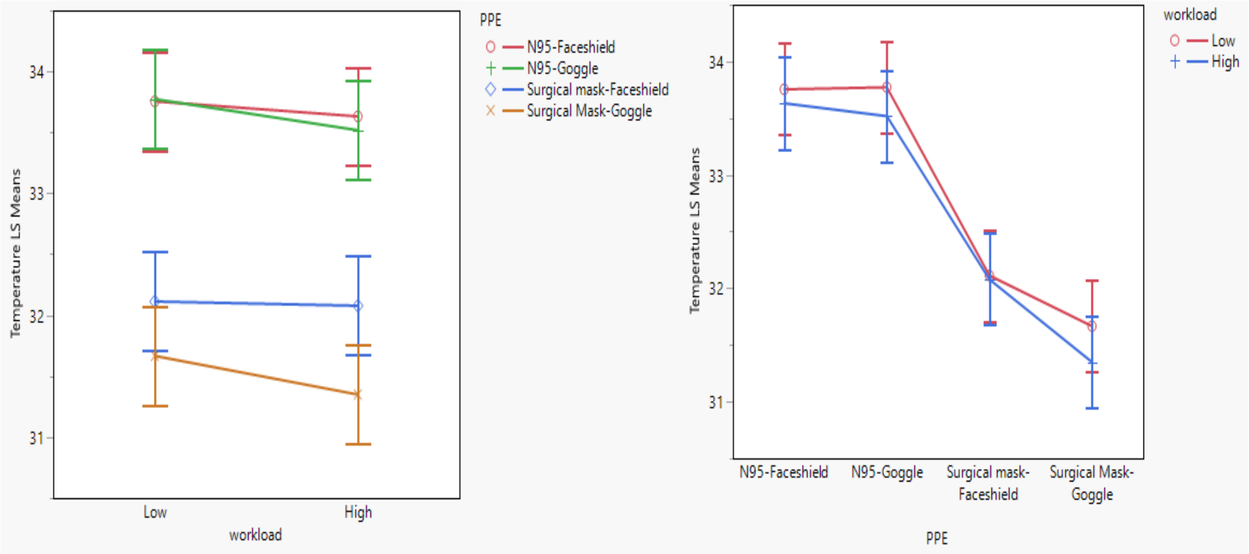
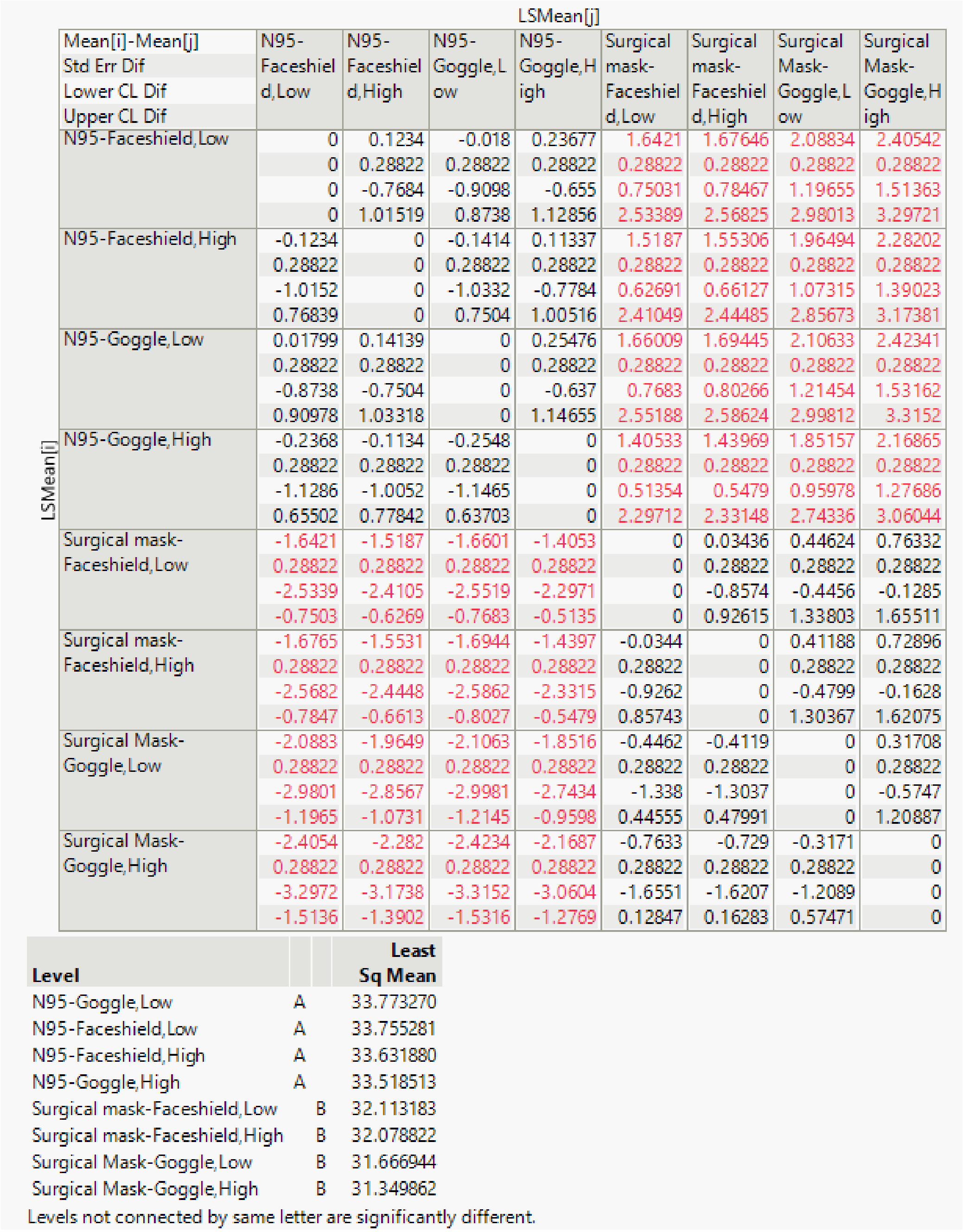


Figure 4.7. Least Square Mean Plots by Workload (Right) and by PPE (Left)

Table 4.11. LSMeans Differences Tukey HSD



LSMean[j]

LSMean[i]	Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	N95-Faceshield,Low	N95-Faceshield,High	N95-Goggle,Low	N95-Goggle,High	Surgical mask-Faceshield,Low	Surgical mask-Faceshield,High	Surgical Mask-Goggle,Low	Surgical Mask-Goggle,High
	N95-Faceshield,Low	0	0.1234	-0.018	0.23677	1.6421	1.67646	2.08834	2.40542
		0	0.28822	0.28822	0.28822	0.28822	0.28822	0.28822	0.28822
		0	-0.7684	-0.9098	-0.655	0.75031	0.78467	1.19655	1.51363
		0	1.01519	0.8738	1.12856	2.53389	2.56825	2.98013	3.29721
	N95-Faceshield,High	-0.1234	0	-0.1414	0.11337	1.5187	1.55306	1.96494	2.28202
		0.28822	0	0.28822	0.28822	0.28822	0.28822	0.28822	0.28822
		-1.0152	0	-1.0332	-0.7784	0.62691	0.66127	1.07315	1.39023
		0.76839	0	0.7504	1.00516	2.41049	2.44485	2.85673	3.17381
	N95-Goggle,Low	0.01799	0.14139	0	0.25476	1.66009	1.69445	2.10633	2.42341
		0.28822	0.28822	0	0.28822	0.28822	0.28822	0.28822	0.28822
		-0.8738	-0.7504	0	-0.637	0.7683	0.80266	1.21454	1.53162
		0.90978	1.03318	0	1.14655	2.55188	2.58624	2.99812	3.3152
	N95-Goggle,High	-0.2368	-0.1134	-0.2548	0	1.40533	1.43969	1.85157	2.16865
		0.28822	0.28822	0.28822	0	0.28822	0.28822	0.28822	0.28822
		-1.1286	-1.0052	-1.1465	0	0.51354	0.5479	0.95978	1.27686
		0.65502	0.77842	0.63703	0	2.29712	2.33148	2.74336	3.06044
	Surgical mask-Faceshield,Low	-1.6421	-1.5187	-1.6601	-1.4053	0	0.03436	0.44624	0.76332
		0.28822	0.28822	0.28822	0.28822	0	0.28822	0.28822	0.28822
		-2.5339	-2.4105	-2.5519	-2.2971	0	-0.8574	-0.4456	-0.1285
		-0.7503	-0.6269	-0.7683	-0.5135	0	0.92615	1.33803	1.65511
	Surgical mask-Faceshield,High	-1.6765	-1.5531	-1.6944	-1.4397	-0.0344	0	0.41188	0.72896
		0.28822	0.28822	0.28822	0.28822	0.28822	0	0.28822	0.28822
		-2.5682	-2.4448	-2.5862	-2.3315	-0.9262	0	-0.4799	-0.1628
		-0.7847	-0.6613	-0.8027	-0.5479	0.85743	0	1.30367	1.62075
	Surgical Mask-Goggle,Low	-2.0883	-1.9649	-2.1063	-1.8516	-0.4462	-0.4119	0	0.31708
		0.28822	0.28822	0.28822	0.28822	0.28822	0.28822	0	0.28822
		-2.9801	-2.8567	-2.9981	-2.7434	-1.338	-1.3037	0	-0.5747
		-1.1965	-1.0731	-1.2145	-0.9598	0.44555	0.47991	0	1.20887
	Surgical Mask-Goggle,High	-2.4054	-2.282	-2.4234	-2.1687	-0.7633	-0.729	-0.3171	0
		0.28822	0.28822	0.28822	0.28822	0.28822	0.28822	0.28822	0
		-3.2972	-3.1738	-3.3152	-3.0604	-1.6551	-1.6207	-1.2089	0
		-1.5136	-1.3902	-1.5316	-1.2769	0.12847	0.16283	0.57471	0

Level			**Least Sq Mean**
N95-Goggle,Low	A		33.773270
N95-Faceshield,Low	A		33.755281
N95-Faceshield,High	A		33.631880
N95-Goggle,High	A		33.518513
Surgical mask-Faceshield,Low		B	32.113183
Surgical mask-Faceshield,High		B	32.078822
Surgical Mask-Goggle,Low		B	31.666944
Surgical Mask-Goggle,High		B	31.349862

Levels not connected by same letter are significantly different.

An initial analysis was conducted to investigate the effects of PPE, workload, and their joint impact on relative humidity. The normality of the relative humidity data was evaluated and confirmed to satisfy the established criteria, as shown in Figure 4.8.

The findings indicated that the individual differences among subjects (as a random effect) did not significantly impact the relative humidity, as detailed in Table 4.12. Moreover, PPE, workload, and interaction effects of PPE and workload were statistically non-significant, with all p-values > 0.05 (table 4.13).

Figure 4.9 represented the workload and PPE interaction plots on relative humidity. It showed that relative humidity is higher for all PPE ensembles at a high workload than a low one.

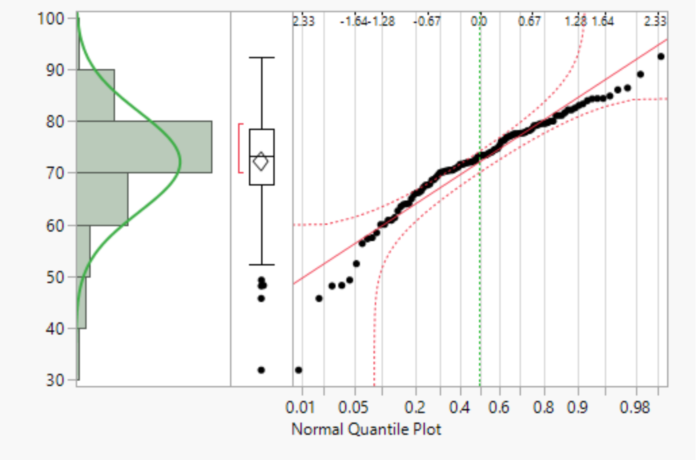


Figure 4.8. Histograms, boxplot, and Normal quantile plot of humidity

Table 4.12. REML variance component estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
subject	0.0011145	0.1012067	0.213803	-0.31784	0.5202529	.6360	0.111
Residual		90.808692	12.653883	70.338918	121.77406		99.889
Total		90.909898	12.648735	70.442881	121.8514		100.000

Table 4.13. Fixed effect tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
PPE	3	3	103	2.1664	.0965
workload	1	1	103	1.3961	.2401
PPE*workload	3	3	103	1.5795	.1989

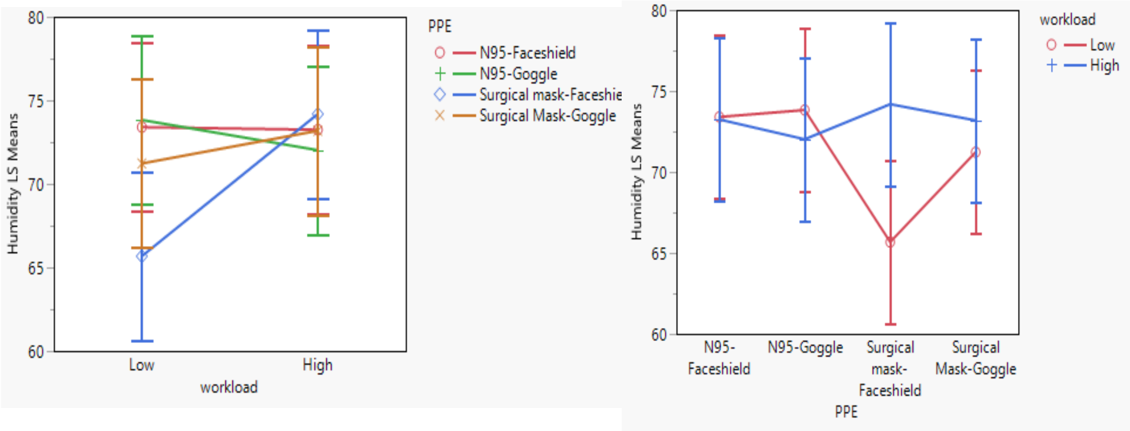


Figure 4.9. Least Square Mean Plots by Workload (Right) and by PPE (Left)

Multicollinearity

The initial analysis with 28 predictors revealed significant correlations, as indicated by a VIF greater than 5, detailed in Table (4.14). Subsequent iterations were conducted to remove highly correlated predictors, resulting in a refined list of 21 predictors. Notably, a strong correlation was observed between maximum temperature, dew point mode, and heat index mode, which was anticipated since the heat index calculations incorporate both temperature and humidity. Both scenarios were incorporated during the later stages of model development to ascertain the more effective model in predicting non-compliance. All VIF iterations are shown in Appendix 2.

Table 4.14. VIF results for all predictors

Feature	VIF
workload	1.564081
humid	4.358498
hot	4.956056
breathresistance	3.318861
itchy	2.908397
tight	3.14755
salty	3.627457
unfit	2.301397
odour	4.084409
fatigue	2.960623
maximumcomfort	**6.36205**
averagecomfort	**6.736292**
maximumdifficulty	**5.559783**
averagedifficulty	**6.971667**
maximumanxiety	**10.58905**
averageanxiety	**10.09255**
averagetemperature	**29.88692**
maximumtemperature	**21.30715**
heatingupslope	1.392605
averagehumidity	**12.4573**
sdhimidity	2.240044
averageheatindex	**35.1564**
modeheatindex	4.257549
averagedewpoint	**40.58915**
modedewpoint	**17.16978**
PPE_N95-Faceshield	inf
PPE_N95-Goggle	inf
PPE_Surgical Mask-Goggle	inf
PPE_Surgical mask-Faceshield	inf

Table 4.15. VIF results after removing correlated variables

Feature	VIF
Workload	1.517981
Humid	4.103396
Hot	4.29843
breathresistance	3.092679
Itchy	2.667624
Tight	2.816349
Salty	3.494716
Unfit	2.200021
Odour	3.658835

Table 4.15. Continued

Feature	VIF
Fatigue	2.540361
maximumcomfort	3.062811
maximumdifficulty	2.59394
maximumanxiety	1.98079
averagetemperature	3.619553
heatingupslope	1.2322
sdhimidity	1.456364
modedewpoint	1.606444
PPE_N95-Faceshield	inf
PPE_N95-Goggle	inf
PPE_Surgical Mask-Goggle	inf
PPE_Surgical mask-Faceshield	inf

Prediction results

Table 4.16. Performance analysis for different models on test data

Predictors	**Metrics**		**Regression models**	
		LR	**LASSO**	**RF**
			Mean (SD)	
All predicators	RMSE	16.809 (3.98)	14.177(3.71)	13.582 (3.23)
	MAE	12.257 (2.35)	9.935 (1.76)	9.477 (1.71)
Removing 1	RMSE	16.806 (3.97)	14.177 (3.7)	13.591 (3.17)
	MAE	11.988 (2.27)	9.934 (1.77)	9.464 (1.74)
Removing 2	RMSE	16.202 (3.38)	14.177 (3.71)	13.71 (3.17)
	MAE	11.850 (2.10)	9.935 (1.77)	9.709 (1.71)
Removing 3 + 2	RMSE	14.905 (2.61)	14.177 (3.71)	13.714 (3.14)
	MAE	10.964 (1.75)	9.935 (1.77)	9.702 (1.76)
Removing 4 + 2	RMSE	14.904 (2.611)	14.177 (3.71)	13.828 (3.17)
	MAE	10.974 (1.75)	9.935 (1.77)	9.838 (1.77)
Removing 4 + 2 + SD humidity	RMSE	14.979 (2.48)	14.177 (3.71)	14.022 (3.19)
	MAE	11.156 (1.76)	9.935 (1.77)	9.998 (1.74)
Removing 3 + 2 + max difficulty	RMSE	14.798 (2.72)	14.177 (3.711)	13.655 (3.18)
	MAE	10.865 (1.77)	9.934 (1.77)	9.655 (1.77)
Feature selected	RMSE	14.245 (2.81)	14.177 (3.71)	13.501 (3.22)
	MAE	10.126 (1.17)	9.935 (1.17)	9.445 (1.17)

1 'maximumcomfort', 'maximumdifficulty', 'maximumanxiety'
2 'averagecomfort', 'averagedifficulty', 'averageanxiety'
3'averagedewpoint','modedewpoint','averageheatindex','averagetemperature', 'maximumtemperature','averagehumidity'
4 'modeheatindex','averagedewpoint','averageheatindex', 'averagetemperature', 'averagehumidity'

The optimal hyperparameters identified through tuning were used to train and evaluate three models. Their performance in predicting non-compliance was assessed using the test metrics RMSE and MAE, with the findings in Table 4.16.

Table 4.16 outlines the performance of eight trials, arranging the results in descending order from models that include all predictors to the final model with the selected predictors. In all trials, RF outperformed the LR and LASSO models in lower RMSE and MAE.

Figure (4.10) illustrated a comparison of actual versus predicted values through scatter plots for the LR, LASSO, and RF models. The scatter plot of the LR model displayed a wide dispersion of data points, signifying it has the most prediction error out of the three. On the other hand, the LASSO model showed a moderate scatter, placing it between the LR and RF models in terms of prediction accuracy. The scatter plot for the RF model demonstrated data points that are most densely clustered around the prediction line, indicating superior predictive performance and a closer agreement between predicted and actual values. This comparison leads to the inference that the Random Forest model is likely the most accurate in predicting non-compliance, followed by the LASSO model, with the Linear Regression model showing the least accuracy in this specific dataset.

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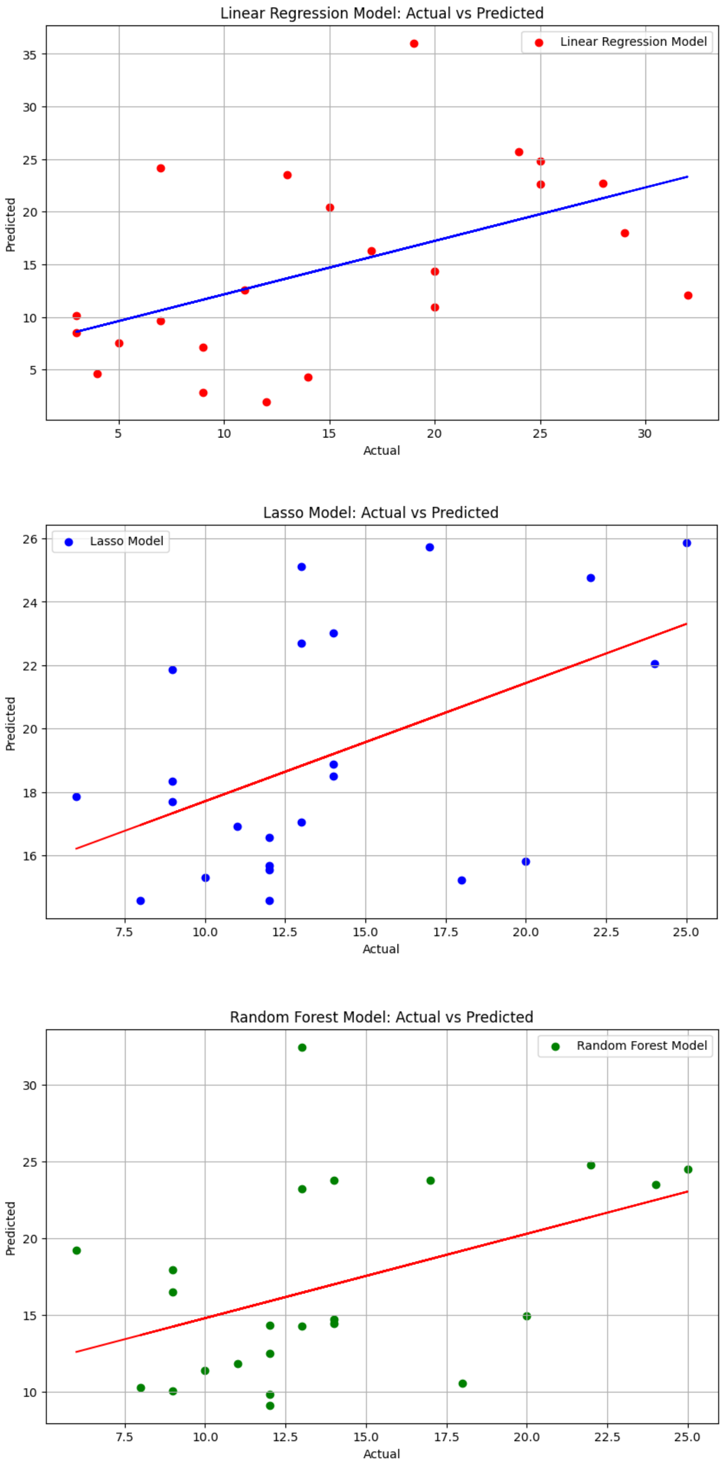

Figure 4.10. Comparison of Actual vs. Predicted Values for Three Regression Models. LR (top), LASSO (middle), and RF (bottom).

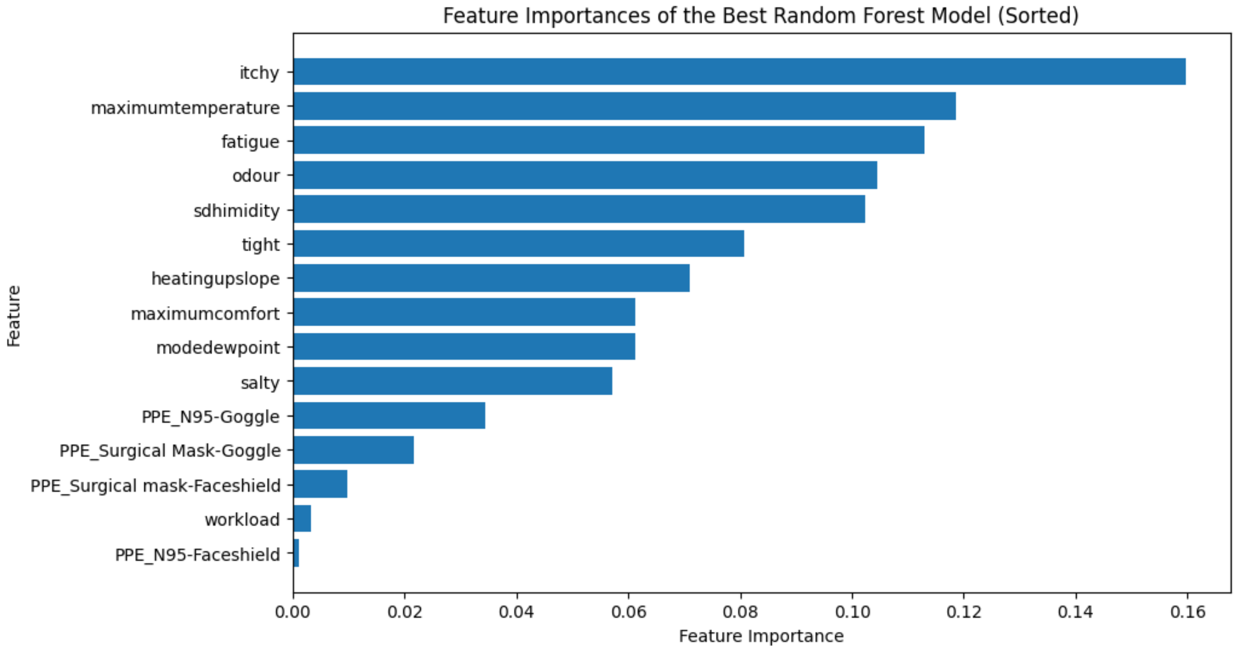

Figure 4.11. Feature Importance of the best RF model

The bar chart (Figure 4.11) represented the sorted feature importances determined by the best-performing RF model. The most influential feature appears to be 'itchy,' with relative importance significantly higher than the others, indicating that it plays a crucial role in the model's predictions. Other notable features include 'sdhumidity', 'maximumtemperature', and 'fatigue', which exhibit moderate importance. Features such as 'odour', 'salty', and 'maximumcomfort' also contribute to the model's decision-making but to a lesser extent. Noteworthy is the presence of several types of PPE, like 'PPE_N95-Goggle', 'PPE_Surgical Mask-Goggle', and 'PPE_N95-Faceshield', which suggests their relevance in the context of the model's application. The importance of 'workload' is relatively lower but still relevant. Collectively, this model's feature importance profile assists in understanding the predictors that most significantly impact non-compliance, which can be valuable for refining the model and focusing on key variables for future data collection and analysis.

One-way ANOVA of MAE

Figure 4.12 presented a Normal Quantile Plot (or Q-Q plot) paired with a histogram and box plot, utilized to evaluate the normality of the MAE from a dataset. From the Q-Q plot, it suggested that the MAE values are normally distributed.

The p-value is 0.0232, which is < 0.05, suggesting a statistically significant difference between the mean responses for the different model types (Table 4.17). A post hoc analysis using Dunnett's test (Table 4.19) revealed that the MAE for the LR model differs significantly from the RF model. However, the MAEs of the RF and LASSO models did not show any significant differences.

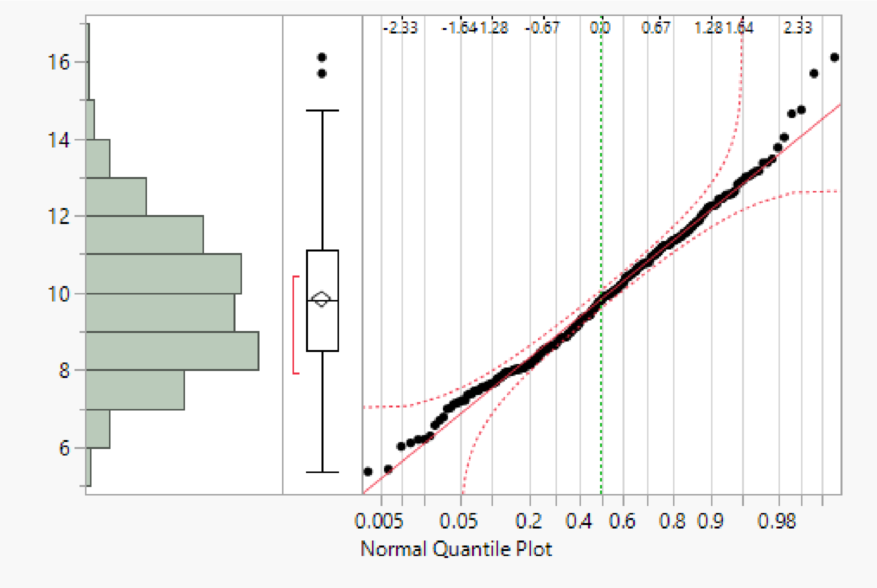

Figure 4.12. Normality checks of the MAE

Table 4.17. ANOVA of MAE for 100 iterations

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model type	2	24.68885	12.3444	3.8111	.0232*
Error	297	961.99779	3.2390		
C. Total	299	986.68664			

Table 4.18. Means of One-way ANOVA

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
LASSO	100	9.9348	0.17997	9.5806	10.289
LR	100	10.1269	0.17997	9.7727	10.481
RF	100	9.4455	0.17997	9.0913	9.800

Table 4.19. LSD threshold matrix (Dunnett's Method)

Level	Abs(Dif)-LSD	p-Value
LR	0.116	**.0149***
LASSO	-0.08	.1002
RF	-0.57	1.00

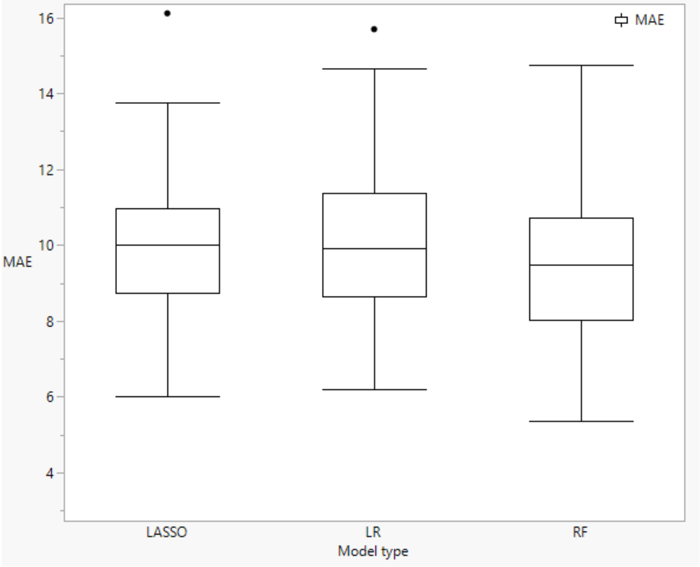

Figure 4.13. Boxplot of MAE means for different models for 100 iterations

The boxplot in Figure (4.13) illustrates the distribution of MAE values for the LR, LASSO, and RF models for 100 iterations. From the boxplots, it seems that the LASSO and RF models have a similar range of MAE scores, with the median for LASSO being slightly higher than for RF, indicating that the RF model may have a slight edge in predictive accuracy. The LR model shows a broader interquartile range, suggesting more variability in its MAE scores across different trials. All models have outliers indicating instances where the MAE was notably higher than typical for the model.

Discussion

We introduced a predictive model for non-compliance among healthcare personnel in direct patient contact. Prior to the model development, we investigated the effect of the PPE and workload on non-compliance and found no statistical significance. Later in the model, we added other variables besides the PPE and workload to predict the non-compliance.

The findings indicate that non-compliance with protective gear was unaffected by the level of protection or workload. This could be attributed to several factors. For instance, goggles and face shields might fog up, and masks may slip, compromising visibility and communication. Consequently, individuals may frequently adjust their personal PPE to ensure clear sight and effective communication, particularly in critical areas like healthcare settings. The performance of PPE is not only contingent on its quality but also on its fit. Ill-fitting masks, goggles, or face shields may require regular adjustments to remain secure or provide a proper seal. This underscores the necessity for PPE that fits various face shapes and sizes. In scenarios with high workloads, individuals might focus more on completing tasks rather than the minor discomforts caused by PPE, leading to fewer adjustments. Those working in demanding or stressful environments typically build resilience and adaptability, learning to manage any discomfort from PPE without neglecting compliance. Ultimately, job requirements might encourage a culture of compliance and adaptation out of necessity.

In addition, it shown that the temperature builds up inside the mask significantly affected by the protection level, which coincided with the previous research [56], [57], [58]. A higher temperature level was significantly built up inside the N95 compared to surgical masks for both low and high workloads. No effect of PPE protection level and workload was found on the relative humidity.

To the best of our knowledge, this research is pioneering in that it designs a simulated experiment, gathers data, characterizes non-compliance, and then constructs a model to predict it. This research revealed that factors influencing non-compliance extend beyond using PPE and workload. It was found that the perceived comfort of PPE and sensation of discomfort, including feelings of itchiness, fatigue, odour, saltiness, and tightness, significantly contribute to non-compliance behavior. Moreover, the study highlighted that the build-up of temperature and relative humidity within the confines of a face mask contributes to the likelihood of non-compliance. In addition, the results showed that the temperature was statistically significantly higher in higher PPE levels but not affected by the workload. On the other hand, there was no significant humidity build-up inside the face mask under different workloads.

In expanding upon this, it is noteworthy that the study underscores the multifaceted nature of non-compliance determinants, suggesting that an interplay of physical discomfort, sensory perception, and environmental conditions within PPE can influence healthcare workers' adherence to safety protocols. The findings indicate the necessity for designing PPE that balances protective function with wearer comfort to mitigate these issues and enhance compliance rates.

The Random Forest model consistently outperformed the LR and LASSO models in all metrics across 100 iterations. The RF model provides more accurate predictions (as shown by RMSE and MAE).

Literature underscores that extended wear of face masks can lead to discomfort and both physiological and psychological effects, potentially reducing compliance towards the end of a shift ([199], [200], [201], [202]). The figure corroborates this, with 'maximumtemperature' being a significant predictor, aligning with thermal stress burden identified as a primary cause of discomfort ([118], [120]). Other sensory discomforts such as 'itchy,' 'fatigue,' 'odour,' and 'salty' are reflected in the figure as factors of importance, which could relate to the additional discomfort factors cited in the literature, like skin irritation and difficulty in breathing ([67], [203], [204]).

Further literature review reveals individual factors like work experience ([48], [56], [97], [96]), discomfort ([54], [57], [58]), poor fit ([54], [57], [58]), and the need to compete and prove expertise ([49]), which may not be directly reflected in the figure but are crucial for understanding compliance. Workload, indicated as 'workload' in the figure, has also been shown to influence PPE compliance significantly ([78], [82], [84], [85], [86], [87], [88], [89], [90], [91]), suggesting that high-stress environments can compromise PPE adherence. Gender, occupation ([97], [96]), and perceptions of PPE's effectiveness ([99], [100]) are additional factors that shape compliance but may not be captured in the feature importance graph.

When combining the empirical data from the graph with the insights from the literature, it is evident that both sources highlight the role of discomfort and sensory challenges as critical factors in PPE non-compliance. The importance of temperature-related discomfort is particularly noteworthy, as it is a significant factor in the model and is emphasized in the literature as a primary cause of discomfort. Thus, addressing the physical and sensory discomfort associated with PPE, especially in high-stress work environments, is essential for improving compliance rates. This could involve developing PPE with better breathability, enhanced comfort, or features that mitigate heat buildup and sensory irritation, fostering a more tolerable and compliant usage of protective gear.

Conclusion

In summary, our MPENC effectively predicts instances of non-compliance with PPE, encompassing face masks and face shields, among healthcare workers (HCWs) operating in environments requiring close patient interaction under varying workloads. The model emphasizes the significance of sensory discomfort and thermal stress as key influencers of PPE adherence. This highlights the critical baseline factors associated with PPE non-compliance, offering valuable insights for developing strategies to enhance compliance. These findings could steer interventions to mitigate discomfort and manage thermal burden, promoting sustained PPE usage and enhancing protective measures among HCWs.

Application

The findings of this research, specifically the prediction of non-compliance, are relevant across various healthcare domains that involve close patient interaction and necessitate the use of PPE like face masks and covers. For instance, in nearly all surgical procedures, face masks and face shields are essential to safeguard the medical team from blood-borne pathogens. Similarly, face masks and shields are crucial for protecting dentists from aerosols and splatter during dental treatments, particularly those involving drilling or oral surgery. The ability to predict non-compliance extends beyond the operating room to potentially urgent and high-risk situations such as cricothyrotomy or emergency tracheostomy.

Additionally, face masks and coverings can be essential even in tasks that do not involve direct patient interaction, such as when technicians handle and process blood, urine, sputum, or other body fluids in a laboratory setting, offering protection against potentially infectious or hazardous substances.

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Appendix 1: IRB approval memo

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office of Research Ethics
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 09/12/2023

To: Fatima Mgaedeh Richard T Stone

From: Office of Research Ethics

Title: ASSESSMENT AND PREDICTION OF COMPLIANCE WITH PROTECTIVE EQUIPMENT AND WORKLOADS AMONG HEALTHCARE WORKERS

IRB ID: 23-220

Submission Type: Initial Submission **Review Type:** Expedited

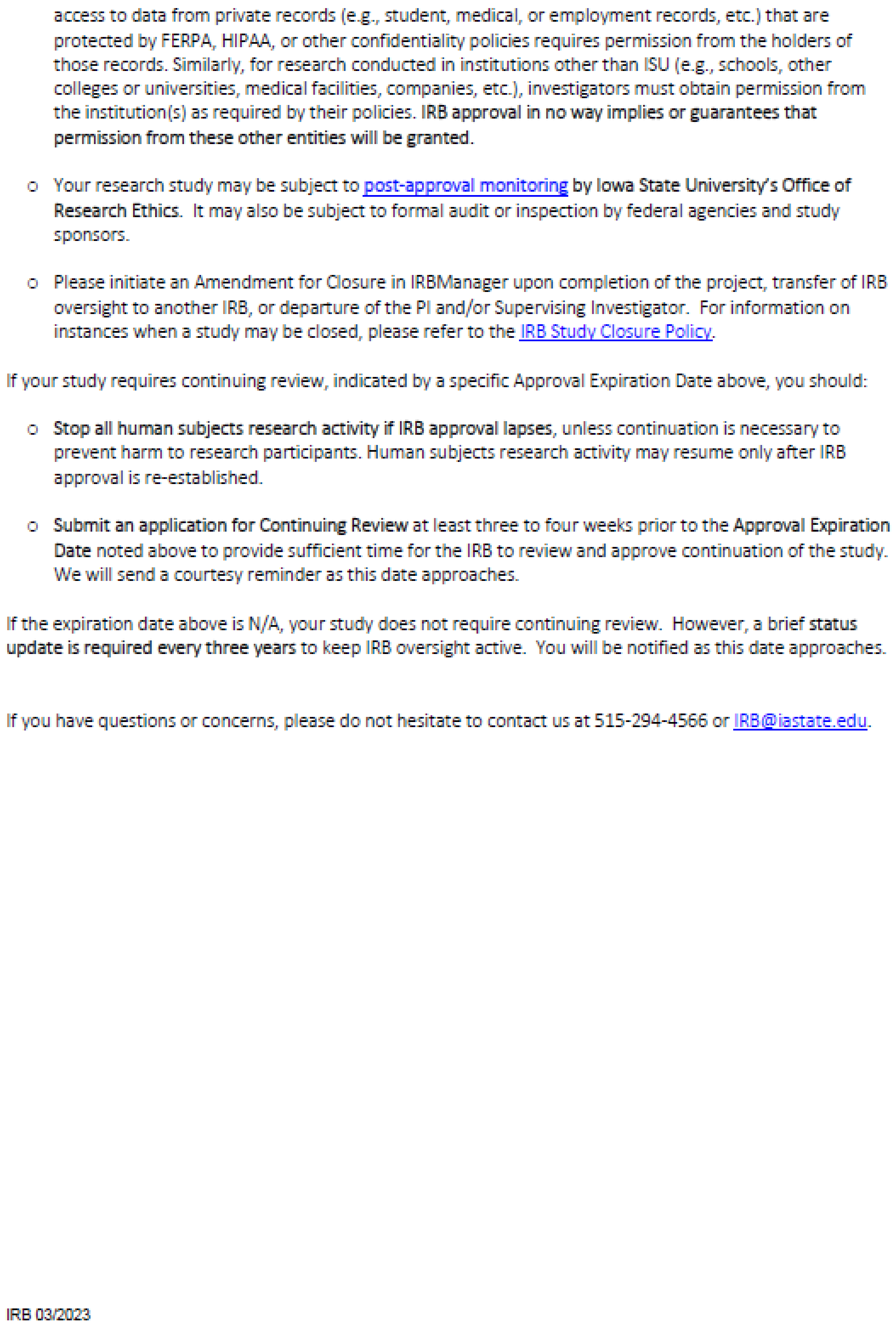
Approval Date: 09/12/2023 **Approval Expiration Date:** N/A

The research project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials, including the recruitment materials and informed consent documents that have the IRB approval stamp.**
- Retain signed informed consent documents **for 3 years after study closure** when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study or study materials, including **addition or removal of study personnel or changes to their institutional affiliation.** Approval of personnel applies only to their institutional affiliation indicated in the most recent approved application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of this project applies only to funding sources that are specifically named in the corresponding IRB application.
- **Immediately inform the IRB of (1) all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks to subjects or others.**
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example,

IRB 03/2023



access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to post-approval monitoring **by Iowa State University's Office of Research Ethics.** It may also be subject to formal audit or inspection by federal agencies and study sponsors.

- Please initiate an Amendment for Closure in IRBManager upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity may resume only after IRB approval is re-established.

- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

If the expiration date above is N/A, your study does not require continuing review. However, a brief **status update is required every three years** to keep IRB oversight active. You will be notified as this date approaches.

If you have questions or concerns, please do not hesitate to contact us at 515-294-4566 or IRB@iastate.edu.

Appendix 2: VIF results for all iterations

Feature	VIF
workload	1.517981
humid	4.103396
hot	4.29843
breathresistance	3.092679
itchy	2.667624
tight	2.816349
salty	3.494716
unfit	2.200021
odour	3.658835
fatigue	2.540361
maximumcomfort	3.062811
maximumdifficulty	2.59394
maximumanxiety	1.98079
averagetemperature	3.619553
heatingupslope	1.2322
sdhimidity	1.456364
modedewpoint	1.606444
PPE_N95-Faceshield	inf
PPE_N95-Goggle	inf
PPE_Surgical Mask-Goggle	inf
PPE_Surgical mask-Faceshield	inf

Feature	VIF
workload	1.486519
humid	4.071998
hot	4.094792
breathresistance	3.075983
itchy	2.63953
tight	2.820047
salty	3.447783
unfit	2.176311
odour	3.614389
fatigue	2.489686
maximumcomfort	3.024352
maximumdifficulty	2.580175
maximumanxiety	1.881043
heatingupslope	1.228338
sdhimidity	1.627829
averageheatindex	2.317429
PPE_N95-Faceshield	inf
PPE_N95-Goggle	inf
PPE_Surgical Mask-Goggle	inf
PPE_Surgical mask-Faceshield	inf

Feature	VIF
workload	1.485439
humid	4.161536
hot	4.072343
breathresistance	3.073493
itchy	2.57178
tight	2.811266
salty	3.464013
unfit	2.181886
odour	3.663729
fatigue	2.592006
maximumcomfort	3.057707
maximumdifficulty	2.596442
maximumanxiety	1.891837
heatingupslope	1.218085
sdhimidity	1.61751
modeheatindex	1.915354
PPE_N95-Faceshield	inf
PPE_N95-Goggle	inf
PPE_Surgical Mask-Goggle	inf
PPE_Surgical mask-Faceshield	inf

Feature	VIF
workload	1.514955
humid	4.083096
hot	4.255648
breathresistance	3.119661
itchy	2.682759
tight	2.818197
salty	3.497537
unfit	2.210287
odour	3.661012
fatigue	2.484525
maximumcomfort	3.060503
maximumdifficulty	2.62674
maximumanxiety	1.977586
maximumtemperature	3.173392
heatingupslope	1.244369
sdhimidity	1.442839
modedewpoint	1.661227
PPE_N95-Faceshield	inf
PPE_N95-Goggle	inf
PPE_Surgical Mask-Goggle	inf
PPE_Surgical mask-Faceshield	inf

Feature	VIF
workload	1.504674
humid	4.114739
hot	4.309511
breathresistance	3.096666
itchy	2.666995
tight	2.819002
salty	3.478408
unfit	2.196266
odour	3.668578
fatigue	2.540279
maximumcomfort	3.034384
maximumdifficulty	2.595178
maximumanxiety	1.979368
averagetemperature	3.841536
heatingupslope	1.235274
sdhimidity	1.617107
averagedewpoint	1.94719
PPE_N95-Faceshield	inf
PPE_N95-Goggle	inf
PPE_Surgical Mask-Goggle	inf

CHAPTER 5. GENERAL CONCLUSIONS

This dissertation delved into two critical areas identified through a comprehensive literature review: the emerging practice of double masking and the prevailing attitudes of non-compliance with PPE.

The recent pandemic and evolving COVID variants prompted recommendations for double masking as a preventive measure. However, these recommendations were made without fully considering the potential for lower compliance. This oversight becomes significant in light of existing literature on the adverse effects of single mask use. Research had documented the negative impact of using just one face mask on various aspects of human functioning, including its users' psychological, physiological, visual, motor, and cognitive capabilities. This evidence highlighted the need for a more nuanced approach to PPE compliance. Moreover, while the literature extensively investigated PPE compliance from broad perspectives, including organizational and individual reasons, it often overlooks the initial interaction between the PPE and the user. Such interaction is crucial, as the proven effects of single mask use on user capacities may directly influence compliance rates, especially with intensified measures like double masking.

A within-subject experimental study was designed to investigate the impacts of double masking on individuals' physical and cognitive capabilities, comfort levels, and anxiety spanned over four visits (no mask, surgical mask, cloth mask, and surgical mask doubled with cloth mask). Findings from this investigation suggested a notable impediment to cognitive performance attributable to donning face masks. Furthermore, it was found that the practice of double masking notably intensified participants' experiences of difficulty, discomfort, and anxiety. This escalation of negative sensations was primarily observed after participants engaged in tasks that demanded both motor and cognitive effort.

While the intent behind double masking is to improve protection against airborne particles, it increased the perceived discomfort or burden of wearing PPE for some individuals. This added discomfort could lead to higher rates of non-compliance as individuals might seek relief from the heat, moisture, and restricted breathing associated with additional layers of masking.

Thus, this dissertation introduced and quantified the phenomenon of non-compliance by designing an innovative within-subject experimental simulation tailored to a healthcare scenario. This research defined non-compliance in terms of the frequency of PPE interactions with its users. Predictive models were developed using a series of predictors and assessed for accuracy using RMSE, and MAE metrics. The RF model demonstrated superior performance in predicting non-compliance over LR and LASSO models. While PPE and workload emerged as essential predictors, the sensation of discomfort and thermal stress stood out as the most influential factors in predicting non-compliance.

In conclusion, this dissertation introduced a predictive model (MPENC) designed to predict non-compliance among healthcare workers at risk of infection due to their proximity to patients and the necessity of using face masks and covers. Moreover, this work laid the groundwork for predicting non-compliance by examining additional factors that could further refine and expand the model's capabilities. Looking ahead, the research presented here holds significant potential interest for organizations like the CDC and WHO as it offers valuable insights into improving compliance with protective equipment among healthcare professionals, thereby enhancing overall patient and worker safety in healthcare settings.

Future Work

Future research directions should aim to enhance our findings' generalizability and address the questions that emerged during this study.

1. **Physiological Impacts:** Our MPENC considered physiological impacts through subjective assessments. However, objective physiological indicators like heart rate, respiratory rate, oxygen saturation, muscle mass, bone mass, body fat percentage, and Body Mass Index (BMI) can also be quantitatively measured and included into the predictive model to enhance its accuracy and comprehensiveness.
2. **Comprehensive PPE Evaluation:** While N95 and surgical masks are the most often used PPE, especially in healthcare settings, it would be beneficial to expand the MPENC by looking at how other kinds of face masks, such as KN95, cloth masks, and different models of N95 masks, influence non-compliance. Another aspect that might improve the accuracy of the model is investigating the relationship between an individual's chance of non-compliance and the quantity of PPE they wear via studies introducing different levels and amounts of protective equipment.
3. **Longitudinal Studies:** While participants in this study were exposed to PPE usage eight times, longer-term research is needed to better understand how PPE compliance changes over longer time periods. This will help to understand how adherence practices vary over time. Examining how time affects compliance patterns may add a new predictor to the MPENC and provide a more dynamic view of PPE use.

Addressing and investigating the suggested future research areas can significantly advance our understanding of PPE compliance, ultimately leading to improved protective strategies and safer working environments.