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The effects of personal protective respirators on human motor, visual, and cognitive skills

Anas Ahmed AlGhamri

Department: Engineering Management and Systems Engineering

THE EFFECTS OF PERSONAL PROTECTIVE RESPIRATORS ON HUMAN MOTOR, VISUAL, AND COGNITIVE SKILLS

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ANAS AHMED ALGHAMRI

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Approved
Susan L. Murray, Advisor
Elizabeth A. Cudney
Steve M. Corns
Katie A. Grantham
Hong Sheng

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ABSTRACT

In oxygen-deficient or toxic environments in which controlling the hazard is not feasible, workers wear personal protective respirators. Hazard controls include but are not limited to engineering controls, such as ventilation, and substituting less hazardous materials. However, respirator selection and the design of tasks that require respirators are critical issues. Understanding the effects of respirators on human abilities is critical to respirator selection and therefore to the safety and efficiency of workers.

This research investigated the effect of respirators on human abilities. A review of the relevant literature was conducted, revealing that respirators can affect physiological, psychological, motor, and visual abilities. However, the effect varies with different types of respirators, environments and task types and difficulty levels. The details of this variance were identified and further investigated through experimentation.

The study compared a dust respirator, powered-air purifying respirator and full-facepiece respirator in terms of their effect on fine motor, visual and cognitive tasks. Thirty participants performed the Hand Tool Dexterity test, Motor-Free Visual Perception test (MVPT-3) and Serial Seven test. Each participant performed each task without a respirator and then while wearing each type of respirator. Task completion time and error rate were measured as indicators of performance. Participants also were surveyed regarding respirator comfort, anxiety level, and perceived task difficulty. ANOVA, least significant difference, and least square means analyses showed that none of the respirators significantly affected task completion time. A significant increase was found in the error rate when participants performed the cognitive test while wearing the full-facepiece respirator.

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1. INTRODUCTION

A respirator is a personal respiratory protective device worn by workers to protect them from inhaling hazardous atmospheric contaminants, such as biological, chemical, nuclear or particle contaminants (NIOSH, 2001). Respirators are either air-purifying or air-supplying; these two categories are sub-classified according to the mechanism by which they operate (29 CFR 1910.134). In 2002, according to a survey by the National Institute for Occupational Safety and Health (NIOSH) and the Bureau of Labor Statistics (BLS), there were 3.3 million American respirator users. Over 40,000 establishments in the U.S. were surveyed to reveal that respirators were used at 619,400 workplaces (NIOSH, 2001).

OSHA standard (29 CFR 1910.134) requires employers to develop a respiratory protection program consisting of a written procedure that governs the use of respirators, primarily for the sake of worker safety. These guidelines were created to increase the effectiveness of respirator use. The standard outlines the program requirements, such as proper respirator selection, training, medical evaluation, and hazard identification. The standard allows for the voluntary use of respirators, as well as for employers to apply personal judgment and customized measures to assess worksite-specific procedures.

According to the NIOSH survey report, of the 619,400 worksites where respirators were used in 2001, 50% used respirators voluntarily, 41% did not provide respirator training to their employees, 53% did not perform medical fitness evaluations, 64% did not have a written respiratory program, and 76% did not do any air sampling for hazard assessment in order to select the proper type of respirator. All of these are factors that could lead to the improper selection or use of respirators. Unless respirators are used properly by trained workers who realize their limitations and understand changing environments, respirators can become hazardous to users.

Previous studies extensively investigated respirators' degree of protection and their physiological and psychological effects. Little attention was given to the risks associated with the use of respirators, such as their effect on productivity and human performance. The risks increase if no careful procedures and standards are followed in selecting and maintaining respirators.

Past research has shown that respirators have the potential to deteriorate the user's performance. They can decrease workers' physical, psychomotor, and visual abilities and increase anxiety (Wu et al., 2011; Johnson et al., 1995; Johnson et al., 1997; Caretti et al., 2001). Some studies have indicated that human performance decreases as a respirator's capability increases (James et al., 1994; Zelnick et al., 1994; Zimmerman et al., 1991).

The objective of the current research was to investigate the effect of respirators and to provide an analysis of respiratory protection selection beyond the hazard type against which the user is protecting and the respirator's level of protection. An experiment also was conducted to study the effect of three types of respirators on human abilities, including motor function, vision, and cognition. An experiment was conducted to quantitatively analyze changes in task completion time and accuracy. The experiment employed a standardized test for each of the abilities studied.

PAPER 1. ISSUES FOR CONSIDERATION DURING RESPIRATOR SELECTION

Anas A. AlGhamri and Susan L. Murray

Anas A. AlGhamri, Department of Engineering Management and Systems Engineering, Missouri University of Science and Technology, Rolla, MO, United States

Susan L. Murray, Department of Engineering Management and Systems Engineering, Missouri University of Science and Technology, Rolla, MO, United States

ABSTRACT

Safety professionals must select respirators that are appropriate for various types of hazards, workplaces, and tasks. Respirators with the same protection level are available in different styles. Research has shown that differences in these styles affect physical performance, comfort, and anxiety differently. This paper analyzes the factors beyond respiratory protection that should be considered when selecting appropriate personal protective equipment (PPE).

During respirator selection, it is important to understand employees' physical, psychological, psychomotor, cognitive and visual abilities and how these are impacted by PPE. Workers must be protected from contamination, but when several models of PPE provide the necessary protection, it is worthwhile to minimize other hazards, such as human error, by minimizing the PPE's interference with human abilities. This paper reviews a number of studies of respirators' effects on humans. In addition, this paper compares respirators with respect to their level of protection. The objective is to guide safety professionals in the respirator selection process by discussing factors beyond respiratory protection.

INTRODUCTION

In 1994, the Bureau of Labor Statistics (BLS) reported 215 deaths resulting from exposure to harmful substances; 110 of these deaths were from oxygen deficiency (BLS, 2006).

Safety awareness regarding respiratory personal protection has increased in the U.S. since that time. A collaborative survey released in 2001 by the National Institute for Occupational Safety and Health (NIOSH) and the BLS reported that, in the U.S., there are more than 3.3 million respirator users at 281,776 work establishments that incorporate respirators as part of their daily work (NIOSH, 2001). This respirator use has contributed to reduced incidences of death. In 2010, 57 deaths resulting from the inhalation of harmful substances were reported (BLS, 2010).

The NIOSH (2001) survey report also revealed that of the 619,400 worksites where respirators were used in 2001, 50% used respirators voluntarily, 41% did not provide respirator training to their employees, 53% did not perform medical fitness evaluations, 64% did not have a written respiratory program, and 76% did not do any air sampling for hazard assessment in order to select the proper type of respirator. All of these are factors that could lead to the improper selection or use of respirators (NIOSH, 2001). Although awareness regarding respiratory protection has increased since then, between 2006 and 2007, respirator-related issues were the third most cited by OSHA inspectors (Doney et al., 2009). Four years have passed since 2007, and respirators are still among the top cited issues. In 2011, OSHA’s reports showed that respirator violations were the fourth most cited violations (OSHA, 2011).

To protect employees from air contamination, employers establish and implement respiratory protection programs (OSHA standard 1910. 134c), including selecting respirators, performing medical evaluations, training, and fit testing respirators (OSHA standard 1910. 134d). Selecting the proper type of respirator should involve evaluating respiratory hazards and identifying workplace and user factors. As an indication of a respirator's ability to purify air from contamination, OSHA and NIOSH have assigned protection factors (APFs) for each type of respirator.

The APF is a critical factor to consider when selecting an appropriate respirator. It is a measure of workplace respiratory protection that a respirator or class of respirators is expected to provide to employees when employers implement a continuing and effective respiratory protection program as specified by OSHA (29 CFR 1919. 134). The APF measures the percentage of the maximum contamination in the atmosphere that a user would inhale in a worst-case scenario. A higher APF indicates that greater performance can be expected from a respirator. The APF is similar to a workplace protection factor (WPF) in that both factors measure the ratio of concentration of contamination outside the respirator to the concentration inside the respirator. However, the WPF is more specific to a certain workplace and a certain respirator type. In this case, the APF for a certain respirator or respirator type is the minimum WPF value that would be experienced by 95% of users of this type of respirator. APFs are the result of experiments conducted by NIOSH and unaffiliated investigators. OSHA extended the research, reviewed all related data and literature, and then assigned new, updated APFs (OSHA, 2009).

Respirators have the ability to protect humans; however, they also can impair human senses and decrease performance. In order to fully realize the benefits and avoid any additional risks of respirators, thus maximizing worker safety, selecting an appropriate respirator is essential. Understanding the nature of a job and the skills required to perform that job efficiently is as important as understanding the type of hazardous substance and the types of respirators and their APFs. OSHA standard (1910.134(d)(3)(i)(A)) recommends using the APF to select a respirator that meets or exceeds the needed protection. During the respirator selection process, one should maximize safety while also considering factors that can affect costs, including costs associated with slow or inaccurate worker performance.

Past research has shown that respirators have the potential to deteriorate the user's performance. They can decrease workers' physical, psychomotor, and visual performance and increase anxiety (Wu et al., 2011; Johnson et al., 1995; Johnson et al., 1997; Caretti et al., 2001). Some studies have indicated that human performance decreases as a respirator's capability increases (James et al., 1994; Zimmerman et al., 1991). Another factor worthy of discussion is the maximum use concentration (MUC). MUC is the upper concentration limit at which a class of respirators is expected to provide protection. It equals the product of the APF and the contaminant exposure limit. When the exposure limit of a certain hazardous substance reaches the MUC, employers may select the next highest level of protection, as recommended by OSHA (29 CFR 1910.134). However, the other types of risks that this action might impose highlight the importance of assessing the tradeoffs between protection from hazards in the atmosphere and possible impairment of senses.

RESPIRATOR TYPES

OSHA (29 CFR 1910.134) groups respirators into two major categories, air-purifying respirators and atmosphere-supplying respirators. Each type is further divided into subcategories according to the respirator's components and technique for providing hygienic air to the user. Respirators also can be classified as loose-fitting vs. tight-fitting, or powered vs. non-powered. In general, air-purifying respirators use filters, cartridges and canisters to remove contaminants from breathed air. Atmosphere-supplying respirators provide clean air from an uncontaminated source, such as a high-pressure tank. An APF is assigned based on both experimentation and the illustrated performance of respirators to prevent contaminants from entering the respiratory system using a filter or face seal. APFs vary from 5 (e.g., the value assigned for a quarter-face, non-powered respirator) to 10,000 (e.g., self-contained breathing apparatus). Table 1 outlines OSHA's categorization for respirators and their corresponding APFs.

Table 1.1. Assigned Protection Factors

Table I: Assigned Protection Factors[5]

Type of Respirator[1, 2]	Quarter mask	Half mask	Full facepiece	Helmet/Hood	Loose-fitting facepiece
1. Air-Purifying Respirator	5	10[3]	50	—	—
2. Powered Air-Purifying Respirator (PAPR)	—	50	1,000	25/1,000[4]	25
3. Supplied-Air Respirator (SAR) or Airline Respirator					
• Demand mode	—	10	50	—	—
• Continuous flow mode	—	50	1,000	25/1,000[4]	25
• Pressure-demand or other positive-pressure mode	—	50	1,000	—	—
4. Self-Contained Breathing Apparatus (SCBA)					
• Demand mode	—	10	50	50	—
• Pressure-demand or other positive-pressure mode (e.g., open/closed circuit)	—	—	10,000	10,000	—

Notes:

[1] Employers may select respirators assigned for use in higher workplace concentrations of a hazardous substance for use at lower concentrations of that substance, or when required respirator use is independent of concentration.

[2] The assigned protection factors in Table I are only effective when the employer implements a continuing, effective respirator program as required by this section (29 CFR 1910.134), including training, fit testing, maintenance, and use requirements.

[3] This APF category includes filtering facepieces, and half masks with elastomeric facepieces.

[4] The employer must have evidence provided by the respirator manufacturer that testing of these respirators demonstrates performance at a level of protection of 1,000 or greater to receive an APF of 1,000. This level of performance can best be demonstrated by performing a WPF or SWPF study or equivalent testing. Absent such testing, all other PAPRs and SARs with helmets/hoods are to be treated as loose-fitting facepiece respirators, and receive an APF of 25.

[5] These APFs do not apply to respirators used solely for escape. For escape respirators used in association with specific substances covered by 29 CFR 1910 subpart Z, employers must refer to the appropriate substance-specific standards in that subpart. Escape respirators for other IDLH atmospheres are specified by 29 CFR 1910.134(d)(2)(ii).

Source: OSHA.gov

Military Respirators

American soldiers wear bulky PPE called mission-oriented protective posture (MOPP) gear, which consists of an over garment, a protective mask, gloves, over boots, and field gear. Not all components are worn every time a threat exists. In less dangerous situations, soldiers might only wear a mask or a respirator. As the threat level increases, additional areas of the soldier’s body must be protected (Airman’s Manual, 2009). MOPP gear levels vary in terms of their personal protective components, components readily available, and components carried. MOPP levels range from 0 through IV, increasing through this range as the threat increases. Many studies have been conducted to clarify the effect of the gear on soldiers' performance. Past research has shown a definite effect of the suit on human abilities and an increasing effect with an increase in the protection level of the suit (Adams et al., 1994; Bensel, 1997; Rauch et al., 1986; Waugh et al., 1984). These studies have shown that the greater the encapsulation of the military protective equipment, the greater the decrement in soldiers' performance. A similar civilian PPE has not been as fully investigated for industrial applications.

Encapsulating Chemical Suits

Another form of chemical protection is the fully-encapsulated chemical suit. These suits provide varying levels of hazmat protection (levels A, B, C, and D) for firefighters and other first responders. Murray et al. (2011) studied the effect of the Level A chemical suit on gross and fine motor tasks. These suits provide a maximum level of respiratory, eye, and skin protection. The wearer is typically fully encapsulated in the protective suit and breathes using a self-contained breathing apparatus (SCBA). The study found that the time required to complete the gross motor task increased by 103%, and accuracy decreased by 34%. The impact of the suit on fine motor tasks was also statistically significant, but to a much smaller degree.

LITERATURE REVIEW

THE EFFECT OF RESPIRATORS ON HUMAN PHYSIOLOGY

The literature is rich with information regarding the physiological effect of respirators. Respirator use can cause changes in heart rate, blood pressure, body temperature, sweat rate, and oxygen consumption (James et al., 1984; Jones, 1991; Zimmerman et al., 1991). Bansal et al. (2009) measured physiological variables while subjects wore respirators and performed light and moderate exertion tasks. The study found that wearing a respirator while performing tasks requiring moderate exertion caused increased inspiratory tidal volume, minute ventilation, respiratory rate, heart rate, and total breath time. In another study, Caretti et al. (2001) found that the resistance to normal breathing imposed by military full-face respirators effects human performance. A strong correlation between treadmill exercise time and a respirator's increasing resistance was found (R=.79). Increasing the respirator's resistance resulted in shorter exercise time as a result of exhaustion.

Wearing a dust respirator also can increase whole body temperature (Nielson et al., 1987). This effect is magnified if the design has no mechanism to release heat, which, when allowed to build up inside a respirator, can cause additional physical stress. Most current respirator designs incorporate an exhalation valve that allows hot exhaled air to be released from the respirator. Some studies have shown that exercising with a respirator increases the temperature and humidity inside the respirator, which accordingly increases body temperature (Guo et al., 2008; Hayashi et al., 2004; Li et al., 2006).

THE EFFECT OF RESPIRATORS ON COGNITIVE ABILITY

The effect of respirators on cognitive ability represents a grey area in this field. Two studies conducted by Caretti (1997) and Caretti et al. (1999) examined this relationship. The first study tested the ability of nine soldiers to perform the California Computerized Assessment Package (CalCap). The instrument tests reaction time, information processing, language skills, rapid visual scanning, and form discrimination. In the second study, eight soldiers participated in a treadmill walking exercise. Then they were tested in serial addition, serial subtraction, logical reasoning, and serial reaction. Both studies found no difference in performance when wearing a military respirator. However, these two studies have their limitations. First, the participants consisted of a small number of well-trained military personnel, so the conclusions may not apply to industrial workers. Secondly, the results of the cognitive tests could be compounded by the mixing of cognitive and visual questions. Lastly, the low number and difficulty of questions asked to subjects could also compound the results.

Other studies have shown that respirators impose a thermal burden upon humans (Guo et. al., 2008; Hayashi et al., 2004; Li et al., 2006), which could negatively affect cognitive ability due to heat stress. Hancock and Vasmatzidis (2002), after conducting an extensive review of numerous studies, concluded that the physiological response to heat stress is well understood; however, they found that the cognitive response remains unclear. Nevertheless, they found that vigilance is not compromised below 85 °F body temperature, but heat stress negatively impacts reaction time and correlates closely with unsafe work behavior. For instance, White et al. (1991) found that wearing a self-contained breathing apparatus and performing treadmill exercise in a thermal-neutral environment can increase the temperature of the human body to 100.2 °F. James et al. (1984) found that wearing a full-face respirator under high-heat/high-work conditions increases the body's temperature to 100.6 °F.

Hancock (1987) studied the effect of exposure time (ET) on performance and developed a model that measures the correlation between these two factors. After exposing subjects to heat for a specific amount of time, he tested the model to determine the decrement coefficient of performance. He focused on vigilance, dual tasks, tracking, simple mental tasks, and physiological tolerance. The study found that the greater the mental workload involved in a task, the more vulnerable performance was to heat stress and exposure time.

THE EFFECT OF RESPIRATORS ON HUMAN PSYCHOLOGY

When a breathing obstacle exists, anxiety increases. Wu et al. (2011) have found that respirators increase anxiety, especially among those who are already anxious. As indicators of anxiety, the study measured the heart rate, respiratory volume, and State-Trait Anxiety Inventory (STAI) of participants wearing half-face respirators; results indicated an additional increase in anxiety for those with higher trait anxiety. This finding supports the original finding by Johnson et al. (1995), who measured the heart rate, blood pressure, and maximal oxygen consumption of 20 participants performing treadmill exercise. The study measured the time until voluntary stoppage as a result of the participant's exhaustion. Participants with higher anxiety exercised for shorter lengths of time and reported an inability to breathe.

Regardless of any type of airway obstruction, stress can cause breathing difficulties (Rietveld et al., 1999). A relationship exists between emotions and breathing. Moreover, physicians find it difficult to treat patients with both depression and respiratory illness because difficulty in breathing can be induced by stress (Nouwen et al., 1999; Rietveld et al., 2003).

THE EFFECT OF RESPIRATORS ON VISUAL ABILITY

Visual acuity and visual range are two notable variables affected by full-face respirators. Zelnick et al. (1994) studied the effect of three types of full-face respirators on 21 participants. The experiment tested the accuracy of detecting a stimulus appearing in different sectors of a visual range (24 sectors within 0° to 360°). The results showed a decrease in performance, as well as differences among the three full-face respirators. This indicates that respirators affect visual range capabilities and that this effect can vary based on the design and level of encapsulation provided by different full-face respirators.

Johnson et al. (1997) supported the findings presented by Zelnick et al. (1994) by studying the visual range awareness of participants wearing full-face respirators for a period of ten hours. The study found that among all visual abilities, such as visual concentration, tracking and reaction, the visual range was affected the most. Respirators also were found to worsen visual acuity by three-quarters of a Snellen chart line. Johnson et al. (1997) tested 10 participants wearing full-face military respirators and performing treadmill exercise. The study used seven levels of respirator lenses to alter visual acuity. This study in particular demonstrates the adverse impact of respirators on vision.

THE EFFECT OR RESPIRATORS ON PSYCHOMOTOR ABILITY

Among the lesser-studied effects of respirators is their effect on psychomotor ability. Nonetheless, a key study in this area was conducted by Zimmerman et al. (1991) to test physical, cognitive, and psychomotor ability among participants wearing three different types of respirators. The study concluded that full-face respirators may decrease movement time by up to 12% and the steadiness of arm-hand movements by 31%.

Waugh et al. (1984) tested military respirators on participants performing two assembly tasks with varying difficulty levels. The first task, rifle assembly, was considered an easy task and requires less hand-eye coordination. The second task was a more difficult fault repair task. There was no significant difference in the performance of the easy task. However, the time increased by 17% when participants wore respirators and performed the fault repair task that required additional hand-eye coordination.

THE EFFECT OF RESPIRATOR TYPE WITH RESPECT TO APF

In the literature review conducted prior to the study presented here, the selection of respirators to be studied did not appear to be uniform or based on consistent criteria. No study was found that compared respirator types with respect to APFs. The current investigation looks at the effect of the compared respirators and analyzes results taking APFs into consideration. The objective is to examine if the respirator's level of protection indicates its effect on performance. Understanding such a relationship would assist safety professionals selecting among respirators with variable or similar APFs. Previous relevant studies were divided into two groups, the first of which compared respirators with similar APFs (Bansal et al., 2009; Harber et al., 2011; Wu et al., 2011).

Respirators with the Same APFs

Dust masks and half-face respirators both have an APF of 10. Bansal et al. (2009) compared the Comfo-Elite half-mask to 3M's N95 model 8510 dust mask. The experiment tested 56 participants on fine and gross motor tasks that included sorting bolts, performing a simulated casting operation, stocking/shelving buckets, packing and delivering boxes to the proper shelves, performing a driving simulation, stocking store shelves, and building a Lego tower. The study measured physiological variables such as inspiratory volume, minute ventilation, respiratory rate, and heart rate. These four variables, though higher with the moderate exertion tasks, were not affected by the type of respirator. The experiment also measured inspiratory time, expiratory time and total breath time. The half-face respirator had the most significant effect on inspiratory and total breath time. The dust mask had a major effect on the expiratory time.

Wu et al. (2011) also compared the Comfo-Elite half-mask to 3M's N95 model 8510 dust mask. The study tested 12 participants on fine and gross motor tasks and measured speed, accuracy, heart rate, work productivity, subjective responses, and anxiety via the State-Trait Anxiety Inventory (STAI). Some of the tests were similar to those used in the previous study. There was no change in speed or accuracy, nor was there a relationship between trait anxiety and the increment in state anxiety due to the use of the half-face respirator ($r = 0.14$), which appears to have higher encapsulation. No statistically significant correlation existed between trait anxiety and level of state anxiety during half-face mask use ($r = 0.38$, $p > 0.10$). However, the half-face mask contributed to higher anxiety levels than the dust mask.

Harber et al. (2011) conducted a similar study of respirator types and motor skill tests. The study tested 107 participants and focused exclusively on comparing dust masks and half-face respirators in terms of their effect on motor skills, measuring the time and accuracy of task completion. There was no statistical significance in the change in performance between the two types of respirators. Although dust masks and half-face respirators differ in design and method of operation, experimentation has shown that they have a similar effect on performance. These results support the assumption that two respirators with the same APF would likely have the same effect on human psychomotor performance regardless of the design of the respirator. However, according to this study, they might produce different effects on physiological and psychological abilities. According to Harber et al. (2011), the half-face mask imposes more stress than the dust mask.

To compare visual effects, Zelnick et al. (1994) compared three full-face respirators in terms of their effect on the visual field. Although the three respirators were all full-face respirators with APFs of 50, they affected the visual field differently. According to this study, having the same APF might not indicate similar visual field range.

Respirators with Different APFs

The second group of studies compared different types of respirators in terms of their physical, cognitive, and psychomotor effects (James et al., 1984; Zimmerman et al., 1991). To compare the effects of different types of respirators, James et al. (1984) subjected five participants to the stress of three different types of respirators, two levels of heat and two levels of workload. The first respirator was a half-face respirator, a Willson Model 1200. According to OSHA, the half-face respirator has an APF of 10. The second respirator was a full-face respirator, a Willson Model 1700, with an APF of 50. The third respirator was a powered air-purifying respirator with an APF of 25. The study based the comparison on the dead space volume of the respirators. The experiment measured participants' heart rate, oral temperature, sweat rate, minute volume, oxygen consumption, and energy expenditure. Five out of six physiological variables showed that the full-face respirator imposed additional stress on participants. The study restated the effect of the larger dead space of the full-face respirator. We considered the results of this research in terms of the respirators' APFs. The results of our analysis support the assumption that a higher APF results in greater physical stress on humans.

To compare different types of respirators in terms of their physical, psychomotor, and cognitive effects, Zimmerman et al. (1991) tested three types of respirators on 12 participants. The first respirator was a 3M disposable dust respirator, model 8710, with an APF of 10. The second respirator was a half-face respirator, North 7700, with an APF of 10. The third respirator was a full-face airline respirator with air supply, with an APF of 1,000. The full-face respirator resulted in more strain and decline in psychomotor performance. The cognitive effect was not clear because the test provided to the participants was extremely difficult, according to the author.

CONCLUSION

An analysis of past studies concludes that respirators with different APF values will affect physiological and psychological performance differently. Respirators with higher APF values can reduce the wearer's physiological and psychological ability, especially if the task involves physical activity. The effect of respirators with different APFs on visual ability is unclear. However, the visual ranges provided by full-face respirators with similar APFs might vary.

No strong evidence suggests that an increase in the APF would decrease psychomotor abilities. The analysis also showed that tasks involving easy to moderate motor skills were not affected differently by respirators with similar APFs. However, although dust respirators and half-face respirators have similar APFs, only the half-face respirator decreased physiological ability and increased anxiety. Also, respirators with similar APFs seem to have no cognitive effect on wearers performing easy tasks.

There is no strong evidence suggesting that respirator use might decrease cognitive abilities, regardless of the protection level provided. Nevertheless, if a task is performed in a high-temperature environment and involves a high level of physical activity or critical mental ability, caution should be taken.

Visual acuity can decrease when wearing full-face respirators due to lens fogging. An experiment was conducted to test the ability of a solution of 3 g of surfactant powder mixed with 100 mL of distilled water to reduce lens fogging. The solution reduced the fogging effect and improved visual acuity from an average Snellen acuity of 20/254 and 20/261 for the right and left lenses to 20/6 and 20/5, respectively (Coyne, 2010).

After a proper respirator is selected, employers must evaluate their respiratory protection programs and continuously ensure that training, medical evaluations and fit testing are implemented (Smithers, 2012). An interactive workshop is a form of training that can contribute enormously to the effectiveness of proper respirator use (Krasowska, 1996; Thomas, 1999). Employers also must ensure the fit of respirators as some studies have found that some individuals are not able to use respirators due their special facial dimensions (Oestenstad et al. 1992; Thomas, 1999).

OSHA reports of fatal injuries from 1984 to 1995 indicate that there were 41 incidents resulting in 45 deaths as a result of asphyxiation or chemical poisoning "while wearing a respirator." Most of these fatalities involved regulatory and procedural violations and could have been prevented by proper training and adherence to regulations (Suruda, 2003).

RECOMMENDATIONS

- OSHA recommends written, worksite-specific procedures under respiratory protection program standard 1910.134(c)(1). It recommends that employers evaluate any respiratory hazards and identify relevant workplace and user factors when selecting respirators. A set of procedures highlighting the skills related to each specific task and how those skills may be affected by the respirator should also be considered.
- OSHA standard 1920.134 (c) states, in general terms, that certain factors may be required for employers to voluntarily use respirators in order to prevent potential hazards associated with respirator use. The current study found that respirators

may cause workers to be less efficient in situations that are hot and have an extended exposure time.

- Based on several studies, dust respirators that are unequipped with an exhalation valve increase heat stress. Thus, dust respirators with exhalation valves should always take preference over those without exhalation valves.
- In addition to WPF studies and experiments, employers can perform additional assessments to ensure successful matching between workers' skills, abilities, job requirements, and PPE.
- The selection of a proper respirator is only the beginning of an effective respiratory program. Fit testing, training, continuous medical evaluation, and respirator maintenance should be maintained to ensure the safety of workers.

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PAPER 2. THE EFFECTS OF WEARING RESPIRATORS ON HUMAN FINE MOTOR, VISUAL, AND COGNITIVE PERFORMANCE

Anas A. AlGhamri, Susan L. Murray, and V. A. Samaranayake

Anas A. AlGhamri, Department of Engineering Management and Systems Engineering, Missouri University of Science and Technology, Rolla, MO, United States

Susan L. Murray, Department of Engineering Management and Systems Engineering, Missouri University of Science and Technology, Rolla, MO, United States

V. A. Samaranayake, Department of Mathematics and Statistics, Missouri University of Science and Technology, Rolla, MO, United States

When selecting a respirator, it is important to understand how employees' motor, visual, and cognitive abilities are impacted by the personal protective equipment (PPE). This study compares dust, powered-air purifying, and full-facepiece respirators. Thirty participants performed three varied tasks. Each participant performed each task without a respirator and then while wearing each of the three types of respirators. The tasks included the Hand Tool dexterity test, the Motor-Free Visual Perception Test (MVPT-3), and the Serial Seven Test to evaluate fine motor, visual, and cognitive performance, respectively. The time required for task completion and the errors made were measured. Analysis showed no significant effect due to respirator use on the task completion time. A significant increase was found in the error rate when participants performed the cognitive test wearing the full-facepiece respirator. Participants had varying respirator preferences. They indicated a potential for full-facepiece respirators to negatively affect jobs demanding advanced cognitive skills such as problem solving and decision making.

Keywords: Dust respirator; PAPR; Full-facepiece respirator; Fine motor task; Visual task; Cognitive task.

PRACTITIONER SUMMARY

Respirators are important safety devices, but they can have the unintentional consequence of reducing human performance. This is especially true if characteristics of the job and worker are not considered during PPE selection. An experiment was conducted to clarify the effects of various types of respirators on human skills. This research expands the understanding of the nature and extent of the effects of respirators on human performance and provides insights to consider when selecting respirators for various jobs.

1. INTRODUCTION

In 1994, the Bureau of Labor Statistics (BLS) reported 215 deaths resulting from exposure to harmful substances; 110 of these deaths were from oxygen deficiency (BLS, 2006). Safety awareness regarding respiratory personal protection has increased in the U.S. since that time. As of 2001, the National Institute for Occupational Safety and Health (NIOSH) and the BLS collaborative survey reported that in the U.S., there are more than 3.3 million respirator users at 281,776 work establishments for whom respirators are part of their daily work (NIOSH, 2001). This has contributed to the reduction in fatalities. In 2010, the number of deaths resulting from the inhalation of harmful substances was reported to be 57 (BLS, 2010).

As mandated and regulated by Occupational Safety and Health Administration (OSHA) standard (29 CFR 1910. 134), if contamination exists in a workplace, and if engineering precautions are not feasible, employers are required to enforce respirator usage. Employers should select the appropriate type of respirator that provides protection without imposing any additional hazard or affecting performance. Respirators are selected based on the hazard type and amount of the hazardous material present. Medical evaluations and fit-testing are performed as part of an effective respiratory protection program.

An assigned protection factor (APF) for a respirator is a measure of its ability to purify contaminated air. The APF is one factor to consider when selecting the respirator type for a given environment. It represents the workplace level of respiratory protection that a respirator or class of respirators is expected to provide to employees when employers implement a continuing and effective respiratory protection program as specified by OSHA's respiratory protection standard (29 CFR 1910. 134). The APF measures the portion of the maximum contamination in the atmosphere that a user would inhale in a worst-case scenario. A higher APF indicates that a respirator should provide higher protection.

While respirators protect humans, they also can decrease performance and impose other risks. It is essential to understand the potential effects that respirators have on humans. Too much respiratory protection might not be the best option if it comes at the cost of a significant increase in errors or a decrease in reaction time. Selecting the proper respirator type requires knowledge of hazards, respirator types, and the potential effects on different human abilities.

Past research studies have explored the effects of wearing respirators; however, the methodologies used were often narrow in context. The objective of this study is to clarify and quantify the effects of respirators on human fine motor, visual, and cognitive skills with respect to task completion time and errors.

1.1 RESPIRATOR TYPES

OSHA (29 CFR 1910.134) groups respirators into two major categories; air-purifying respirators, which are used by 95% of industry (BLS, 2003), and the less common atmosphere-supplying respirators. APFs are assigned based on experimentation and the respirator's demonstrated performance. Each respirator type is further divided into subcategories according to its components and technique for providing hygienic air to users. Examples of the first respirator type, air-purifying respirators, are dust respirators (APF=10), which account for 71% of use in this category, half-face respirators (APF=10), full-facepieces (APF=50), loose-fitting powered air-purifying respirators (PAPR) (APF=25), and hood-powered air-purifying respirators (PAPR) (APF=25). These respirators are shown from left to right, respectively, in Figure 1.

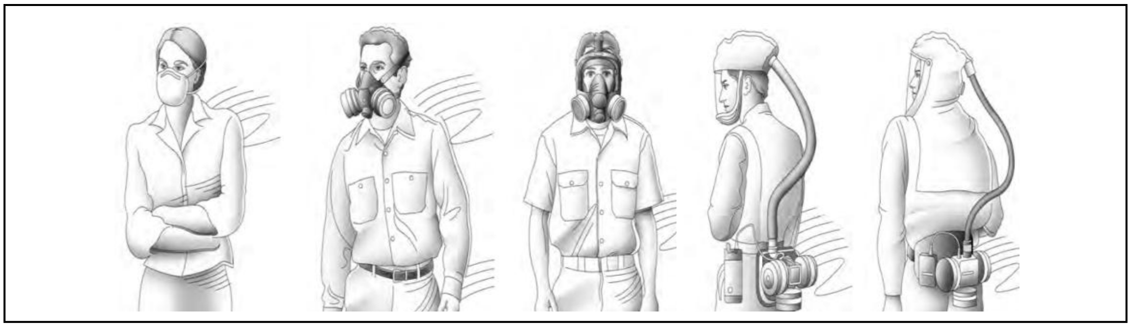

Figure 1: Air-purifying Respirators (OSHA.gov)

Subcategories of the second respirator type, atmosphere-supplying respirators, include full-facepiece supplied-air respirators (SARs) with an auxiliary escape bottle (APF=1,000 or APF = 10,000 if used in “escape” mode); full-facepiece abrasive blasting continuous flow respirators (APF=1,000); and full-facepiece self-contained breathing apparatuses (SCBAs) (APF=10,000 in pressure demand mode). These are shown in Figure 2 from left to right, respectively.

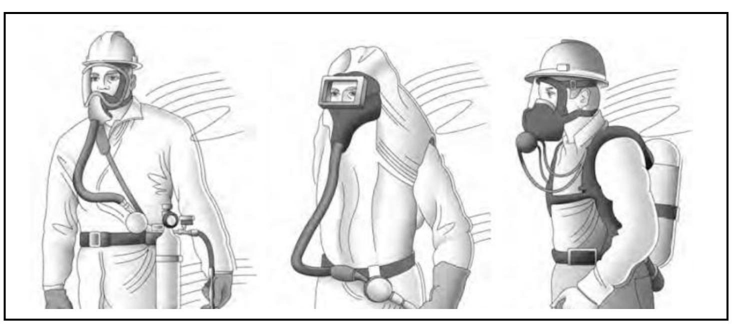

Figure 2: Atmosphere-supplying Respirators (OSHA.gov)

All of these respirators are commonly used in industries including agriculture, mining, construction, and manufacturing. Other types of respirators, such as military and medical respirators, are not classified by OSHA and are not considered in this study.

1.2 THE EFFECTS OF RESPIRATORS ON HUMANS

Past research has shown that respirators have the potential to inhibit the user's work performance. They can decrease workers' physical, psychomotor, visual, and cognitive abilities and increase anxiety (Wu et al., 2011; Johnson et al., 1995; Johnson et al., 1997; Caretti et al., 2001). Some studies have shown that human performance decreases as a respirator's protective ability increases (James et al., 1994; Zelnick et al., 1994; Zimmerman et al., 1991).

Visual acuity and visual range are two notable variables affected by full-facepiece respirators. Zelnick et al. (1994) studied the effect of three types of full-facepiece respirators on 21 participants. The experiment tested the participants' accuracy in detecting a stimulus appearing in different sectors of a visual range (24 sectors in a 0° to 360° range). The results showed a decrease in performance and differences among the effects of three full-facepiece respirators. These results indicate the effect of respirators on visual range capabilities, as well as the effect of the design and the level of encapsulation provided by the three different respirators. These findings were supported by Johnson et al. (1997), who studied the visual range awareness of participants wearing full-facepiece respirators for a period of 10 hours. The study found that among all visual abilities, such as visual concentration, tracking and reaction, respirator use affected the visual range the most. Respirators also were found to worsen visual acuity by 75% on Snellen chart lines. Johnson et al. (1997) tested 10 participants wearing full-facepiece military respirators while performing treadmill exercise. The study used seven levels of respirator lenses to alter visual acuity. This study in particular demonstrates the adverse impact of respirators on vision. No studies were found that tested the effect of respirators on visual perception, which will be studied in the current paper.

Few studies have tested the effect of respirators on the psychomotor ability of humans. A key study in this area was conducted by Zimmerman et al. (1991), who tested three types of respirators on 12 subjects. The first respirator was a 3M disposable dust respirator, model 8710. The second respirator was a half-facepiece respirator, North 7700. The third respirator was a full-facepiece airline respirator with air supply. The researchers studied physical, psychomotor, and cognitive abilities. Physical ability was evaluated using a bicycle ergometer; psychomotor ability by participants' reaction time, finger dexterity, arm-hand steadiness, and grip strength; and cognitive ability through participants' performance in hypothesis testing, Miller analogies and GRE logical and analytical tests. Speed and accuracy were measured in each test. The air-purifying half-facepiece respirator and full-facepiece airline respirator resulted in a 10% increase in oxygen consumption. No change in cognitive performance was found. In the evaluation of psychomotor abilities, steadiness decreased by 31% when participants wore the full-facepiece respirator, and movement time increased by an average of 3% - 12% when participants wore any of the three respirators. According to the author, most of the change in performance resulted from wearing the half-facepiece and full-facepiece respirators.

The study did not find a decrease in cognitive performance due to the difficulty of the tests and their limited number of questions.

Waugh et al. (1984) tested military respirators on participants performing two different assembly tasks with varying degrees of difficulty. The first task was rifle assembly, which is considered an easy task and requires less hand-eye coordination. The second task was a fault repair task. There was no significant difference in performance when participants performed the easy task while wearing military respirators. However, the task completion time increased by 17% when participants wore respirators and performed the fault repair task that required additional hand-eye coordination. Similar studies are mostly applicable in a military context. Soldiers serve as participants, and the tasks performed are more relevant to the military (i.e., rifle assembly). A need exists to test non-military protective equipment using standardized tests on average individuals other than soldiers. Some past studies have subjected participants to physical strain and appear to be studying human endurance more than the effect of protective equipment (e.g., Caretti, 1997; Caretti et al., 1999).

One of the least studied areas is the impact of respirators on human cognitive ability. Caretti (1997), Caretti et al. (1999), and Johnson (1997) studied the cognitive ability of participants wearing military respirators. Zimmerman et al. (1991) studied the cognitive effects of wearing dust, half-facepiece, and full-facepiece respirators. These studies used different methodologies, settings, and severities of conditions. Nevertheless, none of these studies found any effect of wearing a respirator, which is considered surprising by some, especially when considering that respirators also impose a thermal burden upon humans (Guo et al., 2008; Hayashi et al., 2004; Li et al., 2006), which could cause a reduction in cognitive ability due to heat stress. These three studies were concerned with understanding the effect of dust respirators and found that heat inside the respirator can affect the human body. On the other hand, Hancock and Vasmatzidis (2002) conducted an extensive review of numerous studies. They found that vigilance is not compromised below 85° F body temperature, but heat stress has a negative impact on reaction time and correlates closely with unsafe work behavior. These are all signs of changes in cognitive abilities. Given that some respirators, especially dust respirators, can impose thermal effects, one can hypothesize a change in cognitive performance.

Testing another type of respirator, White et al. (1991) found that wearing a self-contained breathing apparatus and performing treadmill exercise in a thermal-neutral environment can increase the human body temperature to 100.2 °F. James et al. (1984) found that wearing a full-facepiece respirator under high-heat/high-work conditions increases the body temperature to 100.6 °F. Hancock's (1987) study provides insight into exposure time (ET) on performance, and he developed a model that measures the correlation between these two factors. After exposing subjects to heat for a specific amount of time, he tested the model to determine the decrement coefficient of performance. The study focused on vigilance, dual tasks, tracking, simple mental tasks, and physiological tolerance, finding that the greater the mental workload involved in a task, the more vulnerable task performance was to heat stress and exposure time.

2. METHODOLOGY

2.1 PARTICIPANTS

Thirty participants (18 male, 12 female) ranging in age from 19 to 60, with an average age of 30.7 and a standard deviation of 12.1, participated in the experiment. All subjects self-reported being in their normal physical state and not having any chronic respiratory illness, allergies, vision defects, or facial hair. One subject was near-sighted and another was far-sighted, but they were still able to perform the visual task. Seven participants were smokers, four had significant experience wearing respirators, and two were left handed. When asked to rate their fitness level on a scale of 1 to 5 (with 5 being the highest level) they rated themselves an average of 3.4 with a standard deviation of .77. On the same scale, they rated their anxiety as 1.7 with a standard deviation of .98.

2.2 RESPIRATORS STUDIED

Respirator selection is critical for research in this area. OSHA's APF classification was used in the selection process to study varying levels of protection. The three respirators used are a dust respirator [3M™ Particulate Respirator 8511 N95, APF=10]; a loose-fitting powered air-purifying respirator (PAPR) [3M™ Belt-Mounted Powered Air Purifying Respirator (PAPR) GVP-Series, APF=25]; and a full-facepiece respirator [3M™ Full-facepiece S 6000 Series Reusable 3M™ Mold Remediation Respirator Kit 69097, APF=50]. The respirators are shown in Figure 3.

Figure 3: Respirators Used in the Experiment

2.3. EXPERIMENTAL TASKS

2.3.1. Hand Tool Dexterity Test

The standardized Lafayette Hand Tool Dexterity Test (model 32521) was used to assess fine motor skill (see Figure 4). This test measures a participant's speed and accuracy at removing and installing bolts using a wrench and fingers. In preparation for the test, the apparatus was placed 12 cm from the edge of the table. Twelve bolts, four of each size, were mounted in three rows on one side of a wooden, U-shaped apparatus with the bolt heads on the inside. A wrench, spanner, and screwdriver were placed near the apparatus. Participants were required to stand during the test. They began the task with their hands on the table. A stopwatch was started when the participant picked up the first tool. Tools were used first to loosen the bolts, and then participants used their fingers to remove the bolts. If a participant dropped any part, it was counted as an error. Participants removed all the bolts in each row on the left side, starting at the top row and working down to the bottom row. Then they installed the bolts on the right side, starting with the bottom row and working to the top row, with bolt heads on the inside.

Participants had to tighten the bolts so that they could not be removed with fingers. Any violation of these procedures was counted as an error. When all the tools were put down, the examiner stopped the stopwatch.

Figure 4: Hand Tool Dexterity Test

2.3.2. Motor-Free Visual Perception Test (MVPT-3)

A sample question from the Motor-Free Visual Perception Test (MVPT-3) is shown in Figure 5. The test measures visual performance by assessing visual perception abilities, including visual discrimination, visual memory, and shape orientation. The test format was modified for this experiment by presenting problems on a computer monitor rather than paper. The researcher advanced the problems via the computer to eliminate the motor skill requirements of the traditional test approach. Five shorter versions of the test were generated from the original MVPT-3. A different version was used for each repetition; each test had the same level of difficulty. The visual test began when the participant was seated in front of the computer. During the test, the participant was shown the stimulus and asked to choose the answer from among multiple choices. The participant indicated the answer aloud and pointed as an examiner sitting behind the participant recorded the response. Time was calculated, and any incorrect answer was considered an error.

The original MVPT-3 measures visual perception skills, including spatial relationships, visual discrimination, figure-ground, visual closure, and visual memory. However, visual short-term memory and spatial orientation questions seem to require the most cognitive, as well as perceptual, skills. This confound is acknowledged by the test developers in that “real world” tasks require both perception and cognition, so the overlap is expected (Colarusso, 2008). The MVPT-3 is easy to administer and score. Moreover, this test is more reliable when the purpose of the study is simply to monitor the change in performance due to a certain stressor, such as the effect of respirators in the current experiment (Bourne, 2010).

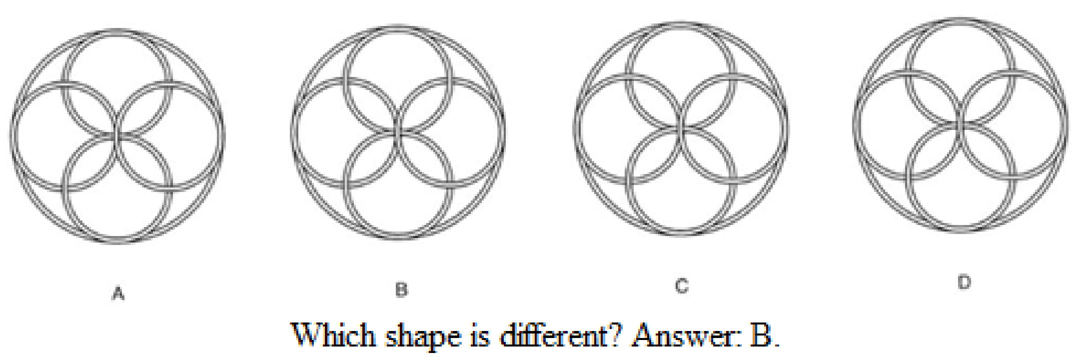

Figure 5: An Example of the Visual Task

2.3.3. The Serial Sevens Test

The Serial Sevens Test measures cognitive ability (Karzmark, 2000). Participants are given a four-digit number and asked to subtract seven from that number, to subtract seven again from the answer, and to continue through fifteen iterations. Time starts when the examiner says the four-digit number and ends with the participant's fifteenth subtraction. Participants provide their answers aloud to the examiner. Each miscalculation is counted as an error. If a participant correctly subtracts seven from an incorrect answer, it is not counted as an error. The examiner uses a sheet with all possible miscalculations listed, so errors can be tracked easily without interrupting the participant. For example if the participant has the number 3,123 and says 3,115 instead of the correct 3,116, a single error is recorded. If the subject then correctly subtracts 7 from 3,115 and gets 3,108, an additional error is not recorded. If the answer is not on the sheet (i.e. stating 115 instead of 3,115) or the participant forgets the current value, the participant is given the correct number, and the subtraction process resumes.

2.4 PROCEDURE

The procedure began with a briefing about the experiment and an informed consent form. A questionnaire was given to participants asking about their age, gender, experience, dominant hand, state of physical health, dexterity, vision, respiratory-related health concerns, anxiety, overall fitness level, and smoking. Subjects then were trained on the three tasks. The investigators also fit-tested the respirators on participants to determine the appropriate size and fit. Participants were given time to become accustomed to the respirators and ask questions.

Participants were assigned randomly to the respirators and the control of not wearing a respirator. After using each respirator type, subjects were asked to assess the comfort of the respirator and the perceived difficulty of completing each task while wearing each type of respirator. They also were asked to rate their anxiety while wearing each respirator. They were instructed to perform each task as quickly and accurately as possible. The experiment was conducted in a large laboratory in a controlled environment with an average temperature of 65° F. Each participant took about 130 minutes to complete the experiment, from signing the consent form to the final repetition. Participants performed each task once with each respirator level without repetition. They were allowed to take a break and were compensated for their time.

2.5 EXPERIMENTAL DESIGN AND STRUCTURE

2.5.1 Variables and Hypotheses

The independent variables in this experiment are respirator type and task type. The dependent variables are task completion time and number of errors. Respirator types included no respirator (control), dust respirator, PAPR, and full-facepiece. Task types included a fine motor task, visual task, and cognitive task.

This study aimed to quantify the effects of personal protective respirators on human motor, visual, and cognitive abilities. The hypothesis of this study was that none of the respirators would affect the completion time or number of errors for any of the task types.

Table 1: Factors, Levels, and Treatment Combination Yields (Yij)

			Task Type, i		
			Fine motor	Visual	Cognitive
		Levels	**1**	**2**	**3**
Respirator Type, j	None	**1**	Y11	Y12	Y13
	Dust respirator	**2**	Y21	Y22	Y23
	PAPR	**3**	Y31	Y32	Y33
	Full-facepiece	**4**	Y41	Y42	Y43

2.5.2 Experimental Structure

This experiment used a split-plot design because changing the respirator type was difficult and time consuming. Each respirator was considered a whole plot, task types were split plots, and participants were blocks. The respirator levels, which were the whole plots, were assigned randomly. Within each whole plot, tasks were assigned randomly as well. A random order was assigned prior to the experiment and recorded in a table to be used during the experiment. The participant wore the first randomly-selected respirator and performed the three randomly-assigned tasks. The same procedure was repeated for the other respirators, including the control of no respirator. Participants spent 15-20 minutes in each respirator, and no two participants experienced exactly the same sequence of respirators or tasks. This experimental design was not only easier to conduct, but was also more representative because the participants were not frequently changing respirators.

3. PERFORMANCE ANALYSIS

The objective of this experiment was to examine the effect of respirators on human fine motor, visual, and cognitive performances. The Statistical Analysis System (SAS) program was used to analyze the data. An Analysis of Variance (ANOVA) was performed on task completion time and number of errors. Least significant difference and least square means analyses were only performed on variables that were significantly affected.

Table 2: ANOVA Results for Time Required (in Seconds)

Source	**DF**	**Type III SS**	**Mean square**	**F value**	**Pr > F**
person	29	956,969.60	32,998.95	25.81	<.0001
respirator	3	10,822.44	3,607.48	2.82	0.0404
person x respirator	87	158,432.37	1,821.06	1.42	0.0253
task	2	14,430,116.00	7,215,058.09	5644.00	<.0001
respirator x task	6	11,804.18	1,967.36	1.54	0.1680
person x task	58	1,050,505.60	18,112.17	14.17	<.0001
ANOVA results using type III MS for person*respirator as an error term:					
Source	**DF**	**Type III SS**	**Mean Square**	**F value**	**Pr > F**
respirator	3	10,822.43	3,607.48	1.98	0.1227

An ANOVA was performed on the first response variable (time) via SAS, yielding the data shown in Table 2, which indicate that the factor of wearing a respirator did not statistically significantly affect task completion time (p-value =.1227 at the .05

significance level). No further statistical analysis was performed because respirators did not significantly affect task completion time.

Performing an ANOVA on the second response variable (error) yielded the data shown in Table 3. The p-value for the respirator factor shows that it is statistically significant (p-value = 0.0232). This p-value suggests that at least one respirator type is affecting the error rate. Therefore, further analysis was conducted to analyze which respirator produced the most significant change. Moreover, an analysis of which specific respirator had the biggest effect on which task type compared with the control condition was performed.

Table 3: ANOVA Results for Errors

Source	**DF**	**Type III SS**	**Mean square**	**F value**	**Pr > F**
person	29	261.78	9.02	7.53	<.0001
respirator	3	16.63	5.54	4.63	0.0039
person x respirator	87	144.78	1.66	1.39	0.0348
task	2	54.24	27.12	22.63	<.0001
respirator x task	6	17.83	2.97	2.48	0.0251
person x task	58	338.09	5.83	4.86	<.0001
ANOVA results using the type III MS for person*respirator as an error term:					
Source	**DF**	**Type III SS**	**Mean square**	**F value**	**Pr > F**
respirator	3	16.63	5.54	3.33	0.0232

Table 4 shows the least significant difference (LSD) analysis of the respirators' effect on the three tasks. Respirators that are linked with the same letter in the t-grouping column are not significantly different from each other in terms of their effect on the error rate. The full-facepiece respirator and PAPR are not significantly different from each other. The PAPR, no respirator, and the dust respirator were not significantly different from each other. The full-facepiece respirator was significantly different from the dust respirator and from the control condition.

Table 4: T-tests (LSD) for Error

Alpha		0.05	
Error Degrees of Freedom		174	
Error Mean Square		1.198	
Critical Value of t		1.973	
Least Significant Difference		0.322	
t Grouping	**Mean**	**N**	**Respirator**
A	2.1	90	4 (full-facepiece)
B A	1.79	90	3 (PAPR)
B	1.68	90	1 (None)
B	1.51	90	2 (Dust respirator)

In order to compare the means of treatment combination errors, a least squares mean (LSM) analysis was performed. Table 5a shows the LSM values. The p-values in Table 5b illustrate how significantly different the means were from each other. The LSM analysis compared treatment combinations in terms of which were producing more errors. The analysis helps to clarify what respirator-task combination yields the most errors. The baseline for comparison was respirator level 1 (None). This comparison was conducted to clarify how performance while wearing a respirator is different from performance without wearing a respirator.

Table 5a: Error LSM Values for Treatment Combinations (TC)

Respirator	**Task**	**Error - LSM**	**TC**
None	Fine motor	1.20	1
None	Visual	2.30	2
None	Cognitive	1.53	3
Dust Respirator	Fine motor	1.47	4
Dust Respirator	Visual	1.60	5
Dust Respirator	Cognitive	1.47	6
PAPR	Fine motor	1.13	7
PAPR	Visual	2.43	8
PAPR	Cognitive	1.80	9
Full-facepiece	Fine motor	1.33	10
Full-facepiece	Visual	2.60	11
Full-facepiece	Cognitive	2.37	12

Table 5b: P-values for Ho: LS Mean (TCi) = LS Mean (TCj)*

i/j	1	2	3	4	5	6	7	8	9	10	11	12
1		0.0001	0.2399	**0.3467**	0.1588	0.3467	**0.8138**	<.0001	0.0352	**0.6377**	<.0001	<.0001
2	0.0001		0.0073	0.0036	**0.0142**	0.0036	<.0001	**0.6377**	0.0786	0.0008	**0.29**	0.8138
3	0.2399	0.0073		0.8138	0.8138	**0.8138**	0.1588	0.0017	**0.3467**	0.4801	0.0002	**0.0036**
4	0.3467	0.0036	0.8138		0.6377	1	0.2399	0.0008	0.2399	0.6377	<.0001	0.0017
5	0.1588	0.0142	0.8138	0.6377		0.6377	0.1005	0.0036	0.4801	0.3467	0.0005	0.0073
6	0.3467	0.0036	0.8138	1	0.6377		0.2399	0.0008	0.2399	0.6377	<.0001	0.0017
7	0.8138	<.0001	0.1588	0.2399	0.1005	0.2399		<.0001	0.0194	0.4801	<.0001	<.0001
8	<.0001	0.6377	0.0017	0.0008	0.0036	0.0008	<.0001		0.0263	0.0001	0.5562	0.8138
9	0.0352	0.0786	0.3467	0.2399	0.4801	0.2399	0.0194	0.0263		0.1005	0.0052	0.0465
10	0.6377	0.0008	0.4801	0.6377	0.3467	0.6377	0.4801	0.0001	0.1005		<.0001	0.0003
11	<.0001	0.29	0.0002	<.0001	0.0005	<.0001	<.0001	0.5562	0.0052	<.0001		0.4102
12	<.0001	0.8138	0.0036	0.0017	0.0073	0.0017	<.0001	0.8138	0.0465	0.0003	0.4102	

* P-value < 0.05 indicates that the two corresponding treatment combinations are significantly different

Treatment combinations corresponding to the same task type were compared to reveal which respirators resulted in significant changes in error. The low p-values of concern are shown in bold in Table 5b. If the p-value shown is significant, the LSM in Table 5a shows which treatment combination results in a larger or smaller error rate. Several findings from the LSM analysis reveal that respirator use did not significantly affect the number of errors made while performing the fine motor task. The number of errors made while performing the visual task decreased significantly when participants wore the dust respirator, which was unexpected. The analysis shows that the number of errors made while performing the cognitive task increased significantly only when the full-facepiece respirator was worn.

4. SUBJECTIVE FEEDBACK ANALYSIS

Each participant completed four repetitions with different levels of respirators. Each repetition contained a sub-set of three tasks. After each repetition with the same type of respirator, participants were surveyed regarding respirator comfort, anxiety level, and difficulty of completing the task with that respirator. The following two sub-sections describe the analysis of the subjective feedback survey. The first sub-section describes the analysis of subjects' responses, and the second describes the correlation between the subjective feedback and the actual performance.

4.1 DESCRIPTIVE STATISTICS

On a scale of 1 to 5, participants rated the respirators' comfort, their anxiety, and the difficulty of the tasks. A rating of 1 is equivalent to a very comfortable respirator, low anxiety and very easy task, respectively. A rating of 5 is equivalent to a very uncomfortable respirator, high anxiety, and a very difficult task. The feedback was gathered immediately after the participant completed a single respirator level so that feedback reflected the participant's actual experience.

Comfort level ratings indicated that participants did not favor the respirator with the lowest APF. This contradicts the expectation that discomfort would increase with an increase in respirator capability. Respirators' comfort rating averages are shown in Table 6a. According to these rating averages, the dust respirator was less comfortable than the full-facepiece respirator, which has a higher APF. Further analysis was performed on individual comfort ratings to reveal that participants had variable respirator preferences (Graph 1). Some participants complained about the heat and humidity inside the dust respirator. These results were also unexpected. When anxiety was rated, the PAPR was the least stressful respirator, followed by the dust respirator and then the full-facepiece respirator (Table 6b).

Participants were asked about the difficulty of performing tasks with respirators. Table 6c shows that the perceived difficulty of performing the fine motor task was highest with the PAPR. Participants performed the fine motor task while standing, so the increase in perceived difficulty could be due to the weight of the PAPR. Table 6d shows that the perceived difficulty of performing the visual tasks was highest with the PAPR and full-facepiece respirator. This was expected because those two respirators cover the eyes. Table 6e shows that the perceived difficulty of performing the cognitive task was highest with the full-facepiece respirator.

Table 6: Subjective Feedback from Participants

Table 6 (a): Comfort		**Table 6 (b): Anxiety**	
None	-	None	1.3
Dust respirator	2.9	Dust respirator	2.0
PAPR	2.5	PAPR	1.7
Full-facepiece	2.7	Full-facepiece	2.5

Table 6 (c): Fine motor task difficulty		**Table 6 (d): Visual task difficulty**		**Table 6 (e): Cognitive task difficulty**	
None	1.4	None	1.4	None	1.4
Dust respirator	1.8	Dust respirator	1.5	Dust respirator	1.8
PAPR	1.9	PAPR	1.7	PAPR	1.8
Full-facepiece	2.0	Full-facepiece	1.7	Full-facepiece	2.1

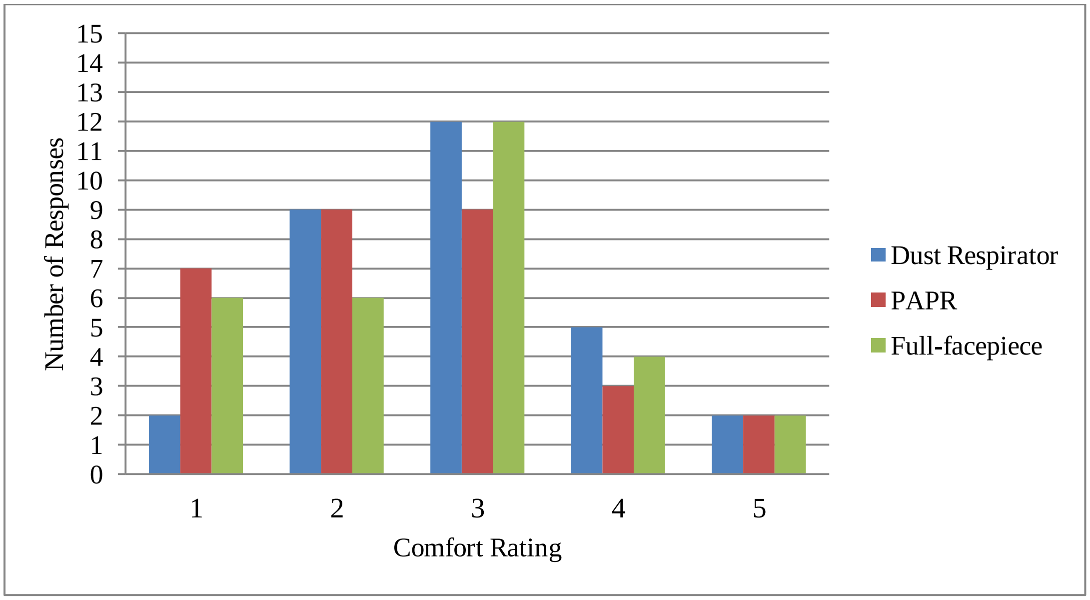

Figure 6: Respirator Preference

As Figure 6 illustrates, only two participants rated the dust respirator as very comfortable, seven participants rated the PAPR as very comfortable, and six participants rated the full-facepiece respirator as very comfortable. The three respirators each received two “very uncomfortable” ratings. This indicates variability in respirator preference among participants.

4.1.1 Correlation of perception with performance

The relationship between the subjective feedback and performance was examined. An analysis was conducted to find the correlation coefficients between difficulty/comfort and performance. The low correlations indicate that the perceived levels of comfort or difficulty do not necessarily reflect performance.

4.1.2 Correlation of task difficulty with performance

Table 7 shows the correlation between the perceived difficulty of a task and the change in task completion time when wearing different respirators. The correlation between perceived difficulty and cognitive task completion time while wearing the full-facepiece respirator was R=0.59. However, this correlation did not significantly affect task completion time for the cognitive task.

Table 7: Correlation between Perceived Difficulty of a Task and Change in Task Completion Time

Correlation between perceived difficulty and fine motor task completion time	
Respirator	Correlation (R)
None	0.18
Dust Respirator	0.45
PAPR	0.15
Full-facepiece	-0.03
Correlation between perceived difficulty and visual task completion time	
None	0.07
Dust Respirator	-0.36
PAPR	-0.33
Full-facepiece	-0.3
Correlation between perceived difficulty and cognitive task completion time	
None	0.32
Dust Respirator	0.31
PAPR	0.24
Full-facepiece	0.59

Table 8 shows the correlation between the perceived difficulty of a task and the change in errors committed during a task while wearing different respirators. The correlation between perceived difficulty and errors committed while performing the fine motor task wearing the full-facepiece respirator was relatively high (R=.59), suggesting that this respirator can affect the wearer's ability to perform fine motor tasks even though there was no increase in the time required. The same is the case for the correlation while wearing PAPR and performing the visual task (R=.57).

Table 8: Correlation between Perceived Difficulty of a Task and Task Errors

Correlation between perceived difficulty and errors committed while performing the fine motor task	
Respirator	Correlation (R)
None	0.33
Dust Respirator	0.29
PAPR	-0.03
Full-facepiece	0.59
Correlation between perceived difficulty and errors committed while performing the visual task	
None	0.35
Dust Respirator	0.18
PAPR	0.57
Full-facepiece	0.25
Correlation between perceived difficulty and errors committed while performing the cognitive task	
None	0.5
Dust Respirator	0.4
PAPR	0.49
Full-facepiece	0.69

The correlation between perceived difficulty and errors committed while performing the cognitive task was the highest when participants wore the full-facepiece respirator (R=.69). This correlation is the highest among all studied correlations, which supports the significant effect of full-facepiece respirators on cognitive task errors.

4.1.3 Respirator comfort and performance correlation

Table 9 shows the correlation between perceived comfort and the change in task completion time. The negative correlations may indicate a tendency to rush tasks while wearing respirators that are uncomfortable.

Table 9: Correlation between Perceived Comfort of a Respirator and Change in Task Completion Time

The correlation between perceived comfort and fine motor task completion time	
Respirator	Correlation (R)
Dust Respirator	-0.26
PAPR	-0.57
Full-facepiece	-0.32
The correlation between perceived comfort and visual task completion time	
Dust Respirator	-0.05
PAPR	0.00
Full-facepiece	-0.14
The correlation between perceived comfort and cognitive task completion time	
Dust Respirator	-0.39
PAPR	-0.29
Full-facepiece	0.01

Table 10 shows the correlation between perceived comfort and change in errors committed while performing a task.

Table 10: Correlation between Perceived Comfort of a Respirator and Task Errors

The correlation between perceived comfort and errors committed while performing the fine motor task	
Respirator	Correlation (R)
Dust Respirator	0.32
PAPR	0.08
Full-facepiece	0.04
The correlation between perceived comfort and errors committed while performing the visual task	
Dust Respirator	0.01
PAPR	-0.09
Full-facepiece	0.01
The correlation between perceived comfort and errors committed while performing the cognitive task	
Dust Respirator	-0.35
PAPR	-0.13
Full-facepiece	0.1

The default feedback value for comfort when no respirator is worn is 1 (very comfortable). With a constant comfort rating, a correlation analysis is not feasible, and there is no correlation with the change in performance.

5. CONCLUSION

The hypothesis that none of the respirators would affect any task type in terms of task completion time or error was rejected. However, the rejection was based only on the significant effect of the full-facepiece respirator on errors made during the cognitive task. This suggests that employers should be cautious if a job requires a full-face respirator and is sensitive to mental abilities, such as critical decision making or vigilance. This finding is also supported by the high correlation between the perceived difficulty of the cognitive task while wearing the full-facepiece respirator and the error rate (R= 0.69). This was the highest correlation among all correlations analyzed between perception and performance. The other significant effect was from the dust respirator. Unexpectedly, the dust respirator resulted in reduced errors during the visual test. The researchers are at loss to explain this finding.

In addition to the ANOVA, the performance of each participant with respect to reaction to respirators was analyzed individually. The analysis showed that respirator preference was different from one participant to another and from one task to another. This variability in preferences concealed the ultimate effect of respirator tasks. This suggests that employers can allow workers to select their preferred respirators as long as the chosen respirators provide the required protection. A respirator that is comfortable for one individual could be uncomfortable for another. This point was never discussed in previous studies, which have tended to study the significance of one respirator over another and have concluded that certain types of respirators are more capable of decreasing human performance. Moreover, some experiments subject participants to severe conditions that could alone alter their performance. The current experiment, performed in an easy-to-moderate setting, concludes that under normal environmental conditions and with easy-to-moderate physical exertion, motor, visual and cognitive performance is not expected to change. On the other hand, performing a cognitive task while wearing a full-face respirator can increase the error rate.

From participants' perspectives, the dust respirator is the least comfortable respirator. This might be due to the accumulation of heat and humidity inside the dust respirator. However, the average task difficulty rating while wearing the dust respirator was the lowest among the three respirators for any of the three tasks. This incompatible feedback is also supported by the lack of a correlation between comfort and performance and between difficulty and performance when wearing the dust respirator. This could indicate that discomfort does not decrease performance. Heat and humidity were less in the PAPR and full-facepiece, as some participants noted; this contributed to the increased comfort rating for these two respirators. Other participants preferred the full-facepiece due its soothing effect. Compared to other respirators, full-facepiece respirators seem more stable and form a firmer seal on the face, which might explain the preference of some participants.

5.1 DISCUSSION

The results of this study contradict other studies, especially regarding changes in cognitive performance. Three similar studies (Caretti, 1997; Caretti, 1999; Zimmerman et al., 1991) concluded that there was no change in cognitive performance while wearing a respirator. The current experiment did not subject participants to any type of physical stress other than wearing the respirators. Yet, the effect of the full-facepiece respirator was significant. Workers can be less efficient and more vulnerable to safety risks if they wear full-facepiece respirators while performing jobs that involve complicated technologies, problem solving, advanced analytical skills, multitasking or decision making. Respirators should be selected with caution, and tasks should be designed according to workers' limited abilities while wearing certain respirators.

This study also found no significant effect of respirators on task completion time. The dust respirator and PAPR did not significantly affect task error rates. The effect of the full-facepiece respirator on fine motor and visual tasks was insignificant. The current study did not elevate the conditions of the experiment in order to affect participants' performance.

Further investigation is needed on non-military respirators. Other categories of respirators, such as atmosphere-supplying respirators, should also be studied. Researchers should be careful when selecting respirators and standardized tests for studies, and selection criteria should be established. Experimental design is also a major factor in reaching reliable and valid conclusions.

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CONCLUSION

This research investigated the effect of personal protective respirators on human abilities. A rigorous literature review and experimentation produced results that will contribute to knowledge of this subject for both researchers and employers. Such knowledge helps in achieving safer, more efficient human-system integration.

The literature review revealed that respirators affect the physiological and psychological abilities of humans. The effect varies with different types of respirators, environments and task types and difficulty levels. Respirators with higher APF values have a greater effect on the wearer's physiological and psychological ability, especially if the task involves physical activity. Some air-purifying respirators, such as dust respirators and half-face respirators, can have the same APFs but different physiological and psychological effects. Cognitive, visual and motor ability represented a grey area in the literature; therefore, the experiment was conducted to test these abilities.

The hypothesis that none of the respirators would affect any task type in terms of task completion time or error was rejected. Data analyses revealed that none of the respirators significantly affected task completion time. A significant increase was found in the error rate when participants performed the cognitive test while wearing the full-facepiece respirator. Employers should be cautious if a job requires a full-facepiece respirator and is sensitive to mental abilities, such as critical decision making or vigilance. Workers might be less efficient and more vulnerable to safety risks if they wear full-facepiece respirators while performing jobs that involve complicated technologies, problem solving, analytical skills, multi-tasking or decision making.

Subjective feedback revealed a high correlation between the perceived difficulty of the cognitive task performed while participants wore the full-facepiece respirator and the error rate (R= 0.69). This was the highest correlation among all correlations analyzed between performance and perceptions of comfort and difficulty. One finding revealed that respirator preferences vary among participants. A respirator that is comfortable for one individual could be uncomfortable for another, and this point was never discussed in previous studies. However, the overall analysis of comfort and anxiety feedback revealed that the dust respirator is the least comfortable respirator. This might be due to the accumulation of heat and humidity inside of it. However, the average task difficulty rating of participants wearing the dust respirator was the lowest among the three respirators for all three tasks. This incompatible feedback also was supported by the lack of a correlation between comfort and performance and between difficulty and performance when wearing the dust respirator. This indicates that discomfort did not decrease performance. Heat and humidity accumulate less in the PAPR and full-facepiece respirators, as some participants noted; this contributed to the increased comfort rating for these two respirators. Other participants preferred the full-facepiece respirator due its soothing effect. Compared to other respirators, full-facepiece respirators seem more stable and seal more firmly on the face, which might explain the soothing effect felt by some participants.

OSHA standard (1910.134) leaves an opening for employer judgment regarding the effect of respirators on workers' productivity. This gap in the standard suggests that workers must be alert to studies that investigate PPE limitations. For example, the word *anxiety* was only mentioned once in the standards, specifically as a yes/no question in

OSHA’s medical evaluation questionnaire. Conversely, the literature is rich with studies of the effect of respirators on human psychology. Another example of this room for judgment is OSHA’s recommendation regarding having written procedures as part of a respiratory program for a particular worksite. OSHA recommends that employers evaluate any respiratory hazards and identify relevant workplace and user factors when selecting respirators. A set of procedures highlighting the skills related to each specific task and how those skills may be affected by the respirator also should be considered.

Further investigation of non-military respirators is still required. Other categories of respirators, such as atmosphere-supplying respirators, also should be studied to expand the range of APF values investigated. Researchers should be critical when selecting respirators for use in experiments. Studied respirators must represent the types of respirators used commonly in various fields. Selection should be based on predefined criteria, thus simplifying the analysis and comparison of results. This also would allow results to be linked to an original criterion, thus making conclusions more significant and applicable to a wider range of respirators and applications. Selection criteria could include the respirator’s type or category, APF, weight, and dead space inside. The experimental design is also a major factor in reaching reliable and valid conclusions.

Some characteristics of the current study contribute importantly to the design of such studies. For example, this study uses the APF as a criterion in selecting respirators for investigation, and it discusses and links relevant OSHA standards to the research results. Previous studies have tended to draw conclusions that certain types of respirators are more capable of decreasing human performance. Moreover, some experiments subject participants to severe conditions that could alone alter their performance. Regardless of the methodologies utilized in some studies, the sample size in some instances was significantly low, which could reduce the power of the test or significance of the conclusion.

VITA

Anas Ahmed AlGhamri was born in Ankara, Turkey, on April 19, 1980. In April 2004, he received his B.S. in Industrial Engineering from the King Abdulaziz University, Jeddah, Saudi Arabia. He worked as a quality assurance engineer at Siemens for two years. In May 2009, he received his M.S. degree in Engineering Management from the University of Dayton, Dayton, Ohio, USA. In May 2012, he received his Ph.D. in Engineering Management from the Missouri University of Science and Technology, Rolla, Missouri, USA.