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Evaluation of Human Performance While Wearing Respirators

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16. Abstract

The goal of this study was to assess the feasibility of respirator use in Air Traffic Control and Technical Operations. We evaluated several models of Powered Air Purifying Respirators (PAPRs) and N95 respirators for usability, effects on human performance, and effects on the wearer's well-being. We found that binoculars could not be used with any of the PAPRs. Wearing a PAPR affected communication, but the characteristics of the respirator, especially the sound level and frequency spectrum of the noise, played a significant role in determining the extent of the effect and the subjective experience of wearing it. The accuracy levels of face-to-face communication were below those that were considered to be minimally acceptable. For the N95 respirators, we found negative effects on face-to-face communication and observed obstructiveness during simulated maintenance.

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Executive Summary

The movement of safe and efficient air traffic is particularly important to our nation's air transportation system in times of national emergency. In the event of a pandemic flu, the Federal Aviation Administration (FAA) may use various techniques to minimize the spread of disease. Some employees may telecommute; however, other employees may engage in tasks that cannot be accomplished remotely. Air Traffic Control (ATC) can only be accomplished at ATC facilities. Respiratory protection is one of the techniques that the FAA may adopt to minimize the spread of disease among staff that cannot function remotely. The goal of this study was to assess the feasibility of respirator use in ATC and Technical Operations. We evaluated several models of Powered Air Purifying Respirators (PAPRs) and N95 respirators for usability, effects on human performance, and effects on the wearer's well-being. We conducted the study in three phases. In Phase 1, we selected three PAPRs from eight alternatives. In Phase 2, we analyzed the sound levels and frequency spectra of the three PAPRs. We also measured human performance with the PAPRs and three N95 respirators. In Phase 3, we evaluated the effect of face-to-face communication when wearing PAPRs.

In Phase 1, we evaluated eight PAPR configurations and selected only three for use in later phases. We based the selection on predefined criteria and the results of several measures, including noise levels produced by each unit and the weight of each unit. We found that there were different features available with the PAPRs, some of which could increase the likelihood of successful use in ATC. We also found that binoculars could not be used with any of the PAPRs because of the face shield. Based on our criteria and the findings, we selected three PAPR configurations: (a) a loose-fitting head cover with the 3M™ Air-Mate™ blower, (b) a full hood with the Bullard PA20, and (c) a full hood with the North CA101.

In Phase 2, we analyzed the sound levels and frequency spectra of the noise generated by each of the three PAPRs. We measured human performance using the PAPRs selected in Phase 1 and three N95 respirators (3M™ 8511, 3M™ 9211, and North 4200) that we selected based on recommendations from the Environmental and Occupational Safety and Health (EOSH) Services Group. We evaluated the effects of using the PAPRs in two tasks: (a) Speech Intelligibility and (b) Visual Performance. We also evaluated the effects of wearing the N95 respirators in two tasks: (a) Speech Intelligibility and (b) Simulated Maintenance. Nine volunteers participated in the PAPR evaluation and two of the nine volunteers participated in the N95 evaluation. We used a repeated measures design, and each participant experienced all conditions.

The results of Phase 2 indicate that wearing a PAPR is likely to affect communication, but the characteristics of the respirator – especially the sound level and frequency spectrum of the noise – also play a significant role in determining the extent of the effect and the subjective experience of wearing the respirator. We observed significant effects on speech when wearing PAPRs, but there were no negative effects on visual performance. Although the participants complained about various aspects of the PAPRs, their ratings of comfort and well-being indicated only slight to moderate effects. For the N95 respirators, we found interference effects of face-to-face communication. We also observed differential ratings of obstructiveness during simulated maintenance.

In Phase 3, we measured performance of the Speech Intelligibility task during face-to-face communication with and without PAPRs. We found that the use of PAPRs had a very significant effect on speech intelligibility, with error levels exceeding those that are considered to be minimally acceptable.

If in the case of a flu pandemic the FAA decides to provide PAPRs to Air Traffic Controllers and N95 respirators to Technical Operations personnel, we recommend the following actions:

- Identify the specific requirements that must be met to reduce the negative effects of PAPR use on ATC tasks and N95 respirator use on Technical Operations tasks.
- Develop workarounds for tasks that cannot be performed with PAPRs.
- Verify that the selected PAPR does not present problems that may compromise safety in an operationally realistic setting.

Even though our results indicate that some types of PAPRs might be acceptable, our evaluation used standardized tests that are different from ATC tasks. There are many concerns that need to be evaluated in a more operationally realistic environment before recommending PAPRs for use by Air Traffic Controllers.

1. INTRODUCTION

The movement of safe and efficient air traffic is particularly important to the nation's air transportation system in times of national emergency. In the event of a pandemic flu, the Federal Aviation Administration (FAA) will use countermeasures to minimize the spread of the disease among its workforce and to maintain National Airspace System operations. The Environmental and Occupational Safety and Health (EOSH) Services Group (ATO-W) participates in the FAA's Crisis Response Working Group for flu pandemic and has tasked the Human Factors Team – Atlantic City (ATO-P) to evaluate whether Air Traffic Controllers and maintainers will be able to perform their operational tasks effectively while wearing respirators.

1.1 Overview

In the event of a pandemic flu, the FAA may utilize various techniques to minimize the spread of disease. Some members of the FAA staff may telecommute; however, others will be engaged in tasks that cannot be accomplished remotely. Air Traffic Control (ATC) can only be accomplished at ATC facilities. Respiratory protection is one of the methods that the FAA may adopt to minimize the spread of disease among staff that cannot function remotely.

One technology is the supplied-air respirator, in which an alternate supply of fresh air is delivered from a tank or from an uncontaminated area through a hose. Another is the Air-Purifying Respirator (APR) – the type considered in this study – which passes contaminated, ambient air through a filtering element. The ratio by which the filter reduces the concentration of contaminant is referred to as the Assigned Protection Factor (APF). The National Institute of Occupational Safety and Health (NIOSH) is the agency responsible for certifying respirators of all types.

There are several types of APRs available. The first type that we studied was the Powered Air Purifying Respirator (PAPR), in which a motor and blower delivers filtered air under positive pressure to the wearer through a hood or head cover (see Figure 1). Since any leakage will be outward, the PAPR does not need to be individually fitted. This type of respirator provides a high APF 1000 with a full hood and an APF 25 with a loose-fitting head cover.

Figure 1. An example of a Powered Air Purifying Respirator.[1]

[1] Photo obtained from the Bullard® website (www.bullard.com).

The second type that we studied was the N95 respirator – a negative-pressure APR – in which air is drawn through a filter as the wearer breathes (see Figure 2). This requires a close fit of the respirator to the face to prevent contaminated air from leaking around the filter. The APF for this type of respirator is typically lower than that for positive-pressure respirators. The N95 respirators that we used in this study reduce the concentration of contaminants by 95% and are in the *not oil resistant* NIOSH category.

Figure 2. An N95 respirator.

In 1992, the FAA issued hooded PAPRs to all the Air Route Traffic Control Centers (ARTCCs) as part of a plan to address widespread concerns of asbestos releases into the air. Controllers don these in the event of an asbestos release so they can hand off their traffic and leave the area. Even though PAPRs have been deployed at the ARTCCs for many years, the FAA has limited experience with the application of PAPRs in long endurance ATC operations.

Because controllers work in close proximity to each other, the FAA's Crisis Response Working Group for flu pandemic is considering the use of PAPRs for Air Traffic Controllers to prevent the spread of the disease. For the Technical Operations personnel, they are considering the use of an N95, a simpler and more compact type of respirator.

Prior studies evaluated the effects of wearing negative pressure respirators on cognitive performance and communication. Although cognitive performance seemed to be relatively unaffected (Caretti, 1999; Johnson, et al., 1997), even with long-term wear (Caretti, 1997), there were detrimental effects on communication (Johnson, et al., 2000). Face-to-face communication with respirators deteriorated quickly as the distance between the speaker and the listener increased (Coyne, Johnson, Yeni-Komshian, & Dooly, 1998).

The Air Traffic Controller's responsibility is to coordinate aircraft movements while maintaining safety with minimum delays (U.S. Department of Labor, 2006). They identify aircraft, issue clearances, monitor air traffic situations, resolve aircraft conflicts, manage air traffic sequences, route or plan flights, assess weather impact, and manage sector and position resources (Alexander, Alley, Ammerman, Hostetler, & Jones, 1987). Their primary tasks involve visual monitoring of tactical radar and auxiliary displays as well as ongoing communications with pilots (via headset), other controllers (via headset or face-to-face), and their supervisors (via face-to-face). Based on the literature, the use of a respirator is likely to degrade face-to-face voice communication (Coyne, et al., 1998) and may affect electronic communication over headsets. Likewise, a face shield may have a detrimental effect on the controller's ability to view critical information at the workstation. Furthermore, these effects may become magnified over time due to discomfort from the respirator or fatigue.

Technical Operations personnel perform maintenance tasks, monitor status displays, and communicate with the controllers. We do not expect that the N95 respirator will have any effect on visual performance or hearing because the respirator covers only the mouth area; however, the N95 respirator may affect communication.

1.2 Purpose

The goal of this study was to assess the feasibility of respirator use in ATC and Technical Operations. We used several models of each type of respirator to sample the available designs and to measure their differential effects (if any). This was not intended to be a market survey of respirators or a selection of the best alternative. To assess feasibility, we measured

1. sound levels of the respirators and their effect on speech intelligibility.
2. visual acuity and field of view.
3. visual detection.
4. ability to perform routine maintenance tasks.
5. subjective ratings of comfort.

We conducted the study in three phases. In Phase 1, we selected three PAPRs from eight alternatives. In Phase 2, we measured human performance with the three PAPRs and three N95 respirators. In Phase 3, we evaluated the effect of wearing PAPRs during face-to-face communication.

2. PHASE ONE

In Phase 1, we evaluated eight PAPR configurations and selected three for use in Phases 2 and 3. Our selection was guided by the following criteria:

1. Select one respirator from each of the three manufacturers represented.
2. Select the quietest respirator from each manufacturer.
3. Select one respirator that uses a loose-fitting head cover.
4. Select two respirators that use full hood head covers.

2.1 Method

2.1.1 Participants

Two members of the research team participated in this evaluation.

2.1.2 Materials and Equipment

A PAPR consists of a head cover or hood (used interchangeably in this report) that is connected to a blower worn on a belt around the waist. In the loose-fitting head cover the ears are exposed (see Figure 3), whereas in the full hood head cover, the head and shoulders are completely covered (see Figure 4). The blowers include a filter and battery pack and come in different sizes and configurations (see Figure 5). Some have all three components integrated into a single unit, whereas others have separate batteries or external filters.

Figure 3. A loose-fitting PAPR head cover.

Figure 4. A full hood PAPR.[2]

Figure 5. Three examples of PAPR blowers with battery packs and filters.

[2] Photo obtained from the North® website (www.northsafety.com).

In this phase, we evaluated a loose-fitting and a full hood head cover with each blower model (representing three manufacturers), for a total of eight PAPRs from available head covers and blowers.

2.1.3 Procedure

We conducted the following activities and selected three PAPRs (head cover or hood with blower combinations) based on the outcomes.

- **Acoustic evaluation**: We used a Bruel & Kjaer 2260 Observer sound level meter with a 1/4" pressure-field microphone to measure the sound levels produced by each PAPR blower at ear level in an anechoic chamber. We also analyzed the Speech Interference Levels (SILs) of the sounds.
- **Visual acuity and field of view**: We used the FAA Near Vision Acuity Snellen Chart (AAM Form 8500-1) to measure near (16") and distant (32") static visual acuity with and without PAPRs. We repeated these measures under daytime and nighttime conditions in the mock Airport Traffic Control Tower (ATCT) at the William J. Hughes Technical Center (WJHTC).
- **Use of other equipment**: We evaluated the effect of wearing the respirator on the use of binoculars and telephones.
- **Current FAA use survey**: We conducted telephone interviews with 17 Safety and Environmental Compliance Managers (SECMs), representing 17 ARTCCs, to establish an anecdotal understanding of current PAPR use and PAPR maintenance practices at the FAA. We used a Field Survey (see Appendix A) to guide the interviews.

2.2 Results

There were differences in the sound levels produced by the different blower units (ranging between 53 dB and 76 dB) and in their weights (ranging between 2 lb, 14 oz and 7 lb, 2 oz). We observed no differences between the PAPRs in visual acuity or field of view.

We found that it was impossible to use binoculars with any of the PAPRs because of the 2.5 in. distance between the eyes and the plastic face shield. The binoculars currently used in the ATCTs do not have a long eye relief. Even if a person could use long eye relief binoculars to accommodate the long distance between the face shield and the eyepiece, the binoculars are practically unusable because of the small field of view. The participants found it difficult to use telephones while wearing the full hood PAPRs.

There were differences in the features available with the various PAPRs. For example, some use a Nickel Metal Hydride (i.e., NiMH) battery, which provides no adverse memory effects, reduces disposal concerns, and is 30% lighter than Nickel Cadmium (NiCad) battery cells. Some units use a warning alarm when the battery is low, whereas other PAPRs alarm when the flow of air to the hood is blocked. Most units provide head covers in various sizes for a better fit. The full hoods had solid, adjustable headband suspensions that supported the hood on the head, whereas the loose-fitting head covers had soft cloth suspensions that could not be adjusted. Some models were available with either a vinyl or fabric belt.

The results of the Field Survey indicate that the current experience with PAPR use in ATC facilities is limited. Only 4 of the 17 ARTCCs have deployed the PAPRs since the FAA issued them in 1992. Of the four ARTCCs that indicated that they had deployed the PAPRs, one ARTCC reported more than 10 occasions and three of the ARTCCs reported fewer than five occasions – PAPR use during those occasions typically lasted less than 1 hour. However, one ARTCC reported that on one occasion PAPRs were used between 1 and 2 hours. The SECMs reported that those who had worn the PAPRs experienced perspiration and fogging of the face shield, which reduced their vision. The participants in the field survey reported problems in maintaining enough PAPR units and parts for all personnel. They expressed communication concerns of blower noise (they could not hear each other clearly because of the fan noise and airflow in the hood) and glare from the face shield. They also mentioned that the headset earpiece popped out inadvertently and that the tube between the hood and blower became disconnected with the slightest force.

There were numerous reports of battery problems (e.g., batteries not holding charges, difficulty charging batteries, and difficulty replacing batteries), broken head cradles and face shields, and difficulty locating replacement parts. Some SECMs reported that the face shield pulled away from the seal and hood because the glue did not successfully hold the hook and pile tape. The limited availability of replacement parts made their jobs more difficult because they had to develop workarounds.

When asked about the continuous use of the PAPRs, the SECMs expressed concern that the existing problems with the care and maintenance of the units could be exacerbated. One SECM suggested that it would be an abnormal circumstance to wear the PAPR for 8 hours and that a degradation of service to the flying public might result.

2.3 Discussion

Based on the guidelines and the findings, we selected the 3M™ loose-fitting head cover and the Air-Mate™ blower (see Figure 6) for the loose-fitting category. Among the respirators we tested, it was the quietest and weighed approximately 3 lbs. Even though we could configure the 3M™ blower with either a loose-fitting or a full hood, we had more options available for the full hood configurations with the other manufacturers.

Figure 6. The 3M™ Air-Mate™ blower with integrated filter and battery.

The PAPRs selected with full hoods were the Bullard PA20 and the North CA101 (see Figure 7). The Bullard had an inflatable collar that prevented outside air from leaking into the hood. It blew in air from the back of the head and weighed approximately 4 lbs. The North had three external filters, and the full hood had a simple straight-down shape. The air blew in just above the head to the space between the face shield and the face. This PAPR weighed approximately 4.25 lbs.

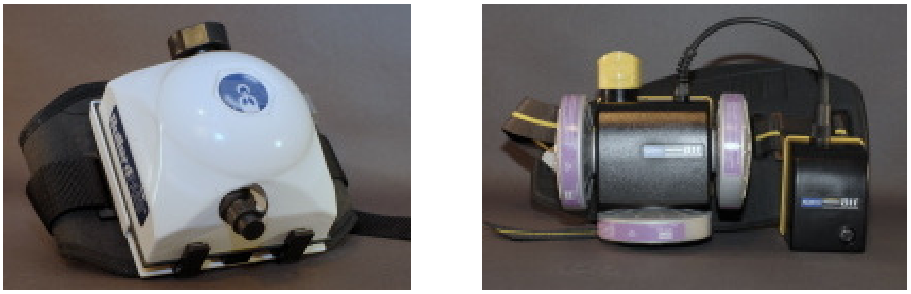

Figure 7. The Bullard PA20 (left) with integrated filter and battery and the North CA101 (right) with external filters and battery.

The participants noticed a difference in the amount of air flow between the three PAPRs. Their perception was that the North CA101 blew the most air and most intensely, with the Bullard PA20 next, and the 3M™ the least. The NIOSH requires all PAPRs to have an airflow amount above 6 cubic feet per minute (cfm). According to a North representative, the North CA101's airflow is 10.2 cfm with a freshly charged battery and a High Efficiency filter.[3] The Bullard literature lists the PA20 airflow as ranging from 7.3 cfm to 8.5 cfm. The 3M™ literature specifies that their blowers meet the NIOSH requirement.

Some of the features that were unique to one model or another may be beneficial in an extended use scenario. The battery alarm, for example, may be particularly useful with units that use NiCad batteries because the battery life decreases over time.

3. PHASE TWO

In the second phase, we measured human performance while using the three PAPRs selected in Phase 1 and three N95 respirators. Based on recommendations from the EOSH Services Group, we selected three N95 respirators (i.e., 3M™ 8511, North 4200, and 3M™ 9211) (see Figure 8).

Figure 8. The three N95 respirators (3M™ 8511, North 4200, and 3M™ 9211) tested in Phase 2.

[3] The High Efficiency filter approved by NIOSH must filter out 99.97% of particles that are 0.3 micrometers in diameter.

We evaluated the effects of using the PAPRs in two tasks: Speech intelligibility and Visual performance. We evaluated the effects of wearing N95 respirators in Speech Intelligibility and Simulated Maintenance tasks.

3.1 Method

3.1.1 Participants

Nine volunteers (3 female and 6 male) working at the WJHTC participated in this phase. The participants had diverse backgrounds and work experiences. Two participants were engineers, 2 participants were retired Air Traffic Controllers, 4 participants were Environmental Safety professionals, and 1 participant was an Engineering Research Psychologist. The ages of the participants also varied, with two of the participants being younger than 25 years, four between 25 and 35 years, one between 46 and 60 years, and two over 60 years of age. None of the participants had facial hair. Three participants wore glasses and 2 participants wore contact lenses. Two participants had some limited experience wearing respirators.

In accordance with the requirements of the Occupational Safety and Health Administration (OSHA) Regulation 29 CFR §1910.134, all nine participants along with one experimenter, who became the speaker for the Speech Intelligibility experiment, were enrolled in the Respiratory Protection Program (RPP) (OSHA, 2004). The participants completed the OSHA Respirator Medical Evaluation Questionnaire that was reviewed by a local medical examiner. All of the participants and experimenters attended a training session on the safe use of respirators, including limitations and capabilities of the respirators, proper donning and doffing procedures, and maintenance and storage of the respirators. The FAA Environmental and Safety Sub-Team (AJP-7932) assisted us in accomplishing all of the required clearances and OSHA RPP training.

3.1.2 Materials and Equipment

We developed three questionnaires: (a) a Background Questionnaire (see Appendix B) to collect relevant information about the participants, (b) a Health and Well-being Questionnaire (see Appendix C) to record their subjective experiences throughout the study, and (c) a Post-test Survey (see Appendix D) to collect feedback about their experiences with each respirator.

In addition to using the N95 respirators, described earlier, we used two styles of headsets (illustrated in Figure 9) during the Speech Intelligibility trials: an in-ear headset and an on-ear headset. These styles of headsets are commonly used by controllers. The participants chose the style they preferred to use in the study, and all but one participant used the on-ear headset.

Figure 9. In-ear (left) and on-ear (right) headsets.

For the Speech Intelligibility task, we used an American National Standards Institute (ANSI, 1989; ANSI §3.2) certified Modified Rhyme Test (MRT) word list containing 300 words. From this list we generated randomized sets of 75 words. Each set contained six monosyllabic words. Some sets had the same initial consonant (e.g., save, same, sale, sane, sake and safe) and some sets had the same final consonant (e.g., hold, cold, told, fold, sold, and gold).

In the Visual Performance Evaluation task, the participants played a game on a central 20-in. Cathode Ray Tube display while monitoring for a target on two 20-in. Liquid Crystal Displays, one on the left and another on the right sides. To represent the visual, cognitive, and motor demands of ATC tasks, we selected the games to be visually and cognitively demanding and used only those that required a keyboard or mouse input. Some of the options included an ATC simulator, Tetris, mazes, Fifteen Puzzles, and Sudoku. The target was a Landolt C (Coren, Porac, & Ward, 1984) (see Figure 10) in one of three sizes and in one of four orientations.

Figure 10. The Landolt C in two sizes and four orientations.

We used the same sound level meter, which we used in Phase 1, to measure sound levels in an anechoic chamber.

For the Simulated Maintenance tasks, we used three maintenance procedures for the removal and replacement of rack-mounted equipment, which included a monitor and keyboard, a voice recorder, and data cables. We also used a questionnaire (see Appendix E) to collect subjective data specific to the tasks.

3.1.3 Procedure

Before initiating the experiment, the participants received and signed a Statement of Ethics and Informed Consent (see Appendix F). It outlined the participants' rights regarding anonymity, confidentiality, and voluntary participation. We assured them (a) that all data and observations would be kept anonymous and (b) that no names (or other identifying information) would be associated with the data. We briefed them about the experiment and the general procedures.

To comply with OSHA Regulations (OSHA, 2004), all nine participants completed all of the requirements to become enrolled in the RPP. Three participants who volunteered for the N95 evaluation went through respirator fit testing. OSHA identifies the N95 face pieces as tight-fitting, and requires that those who will wear these respirators to be fit tested to ensure that they are adequately protected.[4] A Certified Industrial Hygienist fit tested the participants with each of the three N95 respirators (3M™ 8511, 3M™ 9211, and North 4200). She used a TSI Incorporated PortaCount® machine (Thermo-Systems Inc., 2008). The PortaCount® tester was based on a

[4] A fit factor of 100 is required. Fit factor is described as a quantitative estimate of the fit of a particular respirator to a specific individual. A fit factor estimates the ratio of the concentration of a substance in ambient air to its concentration inside the respirator when worn.

miniature continuous flow Condensation Nucleus Counter (CNC). The CNC grew submicron particles to supermicron alcohol droplets and then measured the concentration of the alcohol droplets. The participants donned their respirators and completed a series of eight challenges: normal breathing, deep breathing, head side to side, head up and down, talking, grimacing, bending over, and then again for normal breathing. Each challenge lasted approximately 1.5 minutes. The PortaCount® machine calculated a fit factor for all of the challenges with the exception of grimacing, which receives a qualitative evaluation. All three N95 volunteers passed the fit test with each of the three respirators, but one volunteer decided not to participate in the N95 evaluation.

After completing all of the OSHA RPP requirements, all of the participants completed the PAPR evaluation tasks (Speech Intelligibility and Visual Performance) for each of the three PAPRs. Two of the participants also completed the N95 evaluation tasks (Speech Intelligibility and Simulated Maintenance). Throughout the days of both PAPR and N95 evaluations, the participants completed the Health and Well-being Questionnaire approximately every 2 hours. After they finished evaluating each PAPR or N95, they also completed a Post-test Survey and provided comments about their experiences.

3.1.3.1 PAPR Evaluation

The participants experienced each PAPR for one day for a total of three PAPR evaluation days. During each day, they completed Speech Intelligibility and Visual Performance tasks. On the first day, they completed 5 practice trials in the Speech Intelligibility task. On each day, they participated in baseline sessions for Speech Intelligibility and on Days 1 and 2 for Visual Performance. Table 1 shows a sample schedule for a PAPR evaluation day. One of the key elements in creating the schedule was to ensure that the PAPRs were worn for at least 1 hour at a time, several times during each day.

Table 1. A Sample Schedule for a PAPR Evaluation Day

Time of Day	Length of Time (min)	Task
7:00	5	Well-Being Ratings
7:05	60	Baseline Visual Performance
8:05	25	Baseline Speech Intelligibility
8:30	5	Donning
8:35	25	Speech Intelligibility Session 1
9:00	5	Well-Being Ratings
9:05	60	Visual Performance Session 1
10:05	5	Well-Being Ratings
10:10	5	Doffing
10:15	60	Lunch
11:15	5	Donning
11:20	60	Visual Performance Session 2
12:20	25	Speech Intelligibility Session 2
12:45	5	Doffing
12:50	25	Speech Intelligibility Session 3
13:15	5	Well-Being Ratings
13:20	5	Donning
13:25	60	Visual Performance Session 3
14:25	5	Well-Being Ratings
14:30	10	Post-Test Survey
14:40	5	Doffing

For the Speech Intelligibility task, the participants and an experimenter used headsets to communicate. They were in separate rooms for this task and were not able to see each other. Each trial began when the experimenter spoke a word that was randomly presented on a computer monitor. The participant had to select the spoken word (from among six words displayed on the monitor) and say it back to the experimenter. The experimenter then selected either a *Yes* (if the read back was correct) or a *No* (if the read back was not correct). These trials were exercised through four different conditions:

- In condition 1, neither the experimenter nor the participant wore PAPRs (i.e., baseline condition).
- In condition 2, only the experimenter wore a PAPR.
- In condition 3, only the participant wore a PAPR.
- In condition 4, both the experimenter and the participant wore PAPRs.

The participants completed four Speech Intelligibility sessions each day. We presented 75 six-word sets at each session. We randomized the order of presentation and the positions of the target words. We recorded the participants' accuracy in identifying the spoken word and the experimenter's accuracy in hearing the read back. We also measured the participants' response time to identify the spoken word.

In the Visual Performance task, the participants always wore a respirator, except in the baseline conditions. The participants played a game of their choice on the central display and monitored two peripheral displays (one on each side) for the appearance of a Landolt C (see Figure 11).

Figure 11. Visual Performance task with a PAPR.

We presented targets an equal number of times on the left and right displays, in random locations, in one of three sizes, and in one of four orientations (see Figure 12). The participants' task was to detect the target and press a button on a pad to identify the position of the opening of the ring by pressing one of four buttons corresponding to the four cardinal positions. We recorded the participants' accuracy in the detection of the target and in the identification of its orientation.

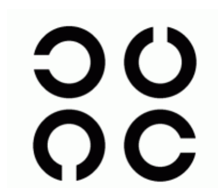

Figure 12. Landolt C in four orientations.

We collected additional sound level measures for each PAPR. We measured the sound levels and SIL for each PAPR. We also measured the sound levels produced when adding a Mode C Intruder (MCI) alarm or an additional PAPR.

3.1.3.2 <u>N95 Evaluation</u>

Two participants experienced all three N95 respirators during one day. They completed one session of Speech Intelligibility and one session of Simulated Maintenance with each N95. They also had one additional Speech Intelligibility baseline session during which they did not wear the respirators. The Speech Intelligibility procedures were the same as those used for the PAPR evaluation, but the participant and the experimenter were located in the same room.

In the Simulated Maintenance task, the participants completed one of the hardware maintenance procedures (see Appendix G) while wearing each respirator. For safety, the equipment was not powered during this test. The participants rated the difficulty of performing the maintenance tasks while wearing the N95 and also the difficulty of the maintenance task itself.

3.2 Results

In this section, we present the results of the evaluations conducted on the three PAPRs and three N95 respirators. First, we discuss the sound level measures for the three PAPRs, as those measures are pertinent to the Speech Intelligibility findings.

3.2.1 PAPR Sound Levels

The sound levels, measured in an anechoic chamber at fast mode (120 ms) under A weighting, showed large differences between the three PAPRs (see Table 2). We measured the sound at ear level for an experimenter wearing the PAPRs. The 3M™ PAPRs produced the lowest sound level at 52 dB (A), and the North PAPR produced the highest sound level at 81 dB (A). For reference, 50 dB (A) is the approximate noise level of an office, 60 dB (A) is the noise level near a freeway or inside a large store, and 70 dB (A) is the noise level of a freight train about 100 ft away or speech at 1 ft away (Peterson, 1972; Stevens & Davis, 1938). When a second PAPR was introduced approximately 1 ft away, the levels measured with the 3M™ and North increased, but the levels measured with the Bullard did not.

Table 2. Sound Level Measurements

Measure	3M™	Bullard	North
Inside the PAPR, at the ear	52 dB (A)	66 dB (A)	75 dB (A)
Inside the PAPR, at the ear, with a second blower on	60 dB (A)	66 dB (A)	79 dB (A)
Inside the PAPR, at the ear, with MCI alarm on: 75 dB (A)	70 dB (A)	66 dB (A)	81 dB (A)
SIL	40 dB	51 dB	64 dB

Note. PAPR = Powered Air Purifying Respirator; MCI = Mode C Intruder; and SIL = Speech Interference Levels.

We also evaluated the effect of wearing respirators on hearing an operational ATC alarm. We sounded the MCI alarm at 75 dB (A). When measured at the ear level of an experimenter who was not wearing a respirator (who stood 5 ft away from the alarm source), the sounds of the alarm and the blowers together were different for PAPRs. These differences were due to factors such as the amount of deflection caused by the head covers (depending on the blower noise, the material of the head cover, its size, etc.). For the 3M™ that exposed the ears, the combined sound level was 70 dB (A). It was 66 dB (A) for the Bullard and 81 dB (A) for the North.

The SIL of the PAPRs also showed large differences. The SIL is the average of the sound levels measured at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz without a weighting filter. This measure indicates the magnitude of the detrimental effect the sound has on the frequencies that are critical for speech perception. Verbal signals for critical functions shall be at least 20 dB above the SIL measured at the operational position, but should not exceed 90 dB (U. S. Department of Defense, 1999). Normal speech typically measures in the range of 60 dB (Levine & Shefner, 1981). Based on the SIL levels listed in Table 2, speakers would not need to raise their voices with the 3M™, but they would need to raise their voices substantially to 71 dB with the Bullard and to 84 dB with the North.

Our loudness sensitivity is higher at higher frequencies. Also, high frequency sounds are perceived as more annoying than low frequency sounds even if they have the same sound level. Consonants typically produce high frequencies between 1000 Hz and 5000 Hz (Schiffman, 1996) and are more critical in speech intelligibility than vowels (Bragdon, 1971). Therefore, noise that has strong high frequency components is more likely to interfere with speech. Figures 13 through 16 present the third-octave frequency analyses of the sound in the anechoic chamber and the sounds created by each PAPR. The anechoic chamber was not completely devoid of sound because of low levels of noise created by the light fixtures. The analyses revealed that the sound levels of the 3M™ were substantially lower in the high frequency range than those of the Bullard and North. The frequency spectrum patterns of the 3M™ (see Figure 14) did not differ much from those of the anechoic chamber (see Figure 13). In contrast, the noise levels in the high frequency levels of the North PAPR (see Figure 16) were much higher than those of the anechoic chamber.

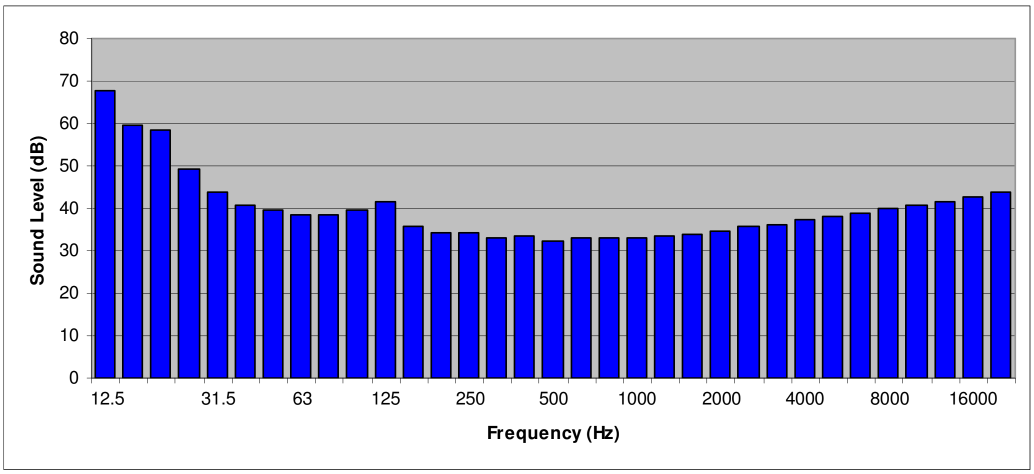

Figure 13. Frequency spectrum of the anechoic chamber.

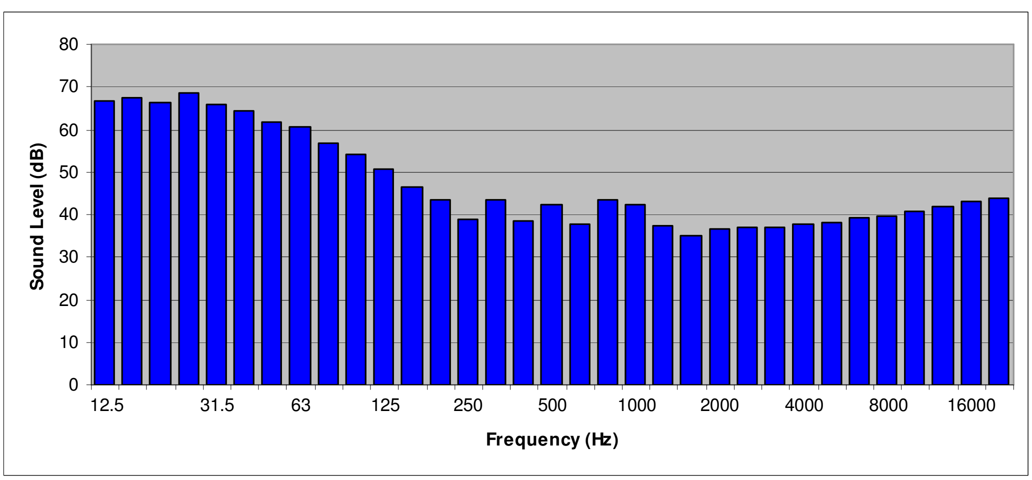

Figure 14. The 3M™ frequency spectrum.

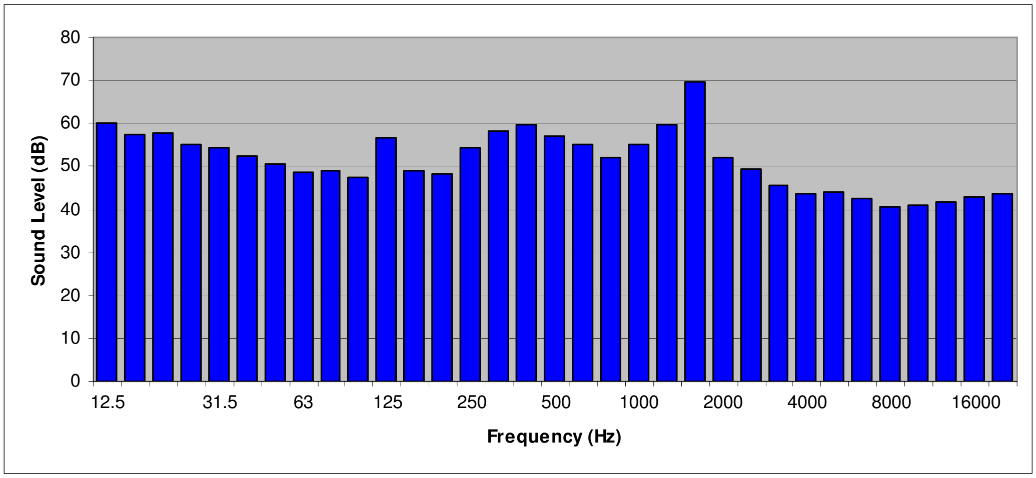

Figure 15. The Bullard frequency spectrum.

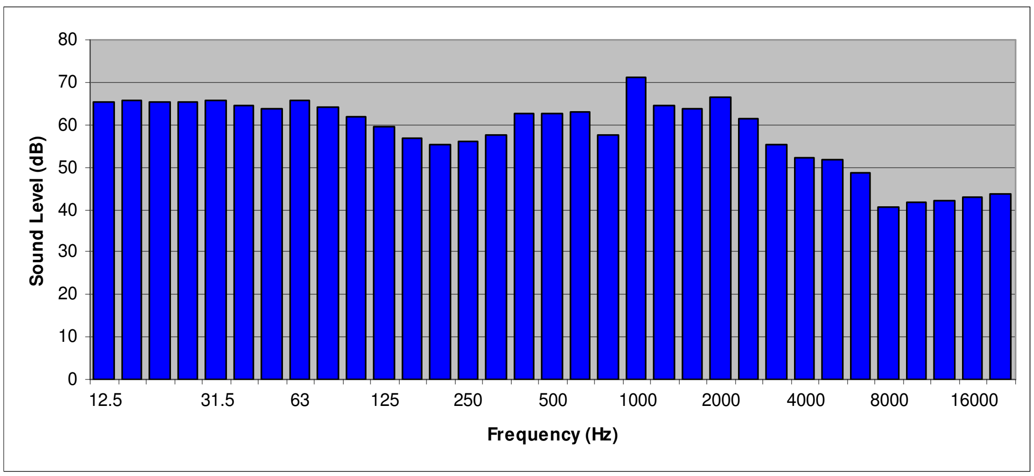

Figure 16. The North frequency spectrum.

3.2.2 Speech Intelligibility with PAPRs

Participant speech intelligibility errors ranged from 3% to 18% and varied widely, depending on the PAPR worn and the condition (see Table 3). We examined the effect of wearing a respirator on speech intelligibility using the recognition error frequencies for each PAPR separately. We used the Friedman test for four conditions representing PAPR wearing situations between the speaker and the listener: Speaker On & Listener On, Speaker On & Listener Off, Speaker Off & Listener On, and Speaker Off & Listener Off. The Friedman test results were not significant with 3M™, but were significant with Bullard, $\chi^2(3, N = 9) = 12.143$, $p = .007$ and North, $\chi^2(3, N = 9) = 18.341$, $p = .000$. The non-parametric Friedman test uses ranks across the levels of the variable and tests its statistics value against a Chi-square distribution.

Table 3. Speech Intelligibility Mean Error Rates and Standard Deviations

		Speaker (experimenter)					
		3M™		Bullard		North	
		Without Respirator	With Respirator	Without Respirator	With Respirator	Without Respirator	With Respirator
Listener (participant)	Without Respirator	0.03 (0.03)	0.04 (0.04)	0.04 (0.04)	0.12 (0.03)	0.04 (0.02)	0.18 (0.04)
	With Respirator	0.04 (0.05)	0.05 (0.03)	0.05 (0.06)	0.10 (0.06)	0.09 (0.07)	0.17 (0.07)

We performed the follow-up tests using Wilcoxon Multiple Matched-Pair Tests at $\alpha = .0083$ level to control the overall α level at .05 for each respirator. Only three pairs for North were statistically significant: Speaker On & Listener On vs. Speaker Off & Listener Off, $z = -2.668$ with $p = .008$; Speaker On & Listener On vs. Speaker Off & Listener On, $z = -2.692$ with $p = .007$; and Speaker On & Listener Off vs. Speaker Off & Listener Off, $z = -2.670$ with $p = .008$.

As shown in Table 3, the listener committed more errors when the speaker wore the respirator, regardless of whether the listener wore the respirator or not. These effects suggest that the interference occurred during the production of the spoken words.[5] The error rates by speech production and speech perception were not independent with the North PAPR, $\chi^2(1, N = 110) = 12.402$, $p = .000$. We observed a similar trend with the Bullard, $\chi^2(1, N = 110) = 2.517$, $p = .075$. The error rates for the 3M™ PAPR conditions were not significantly higher than those of the baseline condition where neither the speaker nor the listener wore a respirator.

We also analyzed the effect of wearing respirators on the experimenter's detecting the participant's read-back errors. There were two kinds of errors (a) the listener (i.e., the participant) selected and read back the correct word, but the speaker (i.e., the experimenter) thought it was the wrong word (i.e., miss) and (b) the listener selected and read back an incorrect word, but the speaker thought it was the correct word (i.e., false alarm). We present the frequencies of misses and false alarms (FAs) for each condition in Table 4.

Table 4. Miss and False Alarm Rates in Detecting Read-Back Errors

			Participant					
			3M™		Bullard		North	
			Without Respirator	With Respirator	Without Respirator	With Respirator	Without Respirator	With Respirator
Experimenter	Without Respirator	Miss	.02	.03	.02	.04	.02	.08
		FA	.18	.14	.11	.27	.24	.43
	With Respirator	Miss	.02	.04	.05	.04	.06	.08
		FA	.41	.26	.20	.34	.18	.54

[5] We are not suggesting that the act of speech production was affected by the use of respirators, rather that the observed effect occurred on the speaker's side of communication rather than the listener's. In this report "speech production" refers to the sound entering the communication channel.

Table 4 shows that both misses and FAs occurred more frequently when the Bullard and North PAPRs were used. We analyzed the misses using χ^2 tests. Even when the experimenter did not wear a respirator, he committed significantly more misses when the participant wore a Bullard PAPR, $\chi^2(1, N = 1285) = 6.827$, $p = .009$; or a North PAPR, $\chi^2(1, N = 1290) = 26.772$, $p = .000$, than when the participant did not wear a respirator. This effect suggests that misses are due to an effect on speech production. With the 3M™, the experimenter wearing the PAPR missed significantly more words when the participant also wore the PAPR than when the participant did not wear the respirator, $\chi^2(1, N = 1290) = 5.965$, $p = .015$. This pattern of findings, again, places the effect on the production end of communication.

For FAs, when the participant read back a wrong word and the experimenter recognized it as a correct word, there was a significant effect of the participant wearing the North PAPR. When the experimenter wore the North PAPR, he committed significantly more FAs when the participant also wore the respirator than when the participant did not wear the respirator, $\chi^2(1, N = 236) = 34.805$, $p = .000$, again, showing an effect of wearing respirators on speech production.

3.2.3 Visual Performance with PAPRs

We observed a learning effect from the first session of the Visual Performance task on Day 1 to following sessions. The first session was always a baseline condition in which the participants did not wear a respirator, but performance in this session was poor (on average, 34 missed targets) as compared to later sessions (on average, 11-14 missed targets). We excluded the data from this session in the analysis. Overall, the participants performed very well in this task and missed only a small number of targets. There were no differences in the patterns of performance between conditions. However, we observed large individual differences in the number of errors committed with each type of PAPR. One participant did not make any errors, whereas the other participants made many more errors with one of the PAPRs than with the other two. There were no clear patterns of performance for these participants.

3.2.4 Health and Well-Being Ratings with PAPRs

We examined rating differences for the Well-being Questionnaire (see Appendix C) between the first questionnaire, which participants completed prior to performing any tasks, and the last questionnaire of the day. Depending on the schedule for the day, the last questionnaire was sometimes administered just after a visual performance session when the participants did not use headsets. Thus, we did not include Item 4, which addresses fatigue from electronic communication, in the analysis.

The participants rated questionnaire items on a 4-point scale with higher ratings indicating greater discomfort. Figure 17 presents the mean ratings by item number for each PAPR. There was a greater increase in discomfort with the North and Bullard PAPRs than with the 3M™ respirators for many of the items.

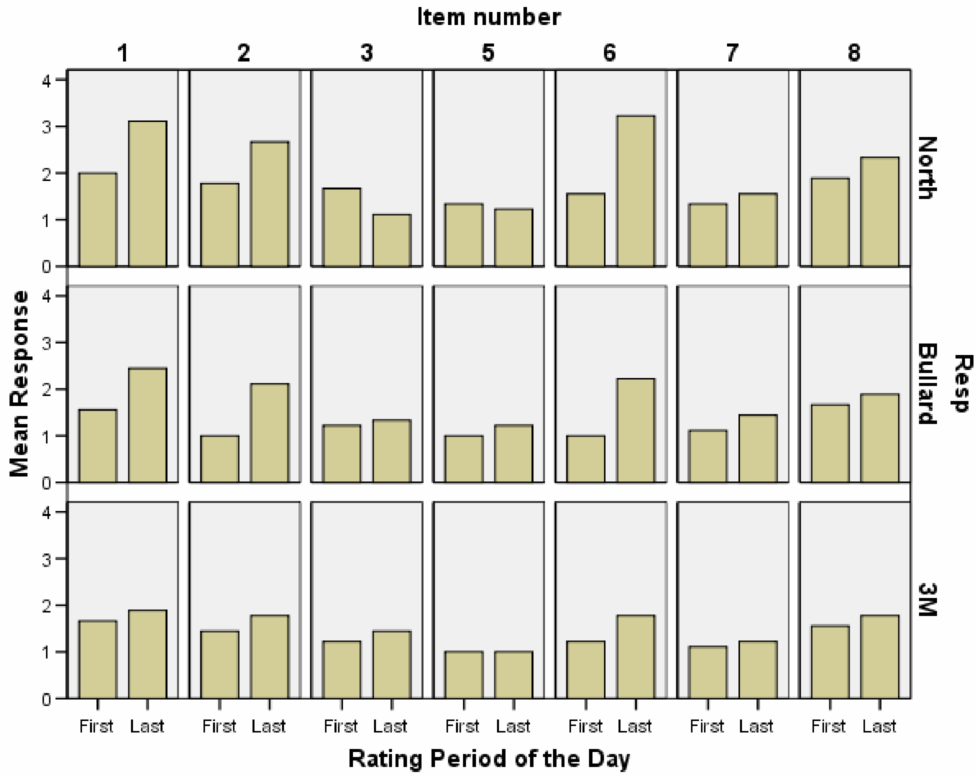

Figure 17. Mean well-being ratings for the first and last rating period by respirator and item number.

Wilcoxon signed-rank tests revealed no significant differences between the first and last ratings with the 3M™ respirators for any of the items. Rating increases were significant for Item 1, which asked how comfortable the participant felt with the Bullard PAPR (z = -2.530, p = .011) and the North PAPR (z = -2.456, p = .014). Item 6, which asked about overall noise levels, also showed significant increases with the Bullard PAPR (z = -2.636, p = .008) and the North PAPR (z = -2.280, p = .023). Item 2, which asked about eye strain, showed only a significant rating increase with the Bullard PAPR (z = -2.271, p = .023).

Even with the observed increases, overall ratings of discomfort on the last questionnaire were moderate with most means remaining below 2 (*very little/somewhat/slightly*).

3.2.5 Post-Test Surveys for PAPRs

Participants filled out Post-test Surveys (see Appendix D) after completing all tasks with each PAPR. They rated survey items on a 5-point scale, with higher values indicating greater discomfort. The results for Items 1 through 9 are illustrated in Figure 18. Overall, the ratings were higher for the North and the Bullard PAPRs than those for the 3M respirator (indicating greater discomfort). However, the Friedman tests for the survey items did not show significant results. Again, the ratings were low, overall, indicating rare occurrences of discomfort and slight to moderate levels of fatigue.

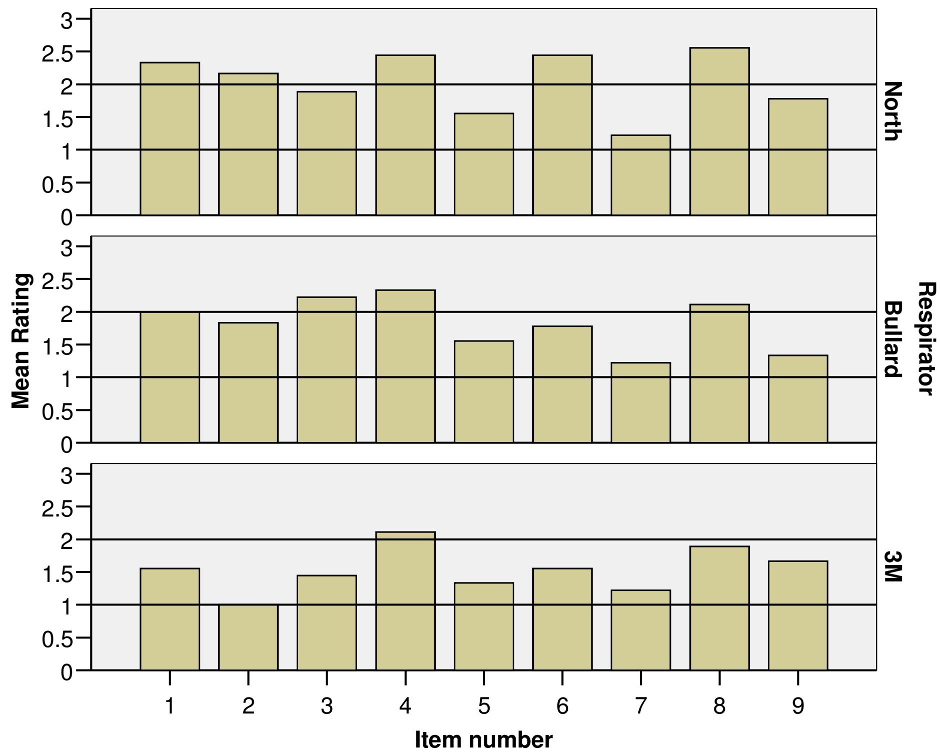

Figure 18. Mean ratings from the post-test survey by respirator and item number.

3.2.6 Subjective Comments on PAPRs

We reviewed the comments that participants made at the end of each day. One frequent comment with all three PAPRs was *difficulty hearing sounds (noise and speech) in the same room*. The following is a summary of the comments for each PAPR.

3M™: The more commonly reported problems were with glare and reflections from the face shield, as well as the noise and sensation of air passing over the ears (Participants' ears were exposed with the loose-fitting head cover). One of the participants said that he adjusted his breathing to reduce noise interference with the listening task in Speech Intelligibility trials. Several participants commented that the PAPR was comfortable overall.

Bullard: Several participants reported problems with the air blowing inside the hood. They complained of dry eyes and dry throats as well as of noise created by the air moving over the headset microphone. Another commonly reported problem was with glare off the face shield caused by overhead lights or the computer screens.

North: Eight out of nine participants reported problems with noise levels and communications. Most of the participants complained about the fit of the hood (reporting headaches from the head bracket, discomfort, inability to effectively position the headset, and irritation on the chin). Several participants reported problems from the air blowing across the face that caused drying or tearing of the eyes and dry lips.

We interviewed the participants after they finished Phase 2 to get their overall subjective evaluation of the respirators. Overall, they reported a preference for the 3M™ PAPR over the others because it was the quietest and most comfortable. Also, they could hear surrounding sounds best with the 3M™ head cover because their ears were exposed. However, participants reported that the North PAPR seemed to have a noticeably stronger air flow in the hood causing higher noise levels, problems with communications, and physical discomfort. The participants complained about the glare from the face shields of all the respirators tested. They also pointed out that the hoses were so stiff and short that it was difficult to maintain a comfortable sitting posture. Overall, they agreed that of the three respirators tested, the 3M™ would be best suited for extended wear.

3.2.7 Speech Intelligibility with N95 Respirators

An analysis of error rates in the face-to-face Speech Intelligibility task with N95 respirators revealed an overall increase in errors when the participants wore respirators (both speaker and listener wore the same N95 respirator) as compared to baseline (neither the speaker nor the listener wore a respirator), with differences between respirators ranging from an error rate of 0.0 to 0.16. Figure 19 illustrates that the performance of both participants was best with the 3M™ 8511 and worst with the North 4200.

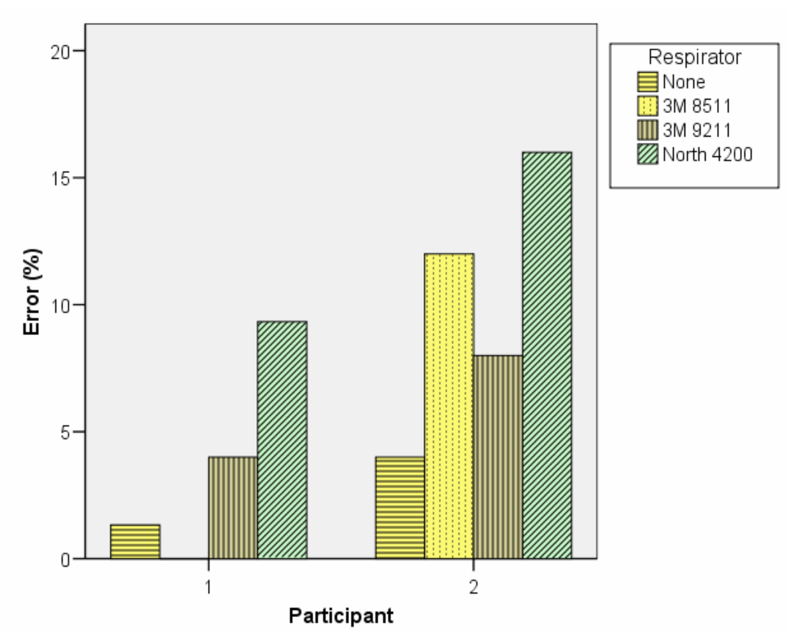

Figure 19. Speech intelligibility errors with N95 respirators.

3.2.8 Simulated Maintenance with N95 Respirators

The participants rated task difficulty and the obstructiveness of the N95 respirators on a 10-point scale that ranged from 1 (*minimally obstructive*) to 10 (*substantially obstructive*). Figure 20 shows that task difficulty did not influence the ratings of obstructiveness. The participants rated the 3M™ 9211 as least obstructive and the North 4200 as most obstructive.

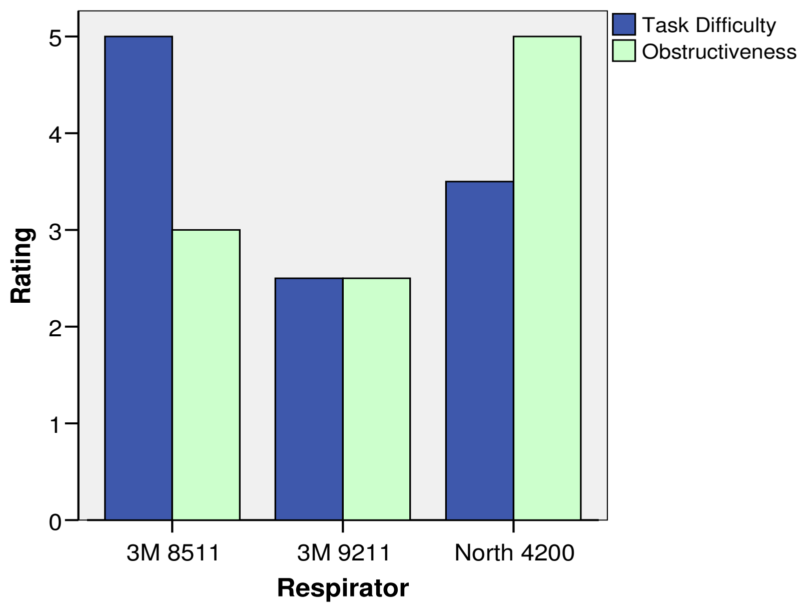

Figure 20. Mean ratings of task difficulty and respirator obstructiveness.

3.3 Discussion

Our findings fall into three categories: physical characteristics of the respirators, human performance, and participants' subjective opinions. The results suggest that wearing a PAPR affects human performance, but the characteristics of the respirator play a significant role in determining the extent of the effect and the subjective experience of wearing it.

We observed significant increases in errors from wearing respirators in the Speech Intelligibility task, with the levels of interference varying from one PAPR to another. This effect and the differences we observed are not surprising given the sound level analyses of the noise generated by each blower. There are differences in the loudness and frequency spectra for the different PAPR models, causing more or less interference with speech. The participants made fewer errors when wearing the 3M™ PAPR, which was the quietest of the three respirators and produced a frequency spectrum that was most similar to that of an empty anechoic chamber.

The participants made most errors with the North PAPR, which was the noisiest PAPR and had the strongest air flow inside the hood, and received many complaints about the fit of the hood. Error rates with the North PAPR ranged from 9% to 17%. A 9% error rate in the MRT is considered acceptable, but a 25% error rate is not acceptable for communication operational equipment (Ahlstrom & Longo, 2003, 7.4.1.2). These findings are of particular importance when considering PAPR use in ATC facilities because communication is such a critical aspect of the controllers' tasks.

In the Speech Intelligibility task, the participants played the part of both listener and speaker (for read backs), and in both cases the findings suggested that the effects of the PAPRs were primarily on the production side of communication. The perception of speech was less likely to be affected with headset use because headsets deliver the sound directly to the listener's ear.

Production, however, was affected by the noise of the respirator, the reverberation of breathing and noise inside the hood, and the sound of air moving across the microphone.

The findings from the Health and Well-being Questionnaire, the Post-test Survey, and the subjective evaluations are also related to the characteristics of the PAPRs. Ratings and comments were more favorable for the 3M™, which was tested with a lighter, less restrictive, loose-fitting head cover that left the ears exposed. The loose-fitting head covers were equipped with a soft headband suspension, which participants preferred over the hard plastic headgear inside the full hoods. Even the least favorable ratings were still in the moderate range, indicating that none of the PAPRs were perceived as very uncomfortable or having severe effects on the participants' well-being.

In general, we did not observe any effects of PAPR use on visual performance. The participants were able to detect and identify the orientation of targets while wearing respirators.

For the N95 respirators, we found interference effects on face-to-face communication. We also observed differential ratings of obstructiveness during simulated maintenance, with the North 4200 rated as most obstructive. The North 4200 was bigger than the other N95 respirators that we tested and was made of a rigid material.

4. PHASE THREE

In ATC, face-to-face communication occurs frequently between controllers, or with their supervisors, and is an important component of the operation. In Phase 3, we measured performance of the Speech Intelligibility task during face-to-face communication with and without PAPRs. We also measured the sound levels produced by the North PAPR in various face-to-face situations.

4.1 Method

4.1.1 Participants

Three members of our research team participated in the experiment.

4.1.2 Materials and Equipment

For the Speech Intelligibility task, we used the same setup as the one used for the N95 trials (i.e., face-to-face communication) in Phase 2, and we used all three PAPRs. For the sound analysis, we used only the North PAPR because we were interested in the general effect of wearing a PAPR. We used a Bruel & Kjaer sound level meter with a ¼-in. pressure field microphone in an anechoic chamber to measure sound levels.

4.1.3 Procedure

For the Speech Intelligibility task, the speaker and listener sat 52 in. apart. The speaker and listener wore the same type of PAPR and completed MRT trials in four conditions: one baseline condition and three experimental conditions. The presentation order of the four conditions for each participant was counterbalanced.

For the sound level measurements, a speaker and listener sat about 52 in. apart. The speaker read a word, and we measured sound levels at the ear of the listener. We collected measures in four conditions:

- In condition 1, neither the speaker nor the listener wore the North PAPR.
- In condition 2, only the speaker wore the North PAPR.
- In condition 3, only the listener wore the North PAPR.
- In condition 4, both the speaker and the listener wore North PAPRs.

4.2 Results

In the Speech Intelligibility task, the noise generated by the respirators affected the participants' ability to correctly recognize spoken words. Mean error percentages with PAPRs ranged from 32% to 55% compared to only 6% for the baseline condition. Figure 21 illustrates the increase in errors for each type of PAPR. There were fewer errors committed with the 3M™ PAPR than with the Bullard and North PAPRS.

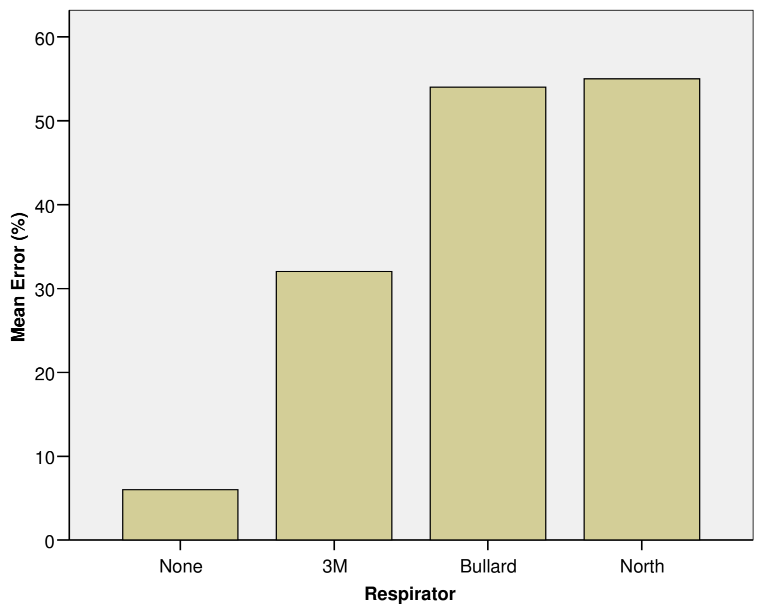

Figure 21. Mean error percentages in the face-to-face speech intelligibility task.

The sound level of the empty experimental room was 50 dB (A). The sound level at the listener's ear was 60 dB (A) when words were spoken while both speaker and listener did not wear respirators (i.e., the baseline condition). As can be seen in Table 4, the noise levels increased substantially when the listener wore the North PAPR, with no additional increase when the speaker also wore the PAPR.

Table 5. Sound Level Measurements for the Different Conditions

		Speaker	
		Without Respirator	With Respirator
Listener	Without Respirator	60 dB (A)	63 dB (A)
	With Respirator	75 dB (A)	74 dB (A)

4.3 Discussion

In Phase 3, we learned that face-to-face communication is problematic with the use of PAPRs. The effect of the Bullard and North PAPRs were greater than that of the 3M™ PAPR due to their higher noise levels. As we discussed earlier, MRT accuracy of 75% is considered minimally acceptable (Ahlstrom & Longo, 2003, 7.4.1.2). The NIOSH requires that communication, as measured with the MRT, be at least 70% accurate when the speaker and listener are 3 m apart (NIOSH, 2008). Our participants sat at a distance of 1.3 m, and performance with the Bullard and North was at 46% and 45%, respectively. This is well below both the Human Factors Design Standard (HFDS) and NIOSH standards. The 3M™ PAPR came closest to meeting the standard with an accuracy of 68% at the shorter distance than the distance of the standard test.

The sound levels of the respirator drowned out the spoken words. As we reported in Phase 2, the North PAPR generates sound levels of approximately 75 dB and a SIL of 64 dB. For critical speech to be heard over this sound, it would need to be 20 dB higher than a SIL of 84 dB (U. S. Department of Defense, 1999), a level that is much higher than the sound level of normal speech.

5. SUMMARY AND CONCLUSION

The purpose of this study was to evaluate the feasibility of conducting ATC and Technical Operations tasks while wearing respirators. We address the feasibility of N95 use by Technical Operations personnel first. Ratings of obstructiveness while performing simulated maintenance tasks varied with different styles of the N95. Similarly, the N95 respirators had differential effects on communication. This indicates that some N95 respirators would be more feasible for use by Technical Operations personnel than others.

Air Traffic Controllers work in close proximity to each other and may require higher levels of protection than those offered by the N95 respirators. Furthermore, the N95 respirators would likely interfere with the headsets that controllers use for communication. For these reasons, the FAA Crisis Response Working Group is considering the use of PAPRs that can provide higher levels of protection than the N95 respirators and that can accommodate headsets. Our findings suggest that there are many potential problems with this approach that would need to be addressed. Although our results indicate that some types of PAPRs might be acceptable, our evaluation used standardized tests that are different from ATC tasks. Therefore, many concerns need to be evaluated in a more operationally realistic environment before recommending PAPRs for use by Air Traffic Controllers.

The participants complained about glare from the PAPR face shield, but they completed visual performance tasks without much difficulty. However, the most critical problem was that participants experienced difficulties in communication while wearing respirators. The effects on speech perception were small, but those on speech production were substantial. This was due in part to the fact that the headsets delivered speech directly to the listener's ear (i.e., speech perception). The sound of the spoken words (i.e., speech production) was affected by the noise of the respirator, the reverberation inside the hood, and the sound of air moving across the microphone.

We found that the use of PAPRs had a very large effect on speech intelligibility in face-to-face communication, with error levels exceeding those that are considered to be minimally acceptable by several standards (Ahlstrom & Longo, 2003; NIOSH, 2008). This is significant because face-to-face communication occurs frequently between supervisors and controllers at ATC facilities.

Some of the other findings that greatly affect feasibility arise from the physical characteristics of PAPRs. In Phase 1, we found that binoculars could not be used effectively with the PAPRs. This eliminates the possibility of using PAPRs in the ATCTs, where use of binoculars is sometimes required. Wearing the respirators while in a seated position was also problematic. Our participants had to adjust the position of the blower on the belt to the side because they did not want to lean back against the blower unit. Even with the adjustment, the PAPRs were far from comfortable for working in a seated position. This is significant because Air Traffic Controllers work in a seated position.

The participants also complained about airflow intensity with some models causing physical discomfort. The participants rated the 3M™ loose-fitting head cover as more comfortable than the full hoods. However, the boom attached at the earpiece of the headset extended towards the mouth under the elastic around the jaw. This created a small gap between the head cover and the face, which might have affected the APF.

The ambient noise generated by the PAPRs is another area of concern. The HFDS (Ahlstrom & Longo, 2003, 12.12.5-12.12.7) indicates that ambient noise in operational areas requiring frequent phone use or occasional speech communications shall not exceed 55 dB (A). With the use of some PAPRs, ambient noise levels exceeded this standard. This increase would require speakers to raise their voices significantly to be heard over the noise.

The findings of this feasibility study are consistent with the reports from the controllers in the field who experienced problems with PAPRs. In addition, the field survey identified existing problems with the availability of spare parts and the maintenance of the hoods and batteries.

If in the case of a flu pandemic the FAA decides to provide PAPRs to Air Traffic Controllers and N95 respirators to Technical Operations personnel, we recommend that they consider the findings of this study and conduct the following risk mitigation activities.

1. *Identify the specific requirements that must be met to reduce the negative effects of PAPR use on ATC tasks.*

The findings of differential effects of the PAPRs suggest that there are characteristics of these respirators that make them more or less feasible for use in communication-intensive tasks such as ATC. In particular, the noise levels produced by the blower, the extent to which the blower interfered with speech, and the characteristics of the head cover or hood probably contributed most to the observed differences. Specific requirements can be derived from the findings reported here for a PAPR that optimizes controller performance and comfort. They include, but are not limited to, requirements for respirator noise level, air flow direction and intensity, hood material, size and weight of the blower unit, PAPR fit, flexibility and length of belts and tubes, and glare off the face shield.

2. *Develop workarounds for tasks that cannot be performed with PAPRs.*

Our results indicated that some tasks could not be accomplished effectively while wearing PAPRs. Since the requirements for performing these tasks are not likely to go away, workarounds should be developed. For example, speech intelligibility for face-to-face communication while wearing PAPRs was too low to be acceptable. The electronic devices can be used for face-to-face communication even when the speaker and listener are next to each other.

3. *Verify that the selected PAPR does not present problems that may compromise safety in an operationally realistic setting.*

This safety issue is especially important because the tasks we used to evaluate feasibility were not representative of the components of ATC. In the Speech Intelligibility task, the participants listened to each word – one word at a time. Controllers use different types of words and speak very quickly. We have measured controller speech during ATC simulations to reach levels of about 300 words per minute. Although one of the PAPRs that we evaluated performed better than all the others, its true impact on ATC tasks will need to be evaluated in a more realistic environment. We recommend shadow mode operations, at an ATC facility, as the most realistic test.

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Acronyms

ANSI	American National Standards Institute
APF	Assigned Protection Factor
APR	Air Purifying Respirator
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATCT	Airport Traffic Control Tower
CNC	Condensation Nucleus Counter
EOSH	Environmental and Occupational Safety and Health
FA	False Alarm
FAA	Federal Aviation Administration
HFDS	Human Factors Design Standard
MCI	Mode C Intruder
MRT	Modified Rhyme Test
NiCad	Nickel Cadmium
NIOSH	National Institute of Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PAPR	Powered Air Purifying Respirator
RPP	Respiratory Protection Program
SECM	Safety and Environmental Compliance Manager
SIL	Speech Interference Level
WJHTC	William J. Hughes Technical Center

Appendix A

Field Survey

Field Survey

The purpose of this survey is to gather lessons learned from the past deployment of Powered Air Purifying Respirators (PAPRs). The following questions address your experiences of PAPR use and maintenance. Please answer to the best of your ability. All responses will be kept anonymous.

Background

The following questions will allow us to describe the sample of participants.

1. What is your current position? ______________________
2. How long have you been in the current position? ______

PAPR Use and Maintenance

3. How many times have PAPRs been used since their deployment at your facility?

   __ less than 10 times __ 10 to 25 times __ more than 25 times

4. What was the typical duration of use? _______
5. What was the longest duration of use? _______
6. Were there any reported difficulties with use of the PAPRs?

   ____

   ____

7. Are there any maintenance activities that are scheduled periodically, such as replacement or cleaning of filters, replacement of batteries, etc.? How often are they performed?

   ____

   ____

   ____

8. Do you anticipate any maintenance concerns with continuous use of the PAPRs?

   ____

   ____

9. Is there any initial or refresher training on PAPR use provided to the staff? How often is the refresher training provided? ____

10. How often are best-fit tests performed? ______________________________________

11. Do you have any additional comments?

____

Appendix B

Background Questionnaire

Background Questionnaire

The purpose of this survey is to gather background information about the individuals who participate in this research. The questions in the survey address participants' personal information, work experience, and their workplace customs (habits). All responses will be kept anonymous.

1. What is your current position/job function? ____
2. How long have you worked in the current position? ______________months / years
3. How often do you wear a respirator on the job?

   __ Never __ Rarely __ Sometimes __ Regularly __ Always
4. How many hours/week or hours/month do you wear a respirator? ___________
5. What is your age?

   __ less than 25 years __ 25-35 years __ 35-45 years __ 46-60 years __ more than 60 years
6. What is your gender?

   __ Female __ Male
7. If Male, do you wear facial hair? __ Beard __ Moustache __ None
8. Do you wear corrective lenses? __ Yes __ No
9. If yes, then what type? __ Glasses __ Contacts
10. Do you have any experience in the air traffic control environment? __ Yes __ No
11. If yes, please describe.

    ____
12. Is there anything else we should know about your participation in this study?

    ____

    ____

Appendix C

Health and Well-Being Questionnaire

Health and Well-Being Questionnaire

We would like to know how the respirator affects your comfort and perceptions. Please circle the answer that best describes your perceptions.

1. How comfortable did you feel over the previous work interval?	Very comfortable	Comfortable	Slightly uncomfortable	Uncomfortable
2. Do you feel any eye strain?	None	Very little	Some	Very much
3. Do you feel any fatigue in your voice from face-to-face communication?	None	Very little	Some	Very much
4. Do you feel any fatigue in your voice from electronic (i.e., telephone or headset) communication?	None	Very little	Some	Very much
5. Did you feel any shortness of breath during the work interval just completed?	None	Very little	Some	Very much
6. What was the overall noise level during the work interval just completed?	Quiet	Somewhat noisy	Noisy	Very noisy
7. How stressed do you feel right now?	Not at all	Slightly	Moderately	Extremely
8. How fatigued do you feel right now?	Not at all	Slightly	Moderately	Extremely

Appendix D

Post-Test Survey

Post-Test Survey

Please complete this survey to the best of your ability. Consider your perceptions and condition over the entire day.

I. Physical and mental state

	Never	Rarely	Occasionally	Regularly	Constantly
1. Presence of physical pain	1	2	3	4	5
2. Feeling of tension or stiffness in your spine	1	2	3	4	5
3. Incidents of fatigue or low energy.	1	2	3	4	5
4. Incidents of congestion or sneezing	1	2	3	4	5
5. Incidents of headaches (of any kind)	1	2	3	4	5
6. Incidents of dizziness or light-headedness	1	2	3	4	5

	Slight		Moderate		Severe
7. If pain was felt, rate the intensity	1	2	3	4	5
8. Highest level of fatigue you felt today	1	2	3	4	5
9. Highest level of stress you felt today	1	2	3	4	5

II. Overall impressions while using respirators

	Never	Rarely	Occasionally	Regularly	Constantly
1. I felt confined by the respirator	1	2	3	4	5

	Immediately	Quickly	After a while	Eventually	Never
2. I got accustomed to wearing the respirator	1	2	3	4	5

	Excellent	Good	Moderate	Fair	Poor
3. Overall my physical well-being is:	1	2	3	4	5
4. Overall my ability to handle stress is:	1	2	3	4	5

	Very low	Low	Moderate	High	Very High
5. Overall workload	1	2	3	4	5

6. Did wearing the respirator impact the quality of your work in any other way? Please explain.

____

____

____

Appendix E

Simulated Maintenance Task Questionnaire

Simulated Maintenance Task Questionnaire

Participant ID:

Date:

Time:

N95 Respirator:

Task:

1. How difficult was the task?

Easy									Difficult
1	2	3	4	5	6	7	8	9	10

2. How obstructive was the respirator in completing the task?

Minimally									Substantially
1	2	3	4	5	6	7	8	9	10

Appendix F

Statement of Ethics and Informed Consent

Evaluation of Human Performance While Using Powered Air Purifying Respirators

Statement of Ethics and Informed Consent

Nature and Purpose of Activity

Thank you for volunteering to participate in the Evaluation of Human Performance While Using Air Purifying Respirators. This is a feasibility study that will evaluate the effects (if any) of respirator use on human performance in tasks analogous to those used in Air Traffic Control.

Who is Eligible to Participate?

Any adult volunteer who can qualify for the Respiratory Protection Program is eligible to participate.

Experimental Procedures

We will explain the procedures and your rights and responsibilities before you begin. The study lasts five days and each daily session will last approximately eight hours. During the first day we will ask you to complete a well-being questionnaire while performing your normal job function. During the remaining four days we will ask you to use several respirator systems; a different one each day. We will ask you to perform communication tasks, visual detection tasks, and simulated maintenance tasks. You will be asked to rate your comfort while wearing the respirators throughout the days. You will never wear a respirator for more than two hours at a time. For some of the communication tasks, we will ask you to wear a headset. For the maintenance tasks, you may lift items of no more than 5 kg. (10 pounds) and use hand tools.

Data Collection Methods

At the beginning of the study we will ask you to complete a background questionnaire. During the communication tasks we will ask you to listen to words and select the spoken word from a list on a visual display, or to speak words. During the visual detection tasks we will ask you to press a key on a keyboard when you detect and recognize targets while playing a video simulation or game. We will ask you to complete a well-being questionnaire periodically throughout the study. Researchers will observe all activities.

Discomforts and Risks

While you are wearing a respirator, you may feel warm or claustrophobic, or experience shortness of breath. While these sensations typically pass in a few minutes, please inform the researcher about any such discomfort as soon as it occurs.

Benefits

Participation in this study provides no direct benefit to you. Your participation benefits the FAA and its workforce in that the data will be used to make future decisions about the use of respirators while performing specific job functions.

Participant's Responsibilities

The results of this effort depend greatly upon your attention to the required tasks, and upon forthright responses to the questionnaire. If there is something you do not understand, please ask a researcher. In addition, to avoid biasing the results, please do not discuss the study with other potential participants until the study is completed in about 30 days.

Participant's Assurances

Researchers from the Human Factors Team – Atlantic City maintain strict standards regarding participant confidentiality and informed consent in all our activities. Our standards are based on the *Ethical Principles in the Conduct of Research with Human Participants* by the American Psychological Association and FAA Order 9500/25, and are structured around four main principles:

- Your participation in this study is completely voluntary. You may withdraw from this assessment at any time without consequence. If you feel you must withdraw for whatever reason, please inform us immediately. In addition, the researchers may terminate your participation if they believe this to be in your best interest.
- Your responsibilities will be clear. We will explain everything to you and answer all your questions.
- Your identity will be kept anonymous. Your responses will be identified by a code known only to you and the researchers conducting the assessment. Your identity will be kept separate from the data you provide. To facilitate this, please do not write your name or any other identifying marks on the questionnaires. Please do not share your participant code with anyone other than the researchers. Your name will not be associated with any data contained in any report or briefing.
- The data you provide will be kept confidential. The *raw* data collected in this assessment will become the property of the Human Factors Team – Atlantic City. The raw data will be analyzed by specialists from this organization and its contractor employees. The raw data will not be made available to other organizations without your permission. The *aggregate* data from this assessment will be presented in briefings and reports made by the group. These data will take the form of averages, standard deviations, and other statistics.
- Results – The Study Report will be provided upon request.

If you have any questions about this study or need to report any adverse conditions you may contact the researchers conducting the study, the Primary Investigators Dr. Tanya Yuditsky or Dr. Sehchang Hah. You may also contact Dr. Earl Stein (609) 485-6389, the Human Factors Team – Atlantic City Manager, at any time with questions or concerns.

I have read this consent document. I understand its contents, and I freely consent to participate in this study under the conditions described. I have received a copy of this consent form.

Research Participant: ______________________ Date: _____________

Investigator: _____________________________ Date: _____________

Witness: ________________________________ Date: _____________

Appendix G

Simulated Maintenance Procedures

1. Remove and Replace Chassis Mounted Monitor and Keyboard

A. Remove

1. Open front and rear doors of cabinet.
2. Ensure power cables for cabinet are disconnected.
3. From the front of the cabinet, release the thumbscrews and pull the computer handle until the slide locks engage.
4. Disconnect the power, keyboard, and monitor connections at the rear of the computer assembly.
5. Using a screwdriver, remove the 4 small screws on the rectangular box located at the rear of the computer. NOTE the short and long screw positions.
6. Remove the cable alignment arm away from computer assembly. NOTE the position/alignment of the cable arm assembly.
7. Release the slide locks by pushing them in and remove the computer from the cabinet.

B. Replace

1. Align slide rails of the computer with the chassis rails and push the computer forward until it clicks/locks into place. Ensure the cable connections are free.
2. Reinstall the cable alignment arm and screws removed in step 5.
3. Install the power and keyboard connections onto the cable alignment connectors. Ensure monitor connector is not restricted.
4. Connect monitor cable.
5. Check computer slides for operation and restrictions, by pushing in the slide locking tabs and sliding the computer into the chassis.
6. Push computer in and engage the thumbscrews.
7. Close computer chassis doors.

2. Remove and Replace a Voice Recorder

A. Remove

1. Open front and rear chassis doors.
2. Locate and note the placement of the Marantz Voice Recorder.
3. Disconnect electrical power cable.
4. Remove power cable and data dressings. WARNING: Cable ties may be sharp and cause injury. Use caution.
5. Remove cable jacks. NOTE the location and labeling of each cable to facilitate installation at a later time.
6. Remove the 4 screws that secure the Marantz Voice Recorder to the front of the chassis. CAUTION: Unit may be heavy when released. Use caution. Do not permit the equipment to fall.
7. Remove voice recorder from chassis.

B. Replace

1. Install voice recorder into position and secure to chassis with 4 screws. Ensure power cable is not restricted or constrained.
2. Connect and dress power cable.
3. Connect and dress data cable jacks into proper location.
4. Close and secure the chassis doors.

3. Remove and replace Data Cable

1. Open front and rear chassis doors.
2. Locate the Marantz Voice Recorder Deck A inputs on the rear of the assembly and remove. NOTE the location and labeling of each cable to facilitate installation at a later time.
3. Remove the left and right XLR inputs and the left ¼" input jacks on the Yamaha Digital delay assembly.
4. Remove cable ties and cable assembly. WARNING: Cable ties may be sharp and cause injury. Use caution.
5. Install the new cables into the proper location.
6. Dress the cables for safety and security.
7. Close front and rear chassis doors.