Human Performance
While Wearing Powered Air-Purifying Respirators (PAPRs)

We evaluated a loose-fitting head cover Powered Air-Purifying Respirator (PAPR) and two full hood PAPRs for communication-intensive workers such as air traffic controllers. We measured the sound levels of respirator blowers and analyzed the frequency spectrum of the blowers. Nine volunteers participated in the speech intelligibility and visual performance experiments for three days. We administered questionnaires to collect their feedback on respirator use. Our results showed that wearing a PAPR negatively affected both face-to-face and headset communications, usability, and comfort level significantly. The characteristics of the respirator, especially the sound level and frequency spectrum of the noise, played a significant role. We also found that it was impossible to use binoculars while wearing any of the PAPRs because of the distance between the eyes and the plastic face shield of the hood, about 2.5" (6.35 cm).

Various organizations use respirators to protect their employees against harmful agents such as asbestos and particles carrying flu viruses. However, wearing them may degrade performance. Communication-intensive workers such as telephone operators and air traffic controllers may not perform their tasks well while wearing respirators. Controllers monitor tactical radar and auxiliary displays visually and communicate verbally with pilots (via headset), other controllers (via headset or face-to-face), and their supervisors (face-to-face).

There are different types of respirators. One type of respirator supplies fresh air from a tank or from an uncontaminated area through a hose. Another is the Air-Purifying Respirator (APR), which passes contaminated, ambient air through a filter delivered by a blower (Powered Air-Purifying Respirators [PAPRs]) or breathed in by a wearer (a negative-pressure APR).

In this report we present our evaluation results of the PAPRs. We could not find any previous research reports about the effect of wearing PAPRs on human performance. However, there were a few research reports about the effect of wearing the negative-pressure APRs on cognitive performance and communication. They reported detrimental effects on communication, but no cognitive performance degradation (Johnson, et al., 2000).

Our goal was to assess the feasibility of PAPR use in verbal communication-intensive work such as air traffic control. We did not intend to perform a market survey of respirators or a selection of the best respirator. We used several models of respirators to sample the available designs and measure their effects on performance. We conducted the study in three phases. In Phase 1, we selected three PAPRs from eight available PAPRs to us. In Phase 2, we measured speech intelligibility and evaluated visual performance with the selected three PAPRs. In Phase 3, we evaluated the effect of wearing them during face-to-face communication.

PHASE ONE

We evaluated eight PAPR configurations that were available to us and selected three of them for detailed evaluations in Phases 2 and 3.

Method

Participants.

Two members of the research team participated in this evaluation.

Materials and Equipment.

We evaluated a loose-fitting head cover, a full hood cover, and a hardhat with three blower models representing three manufacturers, for a total of eight cover and blower combinations (see Figures 1 and 2). We used a Brüel & Kjær 2260 Observer sound level meter with a Brüel & Kjær 1/4" pressure-field microphone (Model Number: 4938) to measure sound levels generated by the blowers.

Figure 1. A PAPR with a loose-fitting head cover (left) and a PAPR with a full hood cover (right).

Figure 2. PAPR blowers we evaluated (PAPR1, PAPR2, and PAPR3 from the left to the right).

Procedure.

We evaluated sound levels, visual acuity and field of view, and usability of binoculars and telephones while wearing PAPRs.

Results

There were large differences in the sound levels produced by the different blowers, but no significant differences between the PAPRs in visual acuity or field of view. We found that it was impossible to use binoculars while wearing PAPRs because of the distance between the eyes and the plastic face shield of the hood, about 2.5" (6.35 cm). The participants found it difficult to use telephones while wearing the full hood PAPRs. We selected three PAPRs: one (PAPR1) in the loose-fitting head cover category and two (PAPR2 and PAPR3) in the full hood category (see Figures 1 and 2). PAPR1 weighed about 3 lbs (1.4 kg). PAPR2 weighed approximately 4 lbs (1.8 kg). PAPR3 had three external filters unlike PAPR1 and PAPR2 and weighed approximately 4.25 lbs (1.9 kg).

PHASE TWO

This phase lasted three days. We evaluated human performance in speech intelligibility and visual tasks. We also measured the noise levels of the PAPRs and collected the participants' feedback about their experience with the PAPRs.

Method

Participants.

Nine volunteers (3 females and 6 males) participated in this phase. Three participants wore glasses and two participants wore contact lenses. The ages of the participants varied: two of the participants were younger than 25 years, four between 25 and 35 years, one between 46 and 60 years, and two over 60 years of age.

Materials and Equipment.

We used the three selected PAPRs. For electronic communication between the speaker (i.e., the experimenter) and the listener (i.e., the participant) during the speech intelligibility experiment, we used two styles of headsets (illustrated in Figure 3) that are used by air traffic controllers. The participants chose the style they preferred to use in the experiment, and all but one participant chose the on-ear headset.

Figure 3. In-ear (left) and on-ear (right) headsets.

For the speech intelligibility task, we used the Modified Rhyme Test (MRT) certified by the American National Standards Institute (ANSI) (ANSI, 1989). The test consisted of 50 sets of six monosyllable words. The six words of each set had either the same initial consonant (e.g., save, same, sale, sane, sake, and safe) or the same final consonant (e.g., hold, cold, told, fold, sold, and gold). For the visual performance task, the participants played a game on a central 20-in. (50.8 cm) cathode-ray display while detecting a target randomly appearing on either of two 20-in. liquid-crystal displays (see Figure 4). The target was a Landolt C in one of three sizes and at one of four orientations of the opening. We also used questionnaires to collect feedback about the participants' experiences with each respirator.

Figure 4. Visual performance task set up (left) and the Landolt C in four orientations of the opening (right).

Procedure.

To comply with Occupational Safety and Health Administration (OSHA) Regulations (OSHA, 2004), all nine participants completed the requirements to enroll in the Respiratory Protection Program (RPP). This meant that each met minimum health standards. All participants completed an Informed Consent Form.

The participants completed speech intelligibility and visual performance experiments with one of three PAPRs each day.

For the speech intelligibility experiment, the participants and an experimenter were in separate rooms and used headsets to communicate. The participants completed four speech intelligibility sessions of 75 trials each day. The four sessions represented four combinations of PAPR wearing conditions between the speaker (i.e., the experimenter) and the listener (i.e., the participant): speaker with a PAPR & listener without a PAPR, speaker without a PAPR & listener with a PAPR, both with PAPRs, and neither of them with a PAPR.

For each trial, the participant had to select the spoken word among six options displayed on the monitor, click on it with the mouse, and read it back to the experimenter. The presentation order of the conditions was randomly selected for each participant. For the visual performance experiment, the participants' task was to detect the target (Landolt C) and press one of the four buttons on a pad corresponding to the position of the opening of the C. The participants wore a respirator in the experimental session but did not wear it in the baseline session. Each visual performance session lasted an hour.

On Day 1 and Day 2, they started the day with a baseline visual performance session followed by a speech intelligibility session. They had three more experimental visual performance sessions with a respirator on both Day 1 and Day 2. On Day 3, they did not have the baseline visual performance session and thus had only three experimental visual performance sessions.

We also measured the sound levels produced by each PAPR blower by the wearer's ear in an anechoic chamber at the fast mode (120 ms) with A-weighting.

Results

The sound levels showed large differences between PAPRs (see Table 1). The range of the sound levels was between 52 dB (A) of PAPR1 and 75 dB (A) of PAPR3. For reference, 50 dB (A) is the approximate noise level in an office, 60 dB (A) is the noise level near a freeway, inside a large store, or of normal speech (Bragdon, 1971; Levine & Shefner, 1981), and 70 dB (A) is the noise level of a freight train about 100 ft (30 m) away or speech at one foot (30 cm) away (Peterson, 1978).

Table 1
Sound Levels at the ear inside the PAPR

Measure	PAPR1	PAPR2	PAPR3
Equivalent continuous sound level with A-weighting	52 dB (A)	66 dB (A)	75 dB (A)
Speech Interference Level (SIL)	40 dB	51 dB	64 dB

The Speech Interference Level (SIL) of the PAPRs also showed a large range from 40 dB for PAPR1 to 64 dB for PAPR3 (see Table 1). The SIL is the average of the sound levels measured at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz of octave bands without a weighting filter. We used 1/3-octave bands.

The spectra of the PAPRs showed that the sound levels of PAPR1 were substantially lower at high frequencies than those of PAPR2 and PAPR3. 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 1,000 Hz and 5,000 Hz (Schiffman, 1996) and are more critical in speech intelligibility than vowels (Bragdon, 1971).

Speech Intelligibility.

Participant speech intelligibility errors ranged from 3% to 18% and varied widely depending on the PAPR worn and the condition they were in (see Table 2). We examined the effect of wearing a respirator on speech intelligibility using the recognition error frequencies for each PAPR separately. We used Friedman test for four conditions representing PAPR wearing conditions between the speaker and the listener. The Friedman test results were not significant with PAPR1, but were significant with PAPR2, χ^2 (3, N=9) =12.143, p=.007 and PAPR3, χ^2 (3, N=9) =18.341, p=.000.

We performed the follow-up tests using Multiple Matched-Pair Wilcoxon Tests at α=.0083 level to control the overall α level at .05. Only three condition pairs for PAPR3 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), (Speaker On & Listener Off vs. Speaker Off & Listener Off, z = -2.670 with p = .008).

Visual Performance.

Overall, the participants performed well in this task and missed only a small number of targets. There were no differences in the patterns of performance between conditions and between PAPRs, but two participants committed far more errors than others.

Well-Being Ratings, Surveys, and Comments.

We examined the rating differences between the first well-being questionnaire which the participants filled out before performing any tasks and the last one which they filled out at the end of the day. Wilcoxon Signed-Rank Tests revealed no significant differences with PAPR1 for any of the items. Rating increases were significant with PAPR2 (z = -2.530, p = .011) and PAPR3 (z = -2.456, p = .014) for Item 1, which asked how comfortable the participant felt. Item 6, which asked about overall noise levels, also showed significant increases with PAPR2 (z = -2.636, p = .008) and PAPR3 (z = -2.280, p = .023). Item 2, which asked about eye strain, showed a significant ratings increase only with PAPR2 (z = -2.271, p = .023). There were no significant differences in other questionnaire items.

Participants filled out surveys at the end of the day after completing all tasks with a PAPR. Overall, the ratings for PAPR2 and PAPR3 showed higher discomfort levels than PAPR1, but none of the individual χ^2 tests for the survey items across the respirators was significant.

The participants reported a preference for PAPR1 over the others because it was the quietest and most comfortable. Also, they could hear surrounding sounds best with it because their ears were exposed. They reported that PAPR3 had 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. They also found that wearing the respirators in a seated position was very problematic because hoses were too stiff and short.

Table 2
Speech intelligibility Mean Error Percentages

		Speaker (i.e., Experimenter)					
		PAPR1		PAPR2		PAPR3	
		Without Respirator	With Respirator	Without Respirator	With Respirator	Without Respirator	With Respirator
Listener (i.e., Participant)	Without Respirator	3	4	4	12	4	18
	With Respirator	4	5	5	10	9	17

Discussion

The participants made most errors with PAPR3, which was the noisiest and had the strongest air flow inside the hood. Error rates with PAPR3 were 17% when both the speaker and the listener wore it and 18% when the speaker wore it but the listener did not wear it. The negative effect was more pronounced at the speech production side, that is, when the speaker spoke while wearing the respirator, especially PAPR3 as Multiple Matched-Pair Wilcoxon Test results showed.

In tasks where voice communication is critical such as air traffic control, a 25% error rate in the MRT is considered to be unacceptable (Ahlstrom & Longo, 2003). Thus, 17% and 18% are close to the unacceptable level. Ratings and comments were more favorable for PAPR1 which had a lighter, less restrictive, and loose-fitting head cover leaving the ears exposed. It was equipped with a soft headband suspension, which participants preferred over the hard plastic headgear inside the full hoods.

In general, we did not observe significantly negative effects of PAPR use on visual performance. However, we observed large individual differences in the number of errors committed.

PHASE THREE

We measured speech intelligibility during face-to-face communication with and without PAPRs. We also measured the sound levels produced by PAPR3 in various face-to-face communication situations.

Method

Participants.

Three members of our research team participated in the experiment.

Materials and Equipment.

For the speech intelligibility experiment, we used all three PAPRs. For the sound level analysis, we used only PAPR3 because we were interested in the general effect of wearing a PAPR on speech intelligibility. We used the same sound level meter with the same ¼-in. pressure-field microphone we had used in Phases 1 and 2.

Procedure.

During the speech intelligibility experiment, the speaker and the listener sat approximately 52 in. (1.32 m) apart in the same room. In the baseline condition, they did not wear a PAPR. Both the speaker and the listener wore the same type of PAPR in three experimental conditions. The presentation orders of the four conditions for the participants were counterbalanced. For the sound level measurements, the speaker and the listener sat about 52 in. (1.32 m) apart. The speaker spoke a word, and we measured sound levels at the ear of the listener.

Results

Accuracy rates were 68% for PAPR1, 48% for PAPR2, and 45% for PAPR3 compared to 94% for the baseline condition when neither the speaker nor the listener wore a PAPR.

The sound level of the experimental room was 50 dB (A). The sound level at the listener's ear when words were spoken and no respirators were used (i.e., baseline condition) was 60 dB (A). As can be seen in Table 3, the noise levels increased substantially when the listener wore PAPR3.

Table 3
Sound Levels of Face-to-Face Communication Conditions with PAPR3

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

Discussion

In Phase 3 we learned that face-to-face communication was very problematic with the use of PAPRs. The effects of PAPR2 and PAPR3 were greater than that of the PAPR1 due to their higher noise levels. The National Institute of Occupational Safety and Health (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 their accuracy rates were 48% with PAPR2 and 45% with PAPR3. These are well below the NIOSH standard. The accuracy rate of PAPR1, 68%, was also slightly below the NIOSH standard. We believe these rates will fall to lower rates at the NIOSH distance.

The Federal Aviation Administration (FAA) Human Factors Design Standard (HFDS) (Ahlstrom & Longo, 2003) states that verbal signals for critical functions shall be at least 20 dB above the SIL measured at the operational position. As we reported in Phase 1, the SIL of PAPR3 was 64 dB (see Table 1). For speech to be heard over this sound level, it should be at 84 dB (A), a much higher level than normal speech sound level, 60 dB (A).

GENERAL DISCUSSION

The participants complained about glare from the PAPR face-shield, but they completed visual performance tasks without much difficulty. The most critical problem was that participants experienced difficulties in both headset and face-to-face communication while wearing respirators. The sound of the spoken words was affected by the noise of the blower, the reverberation inside the hood, and the sound of air moving across the microphone.

We found that the use of full hood PAPRs had very large effect on speech intelligibility in face-to-face communication with accuracy rates far below than those that are considered to be minimally acceptable by existing standards (Ahlstrom & Longo, 2003; NIOSH, 2008). We found that binoculars could not be used effectively with the PAPRs. This eliminates the possibility of using PAPRs in the Air Traffic Control Towers, where use of binoculars is required. The participants complained that all the respirators and hoses were too stiff and short to maintain a comfortable sitting posture. This is significant because most air traffic controllers work in a seated position.

The HFDS (Ahlstrom & Longo, 2003) indicated that ambient noise in operational areas requiring phone use or speech communications should not exceed 55 dB (A). Two full hood PAPRS we tested generated higher noise level. This would require a speaker to raise their voice significantly to be heard over the noise.

Even though our results indicated that the loose-fitting head cover PAPRs might be acceptable for headset communication, our evaluation used standardized tests that were quite different from the real tasks such as air traffic control tasks. During the speech intelligibility experiment, the participants listened to one word at a time. Controllers use different types of words and speak very fast. We found controller speech rate during air traffic control simulations about 300 words per minute. Therefore, many concerns need to be evaluated in a more operationally realistic environment before recommending any PAPRs for use by communication intensive workers.

We believe the detailed findings reported here will be useful to design better PAPRs for communication-intensive workers.

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