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Effects of respirators on performance of physical, psychomotor and cognitive tasks

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Possible work decrements caused by respirator usage were examined. A battery of physical, psychomotor and cognitive tasks was used to investigate the effects of respirator wear on 12 subjects. A repeated measures experimental design was used to study the effects of three types of respirators: a disposable dust mask; an air purifying half-mask; and a full-face airline mask. Performance while wearing a mask was compared to the control condition without a respirator. The results from the physical work task of riding a bicycle ergometer indicated approximately a 10% increase in oxygen consumption when subjects wore half and full-face masks in comparison to when they performed the tasks without a mask. The results indicate that wearing the respirators did not have a significant effect on the performance of cognitive tasks but did affect significantly the performance of psychomotor tasks such as steadiness of work performance and movements requiring accurate control for positioning of objects.

1. Introduction

The exposure of workers to hazardous amounts of toxic chemicals has long been a concern to labour, management and governmental agencies. The preferred approach to reducing these hazards is a programme of engineering and administrative controls to protect workers by reducing or eliminating the hazards at the source. When the work environment cannot be controlled adequately or during emergencies, respiratory protection equipment must be relied on to protect the operators.

At least three approaches should be used in selecting respirator masks. First, the ability to protect the worker from toxic agents should be evaluated. Second, the cost of using the particular respirator must be considered. Third, the effects of operator performance while wearing the respirator must be determined. This study evaluates only the effects of the respirator on the comfort and performance of the wearer. Although many evaluative tools have been used to determine the effectiveness of a respirator's operation or its physiological effects on the wearer, little attention has been paid to the quantitative assessment of respirator effects on the performance of an operator's task. Such an assessment would be useful not only for evaluating the respirator in terms of worker acceptance, but also in terms of worker productivity. This latter evaluation has major economic implications with regard to determining the true overall cost of different types of respirators or of respirator usage versus engineering control.

In the past, evaluations of respirator effects have concentrated only on the physiological work decrement (Raven *et al.* 1979, Louhevaara 1984). Work decrements as large as 20% resulting from respirator wear were reported. These findings, however, were attributed mainly to the weight of large, bulky respirators, such as self-contained breathing apparatus. A number of studies did not differentiate between the combined effects of respirator usage and heat stress (Goldman 1970, James *et al.* 1984, Johnson and Cummings 1975). Other studies examined the combined effects of respirator usage and protective clothing (Goldman 1963, Atterbom and Mossman 1978, Martin and Goldman 1972). Where some studies, such as that of Louhevaara *et al.* (1985), showed increased workload requirements with respirator usage and therefore reduced productivity, others such as Dahlback and Balldin (1984) did not observe any effect, perhaps because their experimental design did not allow for a true control condition with no respiratory interference to the subject during his/her exercise.

By contrast, a review of the literature by Morgan (1983) indicated that little is known about cognitive decrements and psychomotor decrements. Withey (1981) stressed the need for a systematic study of respirator effects using a battery of tasks. Goldman (1985) felt that tasks involving decision-making and judgment would suffer from performance decrements before physical tasks. Since performance effects of respirators may be task dependent, a battery of tasks was selected to describe respirator effects sufficiently.

2. Methods

A comprehensive study was conducted to investigate test procedures which could be used to determine quantitatively any decrement in work performance due to the use of a respirator. The subjects' responses were monitored while wearing three types of respirators and performing three tasks. The three types of work tasks, physical, psychomotor and cognitive, were selected to represent the broadest spectrum of simulated work tasks.

Physical performance was tested with subjects pedaling a cycle ergometer at a constant rate and with a constant load. The bicycle load was designed to simulate a moderate work rate for an average healthy subject, of approximately 280 to 350 W (Astrand and Rodahl 1986). Work decrement was estimated indirectly by the increase in oxygen consumption ($\dot{V}O_2$), which was correlated to measured heart rate (HR).

Psychomotor performance involves motor behaviour, typically combining manual manipulation and decision making, and forms the basis of much repetitive industrial work. Fleishman (1975) identified 11 psychomotor factors which describe a spectrum of psychomotor abilities. The following four of Fleishman's 11 factors were chosen as being representative for the types of performance required while wearing respirators: arm-hand steadiness; control precision; finger dexterity; and reaction time.

The steadiness task tested the first factor of arm-hand steadiness. The pursuit rotor task measured both arm-hand steadiness and the second factor of control precision. The one hole test evaluated the third factor of finger dexterity. The fourth factor of reaction time was measured by a four choice reaction time task. The hand dynamometer which measured grip strength served as an additional diagnostic aid in evaluating respirator effects on psychomotor skills. Due to the physiological studies on mask usage (Raven *et al.* 1979), one might expect to see patterns of work decrement on the psychomotor tasks tested in this experiment.

The third category of tasks was cognitive. Due to the repeated measures design of the study, the selection of the cognitive tasks was limited to those which would show no obvious effects of practice. Tests were also selected based on the availability of material to occupy subjects for the total time of experimentation. These constraints led to the selection of standardized Miller Analogy, GRE logical and GRE analytical tests as well as a hypothesis test (Levine 1966).

2.1. *Subjects*

Twelve male Purdue University students with an average age of 20·5 years (range: 18 to 24 years), average height of 1·85 m (range: 1·70 m to 2·01 m and average weight of 77 kg (range: 61 kg to 93 kg) participated in this experiment. To control for as many subject-related variables as possible, a careful prescreening of the potential subjects was performed. Non-smoking college students with no chronic illnesses, allergies or asthma were accepted. In addition, a subject was only accepted if he did not need to wear glasses during the tests, had no excess facial hair and had no abnormal facial characteristics, three important factors in fitting respirators. Finally, subjects of average physical fitness status (determined by their indication of participation in three to four weekly exercise sessions) were considered optimal.

All subjects underwent a medical evaluation which included a questionnaire similar to that used in the Occupational Safety and Health Administration (OSHA) Asbestos Standard (US Code 1989), a physical examination and a pulmonary function test. The questionnaire included questions pertaining to physical characteristics, past medical conditions, respiratory ailments, family medical histories, presence of a persistent cough or wheezing, personal habits such as smoking and level of exercise. Only two potential candidates had to be rejected, one due to subnormal spirometry and one due to obesity. All 12 accepted subjects were normal by examination and spirometry.

Subjects were fit-tested for the half-mask respirator to ensure adequate fit. Subjects were trained in donning and wearing the full-face airline respirator. They attended a 2 h respirator wearer's training and orientation programme before beginning the actual experimental sessions to simulate the same experience that a typical worker would receive. During the experiment, subjects used their preferred dominant hand, which, for this sample was the right hand.

2.2. *Respirators*

The three respirators chosen for the study were selected to represent the more commonly used types of respirators in industry and included: a disposable dust mask (3M Model 8710); a rubber half-mask with High Efficiency Particulate Air (HEPA) cartridges (North Series 7700–30); and a full-facepiece airline respirator in pressure-demand mode (Drager Nova Model) with Grade D breathing air supplied from compressed air cylinders. Small, medium and large face pieces were available for the half-mask in the fitting sessions, with one subject requiring a small, seven subjects wearing medium-sized ones and four subjects needing a large. The disposable and full-face masks were of one standard size.

2.3. *Experimental design*

The purpose of the experiment was to compare the performance of subjects on various tasks under four conditions involving respirators. These were control (no mask), dust mask, half-face mask and full-face mask. To maximize the power for these comparisons, a repeated measures design was used. Each subject performed the physical, cognitive and psychomotor tasks under each of the respirator conditions of interest.

There is no standard time interval for typical industrial usage of respirators. The time interval can range from a few minutes to 8-h. The experimental session length was set at 2 h, which was judged to be of sufficient duration to allow the effects to be observable. Each 2-h session was broken down into three 40-min sub-sessions, or trials, in which the subject worked for the first 30 min, followed by a 10 min rest period. In any given session, only one of the three task types was performed with only one respirator condition.

The 12 subjects were randomly assigned to two groups of six subjects each. Because part of the design was to compare results obtained with subjects wearing masks to results without masks, the order in which the control or no-mask condition occurs could introduce bias due to a possible practice affect. One design to cancel out this practice affect would have been to randomize the order of all four mask conditions—the no-mask and the three mask types. However, it was felt that by positioning the control first for half the subjects and last for the other half, not only would the final results cancel out the practice effect, but this effect, if any, could be identified by examining the F and p values for the analysis of variance term of mask or of mask by group for the group effect. Within each group, a Graeco-Latin square was used to determine the combinations of the order of the tasks and the order of the masks.

The experimental null hypothesis that the performance would be the same for the four experimental conditions was examined by an analysis of variance model. The discussion of the results are confined to the main effects of the mask type and the planned comparison of the control condition versus the mask conditions. Because this comparison was planned before the data were collected, it was tested using a 0·05 alpha level. If the original null hypothesis was rejected or the contrast showed a significant difference between the control and the average of the three masks, additional tests of statistical significance for the intercomparisons (between each respirator and the control, and between each type of respirator) were conducted. These comparisons used the Bonferroni multiple comparison procedure to examine which pairs of mask conditions differed significantly. Since there are six paired comparisons, the normally accepted level of significance of $p \leq 0.05$ (the Type 1 error) must be divided among these six pairwise comparisons. Thus, for this statistical analysis, a t-test for each comparison of group means must meet the criteria of $p \leq 0.0083$ to be judged statistically significantly different.

For purposes of convenience of presentation, each of the three performance variables are presented separately, followed by an overall discussion of the results.

3. Physical performance

3.1. *Equipment*

Exercise was performed on a standard, single-wheel cycle ergometer (Model 868, Monark). The ergometer was equipped with a tachometer and weights for adjusting the workload. A Metabolic Measurement Cart (MMC Horizon System, SensorMedics) was used to collect oxygen consumption data ($\dot{V}O_2$) and heart rate (HR) data, in conjunction with a six-lead electrocardiogram (ECG) monitor (EK-8, Burdick). Blood pressure (BP) was collected manually with an arm-cuff sphygmomanometer.

3.2. *Procedure*

At the beginning of each physical task session after measurement of a resting HR and BP, a submaximal graded exercise test was performed with the subject on the ergometer. After chest leads were attached, the subject donned the mouthpiece headgear (with the nose clipped shut) so that his exhaled breath would be collected and his oxygen consumption analysed with the metabolic cart. The subject then pedaled through successively increasing loads. The purpose of this procedure was to generate a subject- and session-specific calibration curve correlating $\dot{V}O_2$ with HR. The rationale for this correlation was to allow the measurement of the HR variable during the subsequent respirator sessions to represent the values of $\dot{V}O_2$ needed for the results since $\dot{V}O_2$ could not be measured while the respirator was worn. By establishing the HR: $\dot{V}O_2$ correlation before each session, the effect of the day to day variability on the estimate of $\dot{V}O_2$ was minimized.

In order to understand the relationship between work output and physiological parameters, either the work output or the physiological parameter should be held constant. Since it is difficult to maintain a constant ventilation rate or HR status, the parameter selected to judge work performance was the change in $\dot{V}O_2$ while maintaining a constant external workload. The ergometer load was set at 1 kg of wheel resistance and the subject was asked to pedal at a rate so the tachometer reading would remain at 20 km/h. This combination of resistance and pedal rpm is equivalent to a workrate of 350 W and resulted in a moderate work level of approximately 25–30% of the estimated $\dot{V}O_2$ maximum. Both the subjects' pedal speeds and wheel loads were periodically monitored during each session by the experimenter and were found to be stable. An increase in $\dot{V}O_2$ necessary to maintain the predetermined constant workload while wearing a respirator compared to the $\dot{V}O_2$ level when not wearing a respirator would be indicative of increased work expenditure. This increase in required work effort can be considered a deteriment to efficient work productivity and can be used as an estimate of work performance decrement. Since $\dot{V}O_2$ cannot easily be directly measured while wearing a respirator, the measurement of HR was used to estimate $\dot{V}O_2$ by the previously mentioned correlation curve method. The only alternative for measurement of $\dot{V}O_2$ would have been to alter the respirator or incorporate it into the exhaled air hose circuit. Such an approach, however, would not allow the subjects to wear the respirator in the same manner as that worn in actual use. Given that the linear relationship between $\dot{V}O_2$ and HR produced correlation coefficients ranging from 0·95 to 0·99, and that a new correlation curve was generated for each session, it was felt that this indirect method of $\dot{V}O_2$ measurement while wearing the respirator with no modifications offered the best method of assessing work performance output that would represent actual usage.

After the subject had recovered from the graded exercise test and his heart rate returned to its starting value, the three 30 min ergometer sessions, separated

Table 1. Means and standard deviations for physical task.†

Task	Control	Dust mask	Half-face	Full-face
$\dot{V}O_2$ (litres/min)	1·08 (0·11)	1·12 (0·16)	1·17* (0·15)	1·19* (0·13)
Systolic BP (mmHg)	135·6 (10·8)	137·0 (8·9)	138·5 (9·4)	140·9* (11·5)
Diastolic BP (mmHg)	74·0 (8·1)	74·3 (8·1)	74·8 (5·3)	78·4* (5·5)

†One standard deviation is given in parentheses below the mean.
*Statistically significantly different from the control value, $p \leq 0{\cdot}0083$ (based on $\alpha = 0{\cdot}05$).

Table 2. Summary of significant task decrement† percentages.

	Respiratory type		
Task	Dust	Half	Full
Physical			
$\dot{V}O_2$	+4	+9*	+11*
Cognitive			
Miller analogy	+4·6	−20*	−26*
Psychomotor			
Steadiness	+0·8	+3·1	−31*
One hole test			
Pin count	−4	−6	−6
Grasp time	+3	0	+10·5
Movement time	+19*	+15*	+14*
Position time	+7	+7	+11
Reach time	+11	+11	+12

†Percentage difference between respirator type and control.
*Statistical significance based on comparison of means.

by the 10 min rest sessions, were begun. Blood pressure measurements were collected every 10 min, with a resting HR and BP collected at the conclusion of the last rest period. Heart rate measurements were collected automatically by the ECG monitor every 15 s. These data were later reduced to average values per trial and converted to average $\dot{V}O_2$ per trial from the calibration curve for that session.

3.3. *Results*

The means and standard deviations for each of the three dependent variables for the four experimental conditions are presented in table 1.

The results of the physical task performance tests indicated that blood pressure changes only slightly when a full-face mask is worn. However, while the F ratio and the Bonferroni tests indicated a statistically significant increase in both systolic and diastolic pressures for the full-face respirator when compared to the no respirator condition, this 5% increase (approximately 5 mm Hg) is not considered biologically significant. The increase in $\dot{V}O_2$ with respirators compared to no respirators is statistically significant, $F(1,44)=15{\cdot}37$, $p<0{\cdot}0002$. An examination of the different respirator means indicated the source of difference to be from the half-mask and full-face mask respirators, which required approximately 9% and 11%, respectively, more $\dot{V}O_2$ (see table 2), and thus, conversely can be taken to represent a statistically significant decrease in work performance capability. This assumes a relatively constant energy available for the worker to perform his task. Although trial effects were not seen for the other tasks, $\dot{V}O_2$ requirements did increase with trial. For example, the overall $\dot{V}O_2$ increase for the half and full masks averaged 10% when compared to the control but increased from 7% for the first trial to 15% for the third trial. These trends suggest that the longer the respirator is worn, the more taxing it becomes.

3.4. *Discussion*

The resulting average increase in $\dot{V}O_2$ of approximately 10% (see table 2) for the half and full mask respirators represents a significant performance change due to respirators. It is true that the body has the capacity to increase its oxygen consumption to match an increased work load, due to the redistribution of blood flow to skeletal muscles when they are actively contracting, and due to the shift of the oxygen dissociation curve, making it easier for the cells to obtain the O_2 from the haemoglobin (resulting from increases in carbon dioxide concentration and associated decreases in blood pH). Therefore, one might be tempted to conclude that simply measuring an increased $\dot{V}O_2$ requirement due to respirators would not necessarily have any detrimental effect on work performance. However, this increased exertion could also lead to a decrease in the length of time that the worker can perform. Also, when the increased oxygen requirements attributable to wearing the respirator observed under the controlled conditions of this study are added to other stresses often associated with the use of respirators, such as the weight, restrictiveness or heat build up of other personal protective gear or environmental conditions such as heat or confined work quarters, the overall impact may be sufficient to cause a decrement in performance and productivity.

4. Psychomotor performance

4.1. *Equipment and tasks*

4.1.1. *Hand dynamometer:* A hand dynamometer, (Model 78010, Lafayette Instruments) was used to measure basic hand strength in kilograms during the course of an experimental session. Ten trials were performed with a 10 s rest break between trials.

4.1.2. *Pursuit rotor:* A photoelectric pursuit rotor (Model 32534, Lafayette Instruments), was utilized with a triangular template. The tracking task was a clockwise motion at 30 rpm. Time on target and the number of times the stylus left the track of the triangle were recorded by an IBM/PC AT computer. Each subject performed ten trials of 20 s duration with a 15 s rest period between each trial.

4.1.3. *Steadiness:* The instrumentation was a special modification of the steadiness tester (Model 32011, Lafayette Instruments). In this task, subjects held a stylus in a round hole in a metal plate and attempted not to touch the edges of the circumference. The only feedback was the tactile sensation of the stylus hitting the edge and the slight sound of that movement. The abovementioned IBM computer recorded the number of contacts in a 20 s trial period. There were ten trials with 15 s rest periods between each of them. The subject sat in front of the apparatus with his arm away from his body forming a right angle at the elbow, and with the stylus held like a fencing foil. The subject was told to breath normally since holding one's breath facilitates steadiness.

4.1.4. *Reaction time:* A four choice reaction time task was used with a four light and button response panel (Model 63035, Lafayette Instruments). Subjects were instructed to use the forefinger of their dominant hand to make the responses. There were 20 trials in a block with a 40 s rest break between each block. Data were collected from 16 successive blocks of trials. The sequence of lights was determined by a random number generator but there was a check to make sure no light was turned on twice in a row. Response times were measured in milliseconds.

4.1.5. *One hole test:* The one hole test (Model 32036, Lafayette Instruments) developed by Salvendy (1975) measured both large arm movements and finger dexterity. The apparatus consists of a box with a small tray at the base and a hole at the top. A metal plate on the base allows an electrical circuit to be created whenever the subject touches the apparatus while picking up and positioning pins. This allows the measurement by an IBM computer of the amount of time taken to complete each part of the tasks. These component times are called elemental times and are measured in milliseconds.

The task involves picking up a small pin from the tray at the base of the apparatus and moving it up to the top of the apparatus. It is placed into a small hole and released. The apparatus delivers another pin into the tray and the subject repeats the procedure. Several measurements were recorded including the number of pins inserted, and the elemental times needed to do the task. Elemental times consist of reach time, position time, movement time and grasp time. The subject inserted pins for a 1 min cycle and seven cycles were completed in succession without a break.

4.2. *Procedure*

Except for the hand dynamometer, all data were recorded by the IBM PC. Each subject had his own unique random sequence of tasks which was used each time he came into the lab. The entire experimental session was driven by the computer and the researcher just announced the beginning and end of tasks to the subjects.

4.3. *Results*

The means and standard deviations for the ten dependent variables from the five tasks for the four respirator conditions are presented in table 3. The repeated measures analysis described in the previous section was used to analyse each of these variables.

Table 3. Means and standard deviations for psychomotor tasks.†

Task	Control	Dust mask	Half-face	Full-face
Hand dynamometer	48·3	48·9	49·5	49·4
(kg)	(11·7)	(11·1)	(12·2)	(12·7)
Steadiness	2·13	2·12	2·07	2·79*
(times touched)	(1·9)	(1·4)	(1·3)	(2·2)
Pursuit rotor	11·9	12·3	12·1	11·6
(s on target)	(2·9)	(3·6)	(3·2)	(3·4)
Pursuit rotor	42·1	42·0	41·5	43·0
(no. of slips)	(8·0)	(8·3)	(8·7)	(8·2)
Reaction Time	0·481	0·473	0·472	0·474
(s)	(0·046)	(0·035)	(0·041)	(0·039)
One hole				
pins	41·81	40·07	39·41	39·23
(count)	(8·20)	(10·82)	(9·59)	(10·60)
Grasp time	0·246	0·254	0·247	0·272
(s)	(0·069)	(0·100)	(0·079)	(0·111)
Movement time	0·365	0·436*	0·421*	0·415*
(s)	(0·115)	(0·188)	(0·132)	(0·151)
Position time	0·205	0·220	0·220	0·227
(s)	(0·099)	(0·140)	(0·096)	(0·118)
Reach time	0·660	0·724	0·723	0·736
(s)	(0·199)	(0·329)	(0·275)	(0·327)

†One standard deviation is given in parentheses below the mean.
*Statistically significantly different from the control value, $p \leq 0{\cdot}0083$ (based on $\alpha = 0{\cdot}05$).

The ANOVA comparing masks worn during the steadiness test revealed a difference between respirators, $F(3,44) = 4{\cdot}85$, $p < 0{\cdot}004$. An examination of the respirator condition means indicated the source of difference to be from the full face respirator which had a mean number of touches of 2·79 versus a mean of 2·13 touches for the no mask condition. This is a 31% performance decrement.

While the difference between experimental conditions for pursuit rotor measurements of time on target was significant at $p < 0{\cdot}02$ with an $F(3,44) = 3{\cdot}29$, a comparison of the average of the three respirators versus the no mask condition was not significant. An examination of the means from table 3 demonstrates the lack of any changes of real or statistical significance when comparing the scores with any of the respirators to the score without a respirator. The F ratio for the number of slips off the target was also not significant.

The differences between the results with different respirator conditions for the reaction time task were not significant, although a comparison of the average of all three respirators versus the no mask, control condition was significant with $F(1,44) = 4{\cdot}28$, $p < 0{\cdot}04$. However, as with the pursuit rotor task, an examination of the means, with an actual average decrement of less than 2%, and of the Bonferroni comparisons of means, showed no real or statistically significant changes. The differences between respirator conditions for hand dynamometer reading of hand strength were also not significant.

The one hole test has several measurements: number of pins inserted, grasp time, position time, movement time and reach time. Some dependent variables for this task were significant, others were not. The number of pins inserted during a particular mask condition was significant, $F(3,44) = 2{\cdot}85$, $p < 0{\cdot}045$ and a comparison of the control mean to the average of the combined respirators was significant at $F(1,44)=6{\cdot}91$, $p<0{\cdot}01$. Neither the grasp time nor the position time was significant. The movement time results for comparison of masks were significant at $F(3,44)=6{\cdot}9$, $p<0{\cdot}0005$, with a comparison of control to the average of the three respirators also significant at $F(1,44)=19{\cdot}87$, $p<0{\cdot}0001$. Although the reach time comparison of mask results was not significant, the comparison of no mask to mask was significant, $F(1,44)=6{\cdot}12$, $p<0{\cdot}016$. The relative differences between each respirator and the control condition (expressed as percent of change from the control condition) are presented in table 2.

4.4. *Discussion*

The results would indicate that the general diagnostic tasks of hand dynamometer and reaction time were not able to detect any differences in performance caused by respirators. Since other tasks modelling the Fleishman factors—steadiness, and one hole—did show some differences to exist, it is reasonable to assume that any task chosen must be very sensitive and very specific with regard to the attributes measured.

Tests such as the reaction time task, which did not demonstrate any significant effect, are still useful however, as the results, which were times in the 400 millisecond range, were representative of the data usually seen for a four choice reaction time study. This would tend to support the contention that the tests were performed properly and that respirators do not appear to affect reaction time.

From a summary of the task decrements (table 2) it can be seen that only the elemental measurement of movement time showed a statistically significant decrement in performance due to respirators (as demonstrated by a statistically significant increase in movement time, since the longer the movement time, the less efficient is the subject's performance). It is equally important, however, to note the trends of the three other elemental time measures and the accuracy measure of number of pins inserted into the hole. The results indicate an average drop of 5% total pins, and increases in times ranging from 3% to 12%. While these four additional measures do not show sufficient differences in means to be statistically significant, the fact that all five measures do show performance decrements, and for all three respirator types, is felt to be of practical significance.

The decrements of movement and reach times indicate that respirator wear affects the speed of movement more than the accuracy, and specifically the speed of large motor movements more than precise movements of grasping and positioning the pins. What is not demonstrated by these results is any significant differences among the respirators. It can be concluded that either the test was not sensitive enough to detect differences, or, that there is no significant difference in effects of different types of respirators on work performance, at least for this type of psychomotor task.

The results of the steadiness task indicate a rather significant decrement of more than 30%, but only with the full-facemask airline respirator. The exact cause of this decrement may be due to the cumbersomeness of the larger mask with its associated valve and airline, or from the distraction of airflow noises or the inability to control slow breathing.

5. Cognitive performance

5.1. *Tasks*

5.1.1. *Hypothesis testing:* The hypothesis testing task selected was based on Levine's (1966) research with a minor alteration. A problem set consisted of 16 stimulus cards where four are probe or feedback trials and the remainder are no feedback trials. The stimuli have four dimensions each with two values. The four dimensions used were letter, size of the letter, colour and the position of a line above or below the letter. Problem sets were constructed so that there were 3:1 response patterns when accurately solved by the subjects. In any given problem subset of one probe and three blank trials there would be eight possible hypotheses. Thus 24 total sets were made, varying colour and letter, with subjects never seeing any set twice.

5.1.2. *Miller analogies:* Four sample practice tests published in 1986 (Bader and Burt) were selected. Each practice test had 100 questions from which three 30 question tests were randomly constructed for the three tests to be used in each mask condition. Since there were four respirator conditions, four practice tests were used to compile 12 tests with 30 questions each.

5.1.3. *GRE analytical:* Four sample practice tests of the Graduate Record Examination (GRE) published in 1983 (Educational Testing Service) were chosen. The four tests were divided to yield three tests each with eight questions which could be used in each mask condition, for a total of 12 tests. Questions were assigned to the tests randomly to ensure equal difficulty across the sessions and conditions.

5.1.4. *GRE logical:* Four practice tests published in 1983 (Educational Testing Service) were picked to serve as a pool of questions to construct the 12 tests needed for the experiment. Questions from a test were randomized and then selected at random so that each test had eight questions.

5.2. *Procedure*

For any given mask condition each of the 12 subjects had a random order for the presentation of the cognitive tests. Each subsession of a 2 h session was timed to take 30 min followed by a 10 min break and included: 7 min for GRE logical, 7 min for GRE analytical, 10 min for Miller and 6 min for the Hypothesis testing. Allocation of time per standardized test was derived from published guidelines taking into account the number of questions used in this experiment since the original lengths of each test were altered.

5.3. *Results*

Four one-way ANOVAs were run examining the effects of respirators. The means and standard deviations for the four tasks for the three experimental conditions and the control group are presented in table 4.

5.4. *Discussion*

The failure of the GRE tests to show work decrement may be due to the extreme difficulty level of the tests as well as the low number of questions used. Subjects

Table 4. Means and standard deviations for cognitive tasks.†

Task	Control	Dust mask	Half-face	Full-face
Miller	17·030	17·818	13·636*	12·606*
(no. correct)	(2·807)	(2·588)	(2·601)	(2·101)
GRE Logical	3·889	3·722	3·833	3·028
(no. correct)	(1·690)	(1·455)	(1·494)	(1·259)
GRE Analytical	3·417	3·611	3·333	4·083
(no. correct)	(1·787)	(1·090)	(1·484)	(1·876)
Hypothesis test	1·389	1·500	1·264	1·333
(errors)	(1·205)	(1·389)	(1·309)	(1·231)

†One standard deviation is given in parentheses below the mean.
*Statistically significantly different from the control value, $p \leq 0{\cdot}0083$ (based on $\alpha = 0{\cdot}05$).

rarely finished all eight problems. Although respirators might produce work decrements, these tasks were apparently too difficult to allow for the detection of those decrements.

Of the four tests used, only the Miller appeared to show any statistically significant performance decrement. Care must be exercised in the interpretation of these results because of the possibility that the four practice tests may not have been of equal difficulty. The test segments were extracted from four practice tests. Since the same practice test was used for all subjects wearing each particular mask, and if the tests were not of equal difficulty, then test difficulty could confound the results.

To investigate the possibility of confounding, the four sets of three 30 question tests were given to four individuals who took the timed tests in random order and with no respirators. Although a small subset of subjects, the averages of the scores appeared to follow the same pattern as was seen with respirators. The scores for test 2 (used for the dust mask) were 1·6% higher than test 1 (used for no mask). The scores for tests 3 and 4 (used for the half and full face mask respirators, respectively) were 23% and 26% lower than test 1. Thus, it appears that the difficulty levels between tests were different enough to confound the results of the 12 subject experiment. For all practical purposes, it appears that this bias could cancel out the original results, indicating that the Miller analogies, used in this manner, did not detect work effects due to respirators.

In general, cognitive tests are difficult to administer for this type of experimental design due to the carryover effects from condition to condition. Cognitive tasks which are not ability measures might show performance decrements caused by respirators.

6. General discussion

Effects on performance were found in the physical work task, with increased exertion and in the psychomotor tasks, with lessened steadiness and slower arm-hand movements, but not in the cognitive tasks. In general, the tests did not differentiate well among the effects of different respirator types.

It is important to realize that the tests that did not demonstrate any significant differences in performance provide equally useful information. These tests indicate that, based on the study's results, respirators appear to have no effect on the performance of certain tasks, such as cognitive and reaction time skills.

The general findings of this study would indicate that tasks used to evaluate performance must be chosen carefully. The tasks should model specific tasks as opposed to modelling general situations and should measure specific abilities. General tasks such as a reaction time task may not be sensitive enough to be used as future diagnostic tools in respirator evaluation. Respirator usage would seem to have more of an effect on steadiness and large movements and less effect on movements requiring precision. Most differences appear with the full face and half face respirators and future studies should concentrate on those types of mask.

The increase in energy ($\dot{V}O_2$) required to perform work when wearing respirators and working at moderate exercise levels is in itself an interesting finding. However, coupled with the results of the steadiness and One hole test results, this study suggests that a statistically as well as economically significant decrement in work performance may occur when some types of respirators are worn.

7. Conclusions and recommendations

The current study evaluated the effects of wearing a respirator on performance using selected physical, psychomotor and cognitive factors. Further cognitive studies should be conducted to determine if other tests can detect differences in performance due to respirators, or if not, to confirm the suggestion of the results of this study that respirators may not have a significant effect on cognitive performance.

Further psychomotor studies should be conducted to continue testing the One hole test for use in evaluating respirator effects on performance. The significant results of this study should be further validated by testing with heterogeneous subject groups in a laboratory setting as well as with groups of workers in a field situation. Because of the significant results seen with the steadiness test, further testing should be considered for this test also. Other populations which may prove useful to study include females, older workers and experienced respirator wearers.

One of the most important outcomes of the physical task results in addition to replicating previous research showing a work decrement, is to validate the results of the other two task domains, cognitive and psychomotor. The positive results seen in the physical domain within the chosen 2 h study time period support the results seen in the other two domains.

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