

# **Title: A preliminary investigation of the effects of exposure to multiple health stressors using the Physiological Strain Index**

**Authors: Edwards, A. L.<sup>1</sup>, Franz, R. M.<sup>1</sup>, Schutte, P. C.<sup>1</sup>, Steenkamp, T.<sup>1</sup>**

<sup>1</sup> CSIR Laboratory for Mining Innovation, Johannesburg.

## **Abstract**

Proactive evaluation and management of risks associated with exposure to combinations of occupational health stressors requires information on the impacts of individual stressors, as well as their cumulative and combined impacts. The harsh work environment associated with mining imposes physiological strain on mineworkers. Heart rate (HR) and core body temperature ( $T_{cr}$ ) have been shown to be valid and reliable indicators of the physiological strain experienced by humans during physical activity and the physiological strain index (PSI) combines these two parameters. Measurement of the physiological strain caused by individual stressors in a mining environment is confounded by exposure to multiple stressors in various combinations. The research hypothesis was that the occupational health stressors of noise, heat/humidity and physical work would have measurable additive effects on participants' PSI scores. **Method:** Eleven participants (three females and eight males) were exposed to noise, heat and physical work in a controlled experiment. A commercially available biotelemetry physiological monitoring system was used to measure HR and  $T_{cr}$ . PSI was determined while participants rested to provide a baseline, for comparison with their respective PSI scores after exposure to individual stressors and various combinations of stressors. **Results:** The results indicated that noise exposure caused a statistically significant increase in PSI scores. None of the results for exposure to heat alone, physical work alone or the two in combination showed a statistically significant increase in PSI. Simultaneous exposure to all three stressors also increased the PSI but not significantly. Female participants experienced more physiological strain during exposure to noise than males. Male participants experienced more physiological strain from physical work than did females. **Conclusion:** The PSI appears to be a potentially useful means of measuring total physiological strain experienced during exposure to multiple health stressors but further research involving a greater number of participants is necessary to confirm this conclusion. The comparison of findings in real-time workplace situations with the findings of the study could provide information useful in the management of health risks imposed by exposure to multiple stressors in the workplace.

**Key words:** physiological Strain index, multiple health stressors.

## **Introduction**

Mining is an ancient occupation, long recognised as being arduous, and associated with injury, disease and death (1). Some of the impacts on mineworkers are short-term, e.g. recovery from an injury, while others, such as cancer and respiratory conditions (silicosis, asbestosis, pneumoconiosis), as well as NIHL have lasting impact. Dust and noise are inherently associated with mining, as are hot, humid and confined working conditions in some forms of mining (2,3).

The occupational heat stress limits currently used in the South African mining industry have either been based on the physiological responses of young, healthy males, or have been adopted from international agencies. In a similar vein, existing knowledge of the overall physiological cost to mineworkers caused by the nature of their work and environmental conditions in South African mines is also based on the responses of healthy young males.

The changes in the South African political climate since 1994 has improved the gender sensitivity of employment policies and the demographics of the mining industry workforce has changed to include more females. Together with the demand for improved policies and procedures to protect worker health, these changes indicate the need to re-evaluate the physiological strain mineworkers experience while performing various tasks under a range of environmental conditions.

Information on the physiological strain experienced during mining activities would provide a scientifically sound basis from which to assess the relevance of current occupational heat exposure limits, current physical selection criteria, the design of workstations and mining tasks, and occupational health management systems.

## **Physiological Strain**

Two measurements that have shown reliability and validity in monitoring the physiological status of individuals under field conditions are pulse rate or heart rate (HR) and core body temperature ( $T_{cr}$ ) (4). HR is easy to measure (non-invasive) and can be used to estimate the degree and duration of aerobic workload and assess periods of rest. Measuring  $T_{cr}$  is used for assessing the impact of environmental conditions and exercise (work) on the body. Sites used for measuring  $T_{cr}$  include the oesophagus, rectum, mouth, tympanum, and auditory meatus (5). In a laboratory setting, measurement of oesophageal temperature is considered the best site (6) but using this

site is problematic in field assessments: the probes are difficult to insert, cause irritation to the nasal passages, and are impractical to use where individuals are performing strenuous physical work. The measurement of oral temperature under field conditions is also not feasible, or accurate, because irregular breathing patterns (as a result of physical work) can alter oral temperature measures (6).

Studies in the US army and the Israeli military have resulted in a physiological strain index (PSI) based on  $T_{cr}$  and HR two physiological parameters that adequately depict the combined strain reflected by the cardiovascular and thermoregulatory systems (7). Core body temperature indicates the increase in body heat storage during exercise or physical work resulting from an accumulation of heat produced by skeletal muscle contraction, while heart rate reflects demands placed on the circulatory system and is an immediate effector of vasomotor response to metabolic and environmental conditions (8).

The PSI is based on a scale of 1 to 10, with a high value indicating a high risk of heat stress. It was developed using individuals performing exercise in heat under a variety of conditions (e.g. in different heat-related environments, with protective clothing, and with varying hydration levels) (7,8). Comparisons of the PSI based on gender, age, and level of exercise training and intensity have also been conducted (6,9-11). The PSI has been shown to be a simple method for examining the impact of environmental temperatures and exercise (work) stress on individuals in order to predict who might be at risk for heat stress (9). Furthermore, the value of the PSI lies in its ability to rate and compare the strain imposed by various combinations of environmental and work rate conditions, with a reduced risk of error because it is based on these two easily measured parameters. The PSI also provides for five categories of physiological strain. These categories are “no/little strain”, “low strain”, “moderate strain”, “high strain” and “very high strain” (7).

Developments in the field biotelemetry have made tools available such as the CorTemp™ physiological monitoring system that permits real-time measurement and logging of  $T_{cr}$  by means of an ingestible capsule transmitting data to a receiver worn on the belt. This system was evaluated by the CSIR Occupational Health and Ergonomics Research Group during a pilot study conducted in an underground mining environment and found to be a viable measurement method for  $T_{cr}$  (12).

### **Exposure to occupational health stressors**

The measurement of the physiological strain caused by specific occupational health stressors in a mining environment is confounded by the fact that mineworkers are simultaneously exposed to various combinations of stressors, including physical work

under hot, humid, noisy and dusty conditions. Such combined exposures confound the evaluation and prediction of physiological strain from individual stressors, making the management and reduction of risks difficult.

Another confounding factor is that occupational health practitioners are increasingly aware of the synergistic impacts of exposure to multiple health stressors. For example, studies have demonstrated that exposure to noise combined with physical work can exacerbate the auditory effects of noise (13,14). Similarly, exposure to noise and chemical agents also accelerates and exacerbates the development of NIHL (15,16).

The proactive evaluation and management of risks associated with exposure to combined occupational health stressors requires information on the effects of individual stressor, as well as their cumulative and combined effects.

Obtaining information that can be applied to the mining industry requires controlled laboratory conditions that simulate environmental and work conditions in mining. However, not all stressors associated with mining can be applied in a laboratory situation. Those that can be most readily applied are noise, heat, humidity, and physical work.

Measurement of physiological strain is not a traditional method for investigating the effects of noise. In most cases the reason for implementing intervention measures is to prevent the auditory effects of noise exposure, most notably NIHL. However, noise also imposes non-auditory effects on workers and is, therefore, relevant to the evaluation of physiological strain. Non-auditory effects of noise exposure are known to include symptoms related to the autonomic nervous system such as elevated skin temperature, increased pulse rate and blood pressure, constriction of blood vessels, abnormal secretion of hormones and tensing of muscles (17,18,18).

### **Research question**

The research question for this study was: Can significant differences be demonstrated in the level of physiological strain as a result of exposure to heat and humidity, physical exercise and noise individually, and if so, are those differences greater for exposure to the three health stressors in various combinations?

### **Hypothesis**

The research hypothesis was that the occupational health stressors of noise, heat and humidity and physical work will have measurable additive effects on participants' PSI scores.

## **Research design**

An experimental design under ethically controlled and specific laboratory conditions was used. Each participant's baseline PSI was determined at rest for comparison with his or her PSI during exposure to individual and combined stressors.

## **Methodology**

### **Objectives**

The objectives of the study were to evaluate the effect of heat and humidity, physical work, and noise, individually and in combination, and to identify any differences in the responses of male and female participants.

### **Participants**

Eight male and three female volunteers between the ages of 18 and 30 years were recruited to participate in the study. The sample size of the study was limited by time constraints and the cost of equipment such as the thermo-sensor pills.

Males and females were included in the study because, despite most South African mineworkers being male, information on the physiological responses of females to occupational health stressors is required, since legislation requires increased numbers of females in the mining workforce. The age of the participants was limited to 18 to 30 years old, because it was hypothesised that this was the age range of new recruits to the mining workforce and, therefore, facilitated an evaluation of the effects of the health stressors on a young, healthy, non-occupationally exposed population. It was anticipated that this would provide information for future comparisons with the responses of miners in the actual work situation. The inclusion criteria for participants listed below were not intended to include participants that are representative of the mining workforce where there is a high prevalence of conditions such as HIV, TB, NIHL, silicosis and many more, but rather to provide information about the responses of young, healthy individuals to multiple health stressors.

### **Inclusion criteria**

The criteria for inclusion in the study were:

1. Compliance with the minimum acceptable standards of health used to determine fitness for work in underground mines. This was confirmed by an occupational medical practitioner who had knowledge of minimum standards of fitness and was informed about the study and the contraindications for the use of the ingestible thermo-sensor capsule. The medical examination was aimed at ensuring consistency and a thorough investigation of any current or previous conditions that might put participants at risk or impact on the results. Participants'

body mass was determined during the medical examination and at the beginning of each test day, to ensure the correct stepping height (see Table 1) and work rate for each participant.

2. No recent occupational exposure to heat, humidity, noise or physical work.

### **Ethical considerations**

All possible measures were taken to ensure participants' health, safety, privacy and dignity throughout the experiment. Confidentiality of participants' results, no remuneration and the right to withdraw from the study at any time further ensured that ethical considerations were observed. Informed consent was given by means of a signed form by those individuals who agreed to participate after undergoing induction and information-sharing sessions, during which prospective participants' questions and concerns were addressed. Ethical clearance for the experiment was obtained from the University of the Witwatersrand Human Ethics Committee.

### **Data collection**

The CorTemp™ Physiological Monitoring and Polar™ Heart Rate Monitoring Systems were used to determine PSI scores. The CorTemp® system comprises an ingestible thermo-sensor, a POLAR® heart rate transmitter (worn as a chest strap) and a miniature ambulatory data recorder (worn on a belt) to capture data transmitted by the thermo- and heart rate sensors.

Together the two systems monitor, record and report  $T_{cr}$  and HR in real-time. The “thermometer-pill”, a silicone-coated sensor the size of a standard medicine capsule, contains a telemetry system, a micro battery and quartz crystal temperature sensor. While inside the gastrointestinal tract, the crystal sensor vibrates at a frequency that is proportional to the temperature of its surroundings (the body), producing a magnetic flux and a radio signal that is transmitted from the body to the recorder. The sensor continuously monitors body temperature as it travels through the digestive system, passing through the intestinal tract in 24 to 30 hours, according to the individual's rate of motility. The recorder receives, displays, and stores the data in the non-volatile solid-state memory.

The heart rate monitoring system consists of a belt that is based on the design of the POLAR® chest-worn belts commonly used by athletes to measure and transmit HR data to a wrist-worn receiver. Data from both systems were downloaded after each experimental condition to a desktop computer, using the CorTemp™ and POLAR® proprietary software. Data were then captured in a database, using a secure participant-numbering system to ensure confidentiality.

## **Climatic chamber**

The study was conducted in a climatic chamber to ensure precise control of temperature, humidity, and air velocity. Test conditions requiring physical work made use of graded stepping blocks chosen on the basis of each participant's body mass (see Table 1). The climatic chamber was equipped with loudspeakers to produce white noise for test conditions requiring exposure to noise. Noise levels were measured with a calibrated Class 1 (19) sound level meter.

During rest periods participants sat in a temperature-controlled room adjacent to the climatic chamber. A qualified and fully equipped paramedic was present during all exposure procedures.

## **Occupational exposure limits of health stressors**

When simulating exposure to any of the occupational health stressors found in an underground mining environment, researchers ensured strict adherence to the relevant occupational exposure limit (OEL) to prevent any risk of harm or injury to participants.

## **Noise**

In the case of noise, a time weighted average ( $TWA_{8h}$ ) of 85 dBA is the OEL for safe exposure of the unprotected human ear (20,21). The three-decibel exchange rate dictates that, for each 3-dB increase above the 85 dBA OEL, the permissible time for safe exposure is halved (20). This indicates that participants without hearing protection can be safely exposed to 88 dBA for four hours without risk of damage. To provide a margin of safety, the study limited the noise level to 87 dBA for a period of two hours, after which a two-hour rest and recovery period was applied.

## **Heat and humidity**

The difference between the temperature of the air in which physical work is performed and the worker's body temperature determines the environment's capacity for removing metabolic heat produced by muscular contraction. Similarly, the humidity or moisture content of the surrounding air determines the amount of perspired water that can evaporate from the skin surface to cool the skin and blood flowing to it, thereby limiting increases in body core temperature (7).

Air velocity or wind speed also affects the environment's capacity to remove metabolic heat from the skin: a higher air velocity results in a greater volume of air flowing over the skin, causing more evaporation of perspired water and, hence, more cooling. In accordance with mining industry regulations and practice for ensuring adequate ventilation in underground work environments (22), the wet- and dry-bulb temperatures considered together provide an adequate indication of the environment's capacity to

remove metabolic heat and limit heat stress. The study applied a wet-bulb temperature of 30,0°C and a dry-bulb temperature of 31,5°C for exposure to heat and humidity. Air velocity was regulated to 0,4 m·sec<sup>-1</sup>, which is 60 per cent greater than the stipulated minimum for air velocity (22). The use of heat, humidity and air velocity that are below the recommended exposure limits ensured that participants were not at any risk but were still exposed to environmental conditions that approximated those in an underground mine.

### **Physical work**

Participants performed two hours of intermittent light work (10 minutes work/15 minutes rest), and then rested for two hours. The environmental temperatures as described above equated to a wet-bulb globe temperature (WBGT) of 30,8°C. The WBGT OEL is 31,4°C for 50 per cent light work and 50 per cent rest each hour (23). Since participants performed light work for only 40 per cent of the time, the combination of environmental conditions and work rate were regarded as conservatively safe for young, healthy individuals.

The physical work consisted of a two-hour period of block-stepping made up of ten-minute stepping intervals interspersed with 15-minute intervals of rest. Stepping was at a rate of 12 steps per minute, with each participant's stepping height adjusted according to their body mass so as to yield an external workload of 35 watts, positive component. This equated to a light workload, which, together with a 15-minute rest interval after every ten minutes of stepping, was regarded as conservatively safe for young, health individuals.

### **Data analysis**

T<sub>cr</sub> and HR data were used to calculate PSI scores using an Excel spreadsheet with calculations from Moran (7). PSI averages were calculated for 10-minute intervals. The averages of the results for the two-hour period of exposure were calculated for each participant and for each exposure condition, and the results were statistically analysed to evaluate the significance of the differences in participants' responses.

A paired t-test was performed on the PSI baseline measurements and those recorded after exposure to physical work; heat; heat combined with physical work; noise; noise combined with physical work; noise combined with heat; and noise combined with heat and physical work. An analysis of variance (ANOVA) test was performed to evaluate differences between responses to the various experimental conditions.

### **Experimental procedure**

The researchers followed the experimental protocol as summarised in Table 1.



Table 1 Description of experimental procedure

Test day, stressor and duration of exposure	Procedure
DAY 1	
Baseline recordings: two hours	Sit quietly at room temperature (18,0°C wet-bulb/25,0°C dry-bulb) for baseline recordings
Noise: two hours	Sit at room temperature (18,0°C wet-bulb/25,0°C dry -bulb), with 87 dBA white noise
DAY 2	
Heat/humidity: two hours	Sit at 30°C wet-bulb/31.5°C dry-bulb
	Rest at room temperature (18,0°C wet-bulb/25,0°C dry-bulb)
Physical work: two hours	Block-stepping at 12 steps per minute (35 watts) at room temperature (18,0°C wet-bulb/25,0°C dry-bulb) for ten-minute intervals, each followed by a 15-minute rest interval
DAY 3	
Heat and physical work: two hours	Block-stepping at 12 steps per minute (35 watts) at 30°C wet-bulb/31.5°C dry-bulb for ten-minute intervals, each followed by a 15-minute rest interval
	Rest at room temperature (18,0° wet-bulb/25,0°C dry -bulb) for two hours
Heat and noise: two hours	Sit at 30°C wet-bulb/31,5°C dry-bulb, with 87 dBA of continuous white noise
DAY 4	
Physical work and noise: two hours	Block-stepping at 12 steps per minute (35 watts) at 18°C wet-bulb/25,0°C dry-bulb for ten-minute intervals, each followed by a 15-minute rest interval, with 87 dBA of continuous white noise
	Rest at room temperature (18,0° wet-bulb/25,0°C dry -bulb) for two hours
Heat, physical work and noise: two hours	Block-stepping at 12 steps per minute (35 watts) at 30°C wet-bulb/31,5°C dry-bulb for ten-minute intervals, each followed by a 15-minute rest interval, with 87 dBA of continuous white noise

A two-hour rest period was applied between test conditions, to eliminate the effects of the first exposure and avoid confounding the results, as well as to provide participants with an opportunity to rest and recover.

No food was consumed by participants during the exposure period, as this could cause changes in metabolism and thermo-genesis, which could influence physiological responses. Water was available in 250 ml quantities at 15-minute intervals during the course of the physical work exposure conditions and at 30-minute intervals during heat exposure conditions.

## Results and Discussion

The results of statistical analysis on this sample are presented in table 3. The results of the experiment are presented in three different graphs in figures 1 to 3 to facilitate separate evaluations of each health stressor viz. noise, heat and exercise.

Table 2 Statistical analysis of results

Paired Differences								
	Mean	Std. Deviation	Std. Error Mean	95% confidence interval of difference		t	df	Sig. (2-tailed)
				Upper	Lower			
Activity = Physical work	-0.25	1.00	0.30	-0.92	0.42	-0.83	10	0.428
Activity = Heat	0.42	0.84	0.25	-0.15	0.98	1.64	10	0.133
Activity = Heat and Physical work	-0.27	1.26	0.38	-1.12	0.58	-0.70	10	0.497
Activity = Noise	-0.68	1.09	0.31	-1.37	0.01	-2.16	11	0.053
Activity = Noise and Physical work	0.31	1.38	0.42	-0.62	1.24	0.75	10	0.472
Activity = Noise and Heat	0.39	1.19	0.36	-0.41	1.18	1.08	10	0.306
Activity = Noise, Heat and Physical work	-0.49	0.98	0.29	-1.14	0.17	-1.65	10	0.129

Table 2 indicates that only condition that yielded showed statistically significant differences from participants' average baseline was exposure to noise alone (0.053  $p < 0.05$ ).

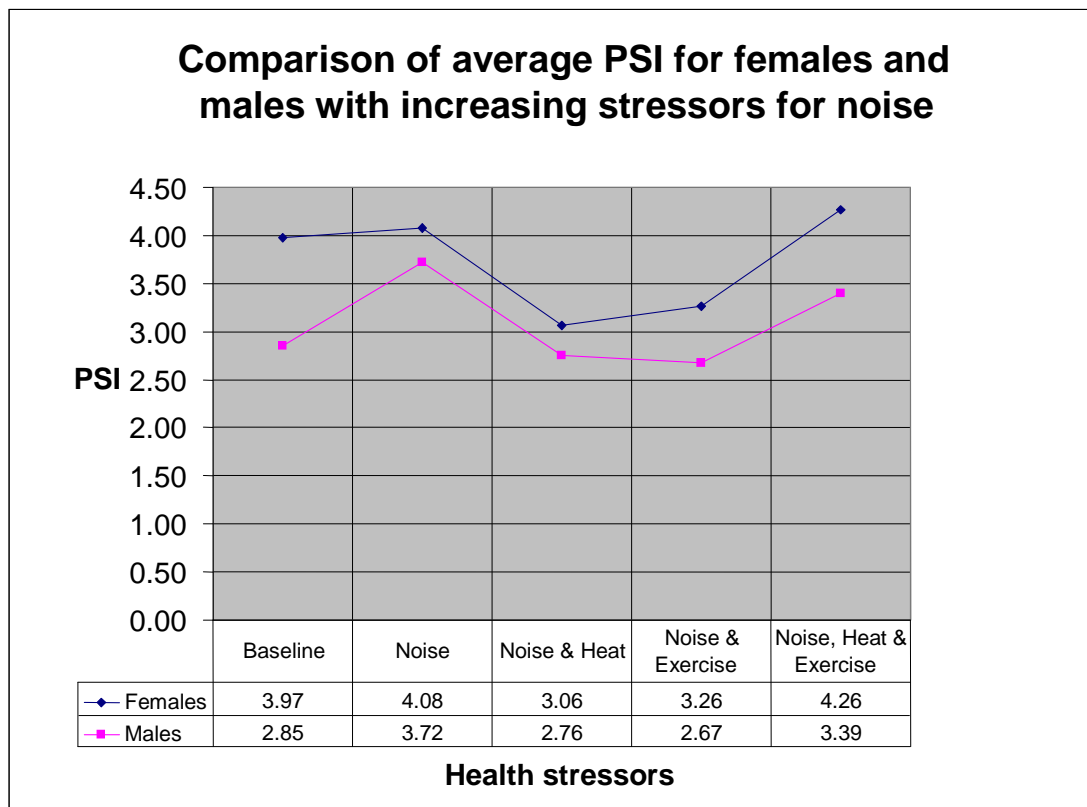


Figure 1 The impact of noise on average PSI

Figure 1 shows that exposure to noise alone causes an increase in the average physiological strain in females but males show very little change in PSI score. However, as indicated in table 3, the difference was shown to be statistically significant. This finding may indicate that the reported non-auditory effects of noise discussed in the introductory section have greater influence than expected, and that the effect is greater on females than on males. The implication of this finding is that attention to the non-auditory effects of noise should be an important motivation for noise control measures and may have increasing relevance as the mining workforce includes more females since they seem to be more effected by noise than males.

Once noise exposure is combined with exposure to other stressors i.e. noise and heat or noise and physical work, the physiological strain decreases to levels below the baseline values. This result is unexplained but may be due to the small sample size and therefore requires further investigation.

When participants were exposed to a combination of three health stressors, physiological strain was greater than for a combination of two, but was still near baseline levels. The statistical analysis confirmed that the differences between these measurements were only significantly different for exposure to noise alone. With the

confidence interval set at 95 per cent ( $p < 0,05$ ), and a small sample size, the significance of this difference is not very robust, and a larger sample size may have provided more definitive results. An ANOVA analysis indicated no significant differences for any of the exposure conditions.

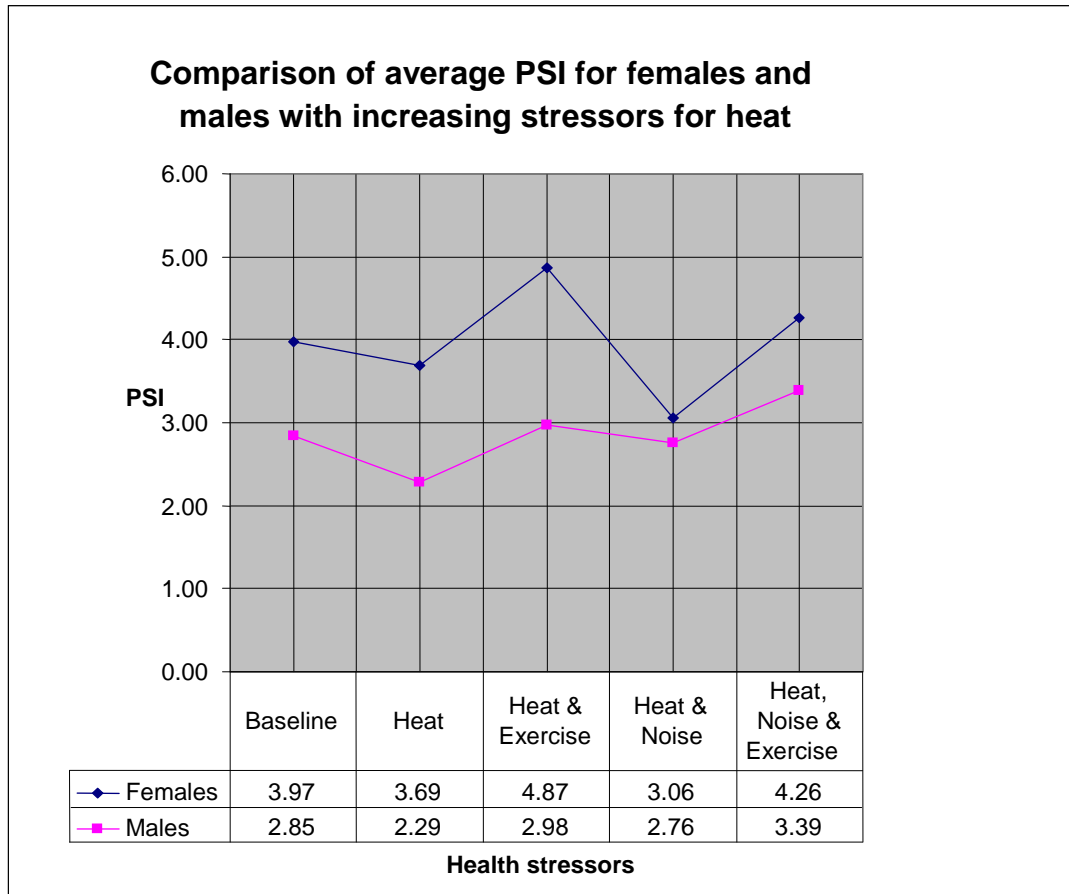


Figure 2. The impact of heat on averaged PSI

Figure 2 illustrates the results from another perspective, namely by examining the impact of heat on averaged PSI scores. In this case the difference in physiological strain experienced by males and females was considerably greater. The results indicate that heat alone caused a decrease in physiological strain compared with baseline responses. This unexpected finding may also be as a result of the small sample size. The physiological strain imposed by heat combined with physical work appears to have had the greatest effect, especially on male participants. This finding may imply that women can be more easily placed in occupations where heat is a stressor, but further research will be needed to confirm the results. The steady increase in PSI score from two stressors to three stressors appears to confirm that the effect of multiple stressors is

additive if heat is one of them. However the increase in PSI score from the baseline was not found to be statistically significant.

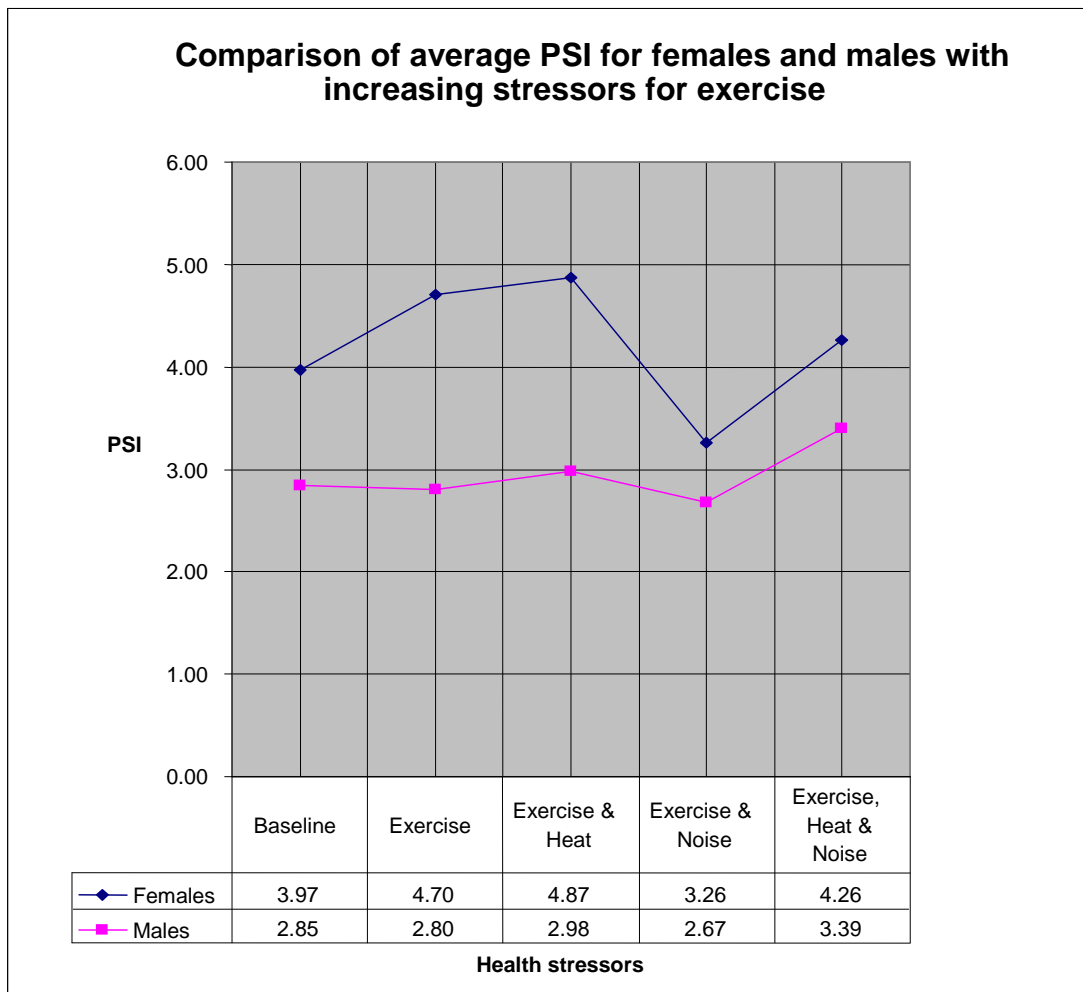


Figure 3 The impact of exercise on averaged PSI

Figure 3 illustrates the effect of physical work on averaged PSI scores. The results, once again, differ considerably for males and females. Females showed very little change in physiological strain for any combinations of physical work with the other stressors. Males on the other hand, experienced a relatively large increase in physiological strain for physical work alone, and even greater increases in their average PSI scores when physical work and heat were combined. Noise combined with physical work reduced the physiological strain, but when all three stressors was applied, the males' physiological strain increased. However, as mentioned previously, the differences are not statistically significant. The implication of this finding may be that females are more able to cope with job categories that involve physical work than would have been expected. Further research, with a larger number of subjects would be essential before this finding can be confirmed.

It must be noted that all the averaged PSI results shown in figures 1 to 3 are within the range of “little strain” to “moderate strain”. The PSI level of seven is indicated as a level that is unacceptable for human health (7). The results have implications for the OELs used in mining. The implication is that when exposure levels are below the suggested OELs, as they were in this experiment, the physiological strain imposed on the worker is acceptable and safe. The comparison of these results with results from an extended working shift and less controlled exposure levels in a real world environment will provide valuable information about the safe exposure of the mining workforce.

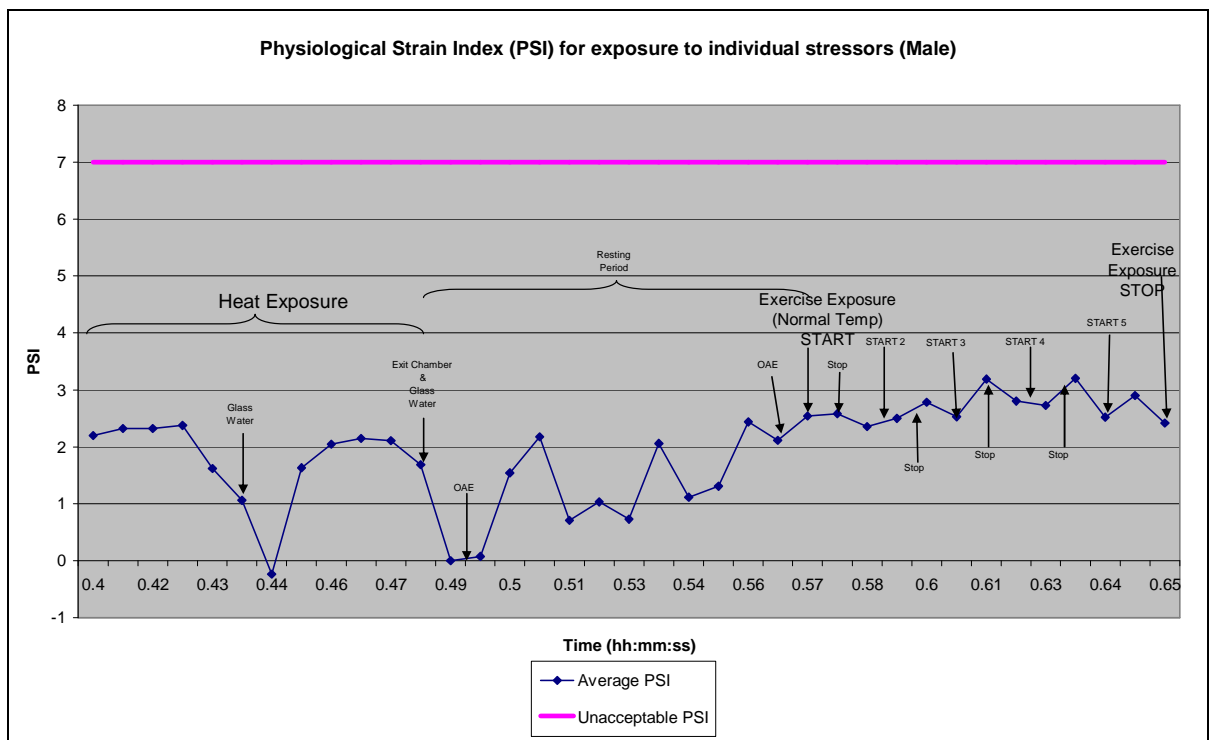


Figure 4. Example of Physiological Strain Index for a male when exposed to heat alone and exercise alone.

The example on the data graph of the PSI experienced by one of the participants in figure 4, indicates the ability of the index to provide comparative information. The comparison of resting PSI with post-exposure results will provide useful information for job category placement in the mining industry. Similarly, pre- and post- intervention measures when using different intervention strategies to reduced physiological strain can also benefit from information from the PSI.

## Conclusion

The method of measurement used in this study namely the CoreTemp™ Physiological Monitoring system is a valid method of determining PSI and could prove a valuable tool

for assessing the relevance of current occupational exposure limits, risk assessment and job selection criteria in terms of physiological strain and gender in future. It also appears to be a useful tool to evaluate gender differences in physiological strain. Use of the CoreTemp™ system in a real-time mining situation has appears to have potential for quantifying physiological strain for various work tasks and selecting well-suited individuals to perform them. The results of the current study were not conclusive, since the severity of exposure was limited for safety and ethical reasons. The higher levels and longer periods of exposure that occur in the mining industry could produce more conclusive results. The health status of the mining workforce is likely to influence the results and comparisons of in situ results with those from the current study should add to the current body of knowledge regarding physiological strain in the workplace. The current study's small sample size limited its investigation of multiple stressors and their impact on PSI, indicating a need for further investigation using a larger sample size.

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Harsh work environment associated with mining imposes physiological strain on mineworkers.

Heart rate and core body temperature combined in a physiological strain index have been shown to be reliable indicators of the physiological strain experienced during physical activity.

A mining environment exposes workers to multiple health stressors in various combinations.

PSI appears to be a potentially useful means of measuring total physiological strain experienced during exposure to multiple health stressors.