Wood Training

Using Wearable Sensors to Identify Early Signs of Heat Distress for Fire-Fighting Training

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Executive Summary

Purpose and research design

The purpose of the project was to determine the safe parameters for firefighting trainers to work within to minimise the health risks from heat exposure. This was done through use of wearable sensors to monitoring biometric data of participants during training exercises with a view to establishing protocols for the training environment.

The aims were to:

- Establish the early signs of heat distress in order to recognise them
- Identify and use appropriate sensors to assist with monitoring the body's reaction to heat under fire-fighting training conditions
- Recommend cooling and rest regimes to avoid heat distress in firefighting training sessions

A literature review was conducted to ascertain the signs of heat distress and to identify what biometric data needed to be monitored. The next step involved identifying the most appropriate sensing method to use. The eq02 life sensor system was used as a wearable sensor as it had been tested under high heat exposure, and can be worn under PPE without impeding the work of the wearer. Participants wore the sensors while engaging in training activities. A phone app was developed to allow qualitative observations which are time-stamped to allow comparison to eqO2 data. An external sensor for ambient temperature was also developed.

Participants were then monitored for heart rate, breathing rate and skin temperature at rest, and during training exercises. Controlled trials were also conducted to ascertain the most effective way of passive cooling appropriate to the training environment.

Findings show that there are essentially two areas of concern.

- One is about management of heat stress – students are more at risk of this than the tutors especially during assessment. New trainers may be at risk of this or if they have not been training often (acclimation advantage lost).
- The second is physiological stress on tutors after regular exposure to hot fires. Tutors that participated were often operating near the capacity in terms of heart

rate and temperature tolerance. Recommendations (see section for more details) includes:

- regular health monitoring,
- procedures for rest, hydration, monitoring, number of wears to be developed and implemented.

List of Contents

Table of Figures

Acknowledgement

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Introduction

M&O Pacific Limited trading as Wood Training is a Private Training Establishment registered with the New Zealand Qualifications Authority. Wood Training provides health and safety training and consultancy services to oil & gas, energy, food processing, transport, construction, engineering & manufacturing, marine & aviation sectors as well as the government. Fire-fighting training is provided in the purpose built Emergency Response Training Centre in Bell Block, New Plymouth, New Zealand.

Fire-fighting trainers are responsible for the safe operation of the Emergency Response Training Centre during training activities. This includes regular use of breathing apparatus (BA) and exposure to live fire burns. Multiple exposures to live burns may cause high levels of physiological and cognitive stress due to the combination of exposure to extreme heat (i.e. live fire) and the sustained use of heavy protective clothing, while engaging in physical activity. Exposure to live fire while wearing full personal protective equipment is commonly referred to as "a wear". Training in summer time may also add to the risk of heat related illness as the ambient temperature adds to the situation.

Each individual has a different physiological tolerance to extreme heat making a one-size-fits-all approach to controls difficult. This project sought to use wearable sensors to monitor the effects of heat on the body with a view to recommending protocols to minimise the impact of heat exposure on trainers in the training environment.

Literature Review

In 2019 WorkSafe New Zealand released a series of guidance documents about managing thermal comfort at work, working safely in extreme temperatures and identified the stages of heat-related illness. These are: heat rash, heat cramps, heat exhaustion and heat stroke. The guidance tends towards advising those who work in high temperatures around machinery or working outdoors in summer. Those working in environments of high humidity or radiant heat are more at risk of becoming susceptible to heat related illness or injury.

According to the National Fire Protection Association (NFPA) injuries involving exposure to heat (as well as smoke and toxic agents) were the most common injuries experienced by firefighters in the United States of America (Campbell, 2021). It reported that 23 percent of injuries from volunteers involved exhaustion, fatigue, dizziness, breathing difficulty or cardiac symptoms compared to the career firefighters at 9 %. They indicate that this difference is likely to do with individual fitness levels of the career firefighters and general nutrition or wellness. It was found that injuries are more likely to happen between the hours of 12 pm and 9 pm. According to the National Institute of Health (United States) cardiac events accounted for approximately 45% of firefighter duty-related deaths each year (Serban, 2019, Kales, Soteriades, Christoudias, & Christiani, 2003). The authors note other risk factors that place strain on the heart such as smoking, and exposure to consecutive live fire burns where heart rate can be 40 bpm higher than normal baseline.

The NFPA reports that around 10% of in line-of-duty deaths with sudden cardiac death was during training activities (Horn, Stewart, Kesler, DeBlois, Kerber, Fent, Scott, Fernhall, & Smith, 2019). A survey of fire service instructors in the United Kingdom indicates that instructors with more than 11 breathing apparatus exposures per month were 4.5 times more likely to experience symptoms of illness (Watkins, Hayes Watt & Richardson, 2018). There is no evidence-based literature that indicates the safe number of wears but the study of physiological responses of instructors suggests that repeated heat exposures may cause chronic inflammation and that increasing the recovery time and limiting the number of heat exposures may reduce the risk of illness.

Dr Richardson of the University of Brighton (2020) working with the Fire Brigades Union investigated firefighters' heat exposure, considerations for preparation, recovery and heat illnesses to help minimise the health risks of live fire exposure for firefighters through the development of an education pack (Richardson, Hayes, Watkins, Wilmott, Relf, Watt, 2018). Dr Richardson notes that firefighting training can cause stress on the body particularly in the summer months, and the production of this education pack recognises the need to manage risks due to heat exposure.

All firefighting activities are dependent on the physiological capabilities of individual firefighters. The Office of the Deputy Prime Minister (United Kingdom) commissioned a paper on the Physiological Assessment of Firefighting Search and Rescue in the Built Environment and indicates that personal baseline fitness levels are important (Optimal Performance Ltd, 2004).

Researchers in the University of Edinburgh indicated that working in high temperatures increases the risk of having a heart attack. One example of this was a firefighter who had worked as an instructor for three years setting fires inside a shipping container three to four times a day, with exposures to heat over 600°C. He was physically fit, but had a heart attack at age 36. It is thought that exposure to repeat high temperatures creates a thickening of the blood. A study by the British Heart Foundation indicated that firefighters' core temperature remained high for three to four hours following exposure to fire, and their blood became stickier and was 66% more likely to form harmful clots. This is due to the combination of fluid loss due to sweating and an increased inflammatory response as a result of the exposure to the fire. The need to take regular rests and have good levels of hydration were recommended (BBC News, 2017).

Various standards that align with the activities of firefighting and instruction indicate recommended rest and recovery time. NFPA 1584 indicates a minimum of 20 minutes following the use of self-contained breathing apparatus (SCBA) or after 40 minutes of intense work without SCBA. The standard also indicates that rehabilitation should include consumption of fluids (drink frequently i.e. every 20 minutes) and removal of protective clothing and employ active and/or passive cooling during the rest and recovery process (NFPA, 2022). It also recommends that firefighters should avoid alcohol and caffeine beverages before activities as this may lead to heat stress. The standard also indicates that fluid containing carbohydrate solution of 4-8% (up to 235 ml) should be consumed every 15 minutes during intensive physical activities that take place for more than an hour (NFPA, 2022). However there is no obligation to observe this standard so there is no formal standardisation of rehabilitation approaches (Kim, Kim, Lee & Lee. 2019). Other authors indicate cooling activity should include removing coats, helmets, gloves, open pants and removing boots if possible (Fullagar, Schwarz, Richardson, Notley,, Lu, & Duffield, 2021).

A recent study at Massey University specifically examined the impact of live fire training on National Training Centre based instructors and indicated that instructors were at greater risk of developing heat illness due to experiencing high heat environments more frequently compared to others (Mündel, Legg, & Laird,. 2020). It was noted that repeated exposure to live fire burns gives instructors heat acclimatisation, but that also increases the physiological strain. Without heat exposure over a number of weeks, instructors' immune systems are able to recover.

In the study by Massey, the instructors indicated that there were no guidelines or specific practices for the avoidance of heat strain before a live fire instruction day other than use Level 2 protective clothing, ensure there is shade, provision of water and electrolyte squelcher drink and some general advice about avoiding alcohol and caffeine. The most common method of preparation was to drink water prior to live instruction, although this was left up to individuals to drink what they felt was best. Some indicated that they were reluctant to hydrate as they wished to avoid the urge to urinate while training. There was no information on how much to drink, what type to drink (electrolyte, carbohydrate, water, what temperature) and to whether to sip or slug the drink.

No instructors were able to articulate what was a suitable rest and recovery time after each live fire session. It was reported that they could tolerate four revolutions a day, but that six was too many. Watt et al (2016) noted that after 15 live burns across 4 weeks, instructors' average heart rate response to the live fire burn was 40 beats per minute higher, lung function was reduced, overall wellness was reduced and there was evidence of some immunological suppression. After 7 weeks with no heat exposure, the immunological cells had returned to normal.

In the United Kingdom, the Fire Service Manual provided general guidance of two hot wears per day, with at least a 2 hour break between wears (Fire Service Manual, 2003) but this takes no account of the activity of the exercise or the physiology of the fire-fighter. Fire Service College gives each activity or wear a score related to perceived exertion. It takes into account the individual's daily state, their heat tolerance and location during the activity (how close to the fire). This system is reportedly hard to manage and The Chief Fire Officers Association indicates more research is needed to be definitive about the safe number of wears (2016).

There remains no clear evidence-based consensus for minising the risks of heat related illness for instructors/trainers who endure repeated live burns and high temperatures. The most likely reason for this is that heat tolerance depends on different physiology and fitness levels and so hard and fast rules do not fit every purpose. There remains a belief that experiencing real fire burns is an important part of training a fire-fighter and so the impact on the trainer who experiences multiple wears (burns) over long periods of time, needs to have further consideration.

What is a Heat Related Illness?

Heat related illness has three stages that need to be monitored, each progressively getting more dangerous for the body. The first stage is heat cramps that normally form as painful brief cramps that can form in the calves, thighs and shoulders (DerSarkissian, 2021). After heat cramps it can progress into heat exhaustion which is when the core temperature has increased to a high fever condition of 40 degrees Celsius (104 Fahrenheit) and would have symptoms like vomiting, nausea, paleness, shallow breathing and a rapid heart rate.

From heat exhaustion it can lead into the most serious stage, heat stroke. Worksafe New Zealand indicates that heatstroke is where the body temperature is above 39.4^{o}C, and if not immediately tended to it can cause damage to the brain, heart, kidneys and muscles, and can even lead to death (Skinner, 2022). This is the most serious of the heat-related illnesses where core temperatures of 40 degrees can cause central nervous system abnormalities causing altered mental status of the person (encephalopathy) and can cause seizures or comas (Richardson at el., 2018).

Most times heat related illnesses are caused by exposure to high environmental heat while doing strenuous physical exercise. For most, a high core temperature is above 37 degrees Celsius. Most occupational health and safety guidelines indicate that a core temperature higher than 38^{o}C presents a risk of heat stress (Serban, 2019). For the people who are acclimated to heat their core body temperature will be lower and their body can reach higher ranges than the normal person without causing any damage to their body (Kenzen, 2021). A study commissioned by the United Kingdom's office of the Deputy Prime Minister indicates this can be as high as 39.5^{o}C (Optimal Performance Ltd, 2004). Looking specifically at firefighters, a core temperature of less than 40^{o}C is considered to be a mild form of heat related illness (i.e. heat exhaustion) (Kim, Kim, Lee & Lee. 2019). National Fire Protection Association standard 1584 indicates that heat exhaustion manifests when there is an elevated body temperature of 38^{o}C with heat stroke over 41^{o}C (NFPA, 2022).

What is Heat Stress?

Heat stress is the feeling that the workers feel due to the combination of metabolic heat production, environmental factors like air temperature, humidity and pressure, and clothing. Even suffering a little bit from heat stress may lead to discomfort and may detrimentally affect work efficiency (Huang et al., 2020). Heat stress is another way of describing when someone is suffering from a heat related illness.

The most common forms of mild-to-moderate heat-related illness include symptoms of intense thirst, weakness, discomfort, anxiety, dizziness, syncope (Richardson at el., 2018). Another set of early symptoms is headache, dehydration, heat rashes, heavy sweating, and muscle cramps (WorkSafe, 2019).

Hyperthermia is an abnormally high body temperature caused by a failure of the heat-regulating mechanisms of the body to deal with the heat coming from the environment. People experiencing heat stress can also have extremity swelling also known as heat oedema, heat cramps which are painful involuntary muscle spasms which can happen during or immediately after exercise. Heat syncope (loss of consciousness) caused by lack of blood pressure and the reduced blood flow to the brain are also other risks of heat stress (Richardson at el., 2018).

Why Stopping Heat Related Illness is Important

If a heat-related Illness is not monitored properly, it can lead to heat stroke and so it is important to have controls in place to minimise these heat-related injuries from occurring.

A study undertaken in California indicated that for every 5 degrees Celsius increase in the mean ambient temperature, workplace injuries were 5 to 7% higher (Flavelle, 2021). They experienced an increase of 393% of hospitalisations for heat related illness during the summer of June 2016 when ambient temperatures reached 29°C (compared to 25°C). For every 10-degree Fahrenheit (2.8 degrees Celsius increase) increase in temperature, there is generally an increase in hospitalisations for heat exposure (Schmeltz at el., 2016).

For the fire fighters that train during the summer in Taranaki the average outside temperature is between 20-25 °C, which means training outside without an additional radiant heat source (i.e. live fire), is already nearing the 25°C threshold considered to be comfortable. As our trainers use live fire situations, they are repeatedly exposing their body to heat and flames, and if not able to properly cool down or rest afterwards, they could be susceptible to injury that is caused by heat or to a heat related illness. Trainers wear personal protective equipment (PPE), which also impedes the normal cooling process of the body as the sweat cannot evaporate. Training is often for a full-day, so firefighters are in full PPE for long periods of time, while also being exposed to the sun.

Vulnerability to Heat-related Illness

Everyone is vulnerable to suffering a heat-related illness but there are parameters that make certain people more susceptible. Males generally do not suffer from heat-related illness as severe as women may do. Males generally have a higher metabolic rate which means that they release more body heat more readily (WorkSafe, 2019).

Females typically have a greater body fat percentage and have fluctuations in hormonal releases which changes their heat tolerance. Women who are going through their luteal phase of their menstrual cycle are more vulnerable to a heat-related illness. During this stage of the cycle women have an increased respiratory demand with an increased need for oxygen consumption (Marsha & Jenkins, 2002).

Age is another factor in affecting how some people are more vulnerable to heat-related illness. The older the person is, the more the sweat glands shrink. They also generally have a lower respiratory capacity which means when working in extreme heat they are more vulnerable (WorkSafe, 2019).

Body type is another factor for heat related illness, with the larger the body size the lower the surface area to body mass ratio, which, when exposed to extreme heat, the body core temperature rises faster (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018).

Certain prescribed medicines can cause a person to suffer from heat-related illness more readily. These following drugs can increase the chances of a heat-related illness based on their effects.

- Diuretics (Water Pills),
- Hypertensive medications (Blood Pressure Medicine),
- Beta-blockers (Heart Medicine),
- Antipsychotics (Anti psychiatric Drugs),

- Anticholinergic (Anti acetylcholine Drugs),
- Antidepressants,
- Anticonvulsants (Anti-Seizure Drugs),
- Migraine drugs.

These drugs affect the user's cardiac output and thirst sensation, which in the long run can impair thermoregulation, sweating and the perception/feeling of heat stress (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018).

Alcohol consumption can cause an increase in heart rate, and long term drinking above the recommended guidelines can lead to ongoing increased heart rate and weakened heart muscle. Regular drinking can cause tachycardia (increased heart rate) or irregular heartbeats and increased blood clots (alcoholthinkagain, 2022). It was found that consuming one standard drink elevated heart rates by 5 beats per minute for the next six hours. With two or more drinks, the increase in heart rate was greater, and remained elevated for up to 24 hours later (Tasnim, Tang, Musini & Wright, 2020; O'Connor, 2021).

Tattooed skin and skin disease can also impair the skin from sweating properly. Temporary illnesses like being hung-over, diarrhoea and fever all impair the body's ability to sweat (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018).

Acclimatisation for Firefighters

For the firefighting trainers, monitoring for heat-related illness may differ in their criteria to that of a participating student. Trainers will be more acclimatised to the heat exposure, meaning that instead of having a baseline for core temperature of around 37.5 ^{O}C their body core temperature will be lower than that, but when exposed to heat their body core temperature and can get up around 38.5 ^{O}C without causing damage to their bodies (Kenzen, 2021). The trainers will have lower core temperature and have a higher sweat rate, this means that they will be able to tolerate heat stress better and will be able to extend their time during the occupational tasks (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018). Acclimatisation is a complex process that allows the body to better cope with heat stress. It enables blood circulation improvement, and heart rate and body temperature decrease (Budica, 2020). To maintain core temperature the body must be able to get rid of excess heat, and it does this by increasing blood flow to the skin which causes heart rate increase (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018). When the body cannot release the heat through the evaporation of sweat (such as wearing firefighter PPE), heat is retained.

New trainers/tutors would need to become heat acclimatised and this will occur naturally, but there are some tips that will help with becoming acclimated quicker (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018). Alternative passive strategies include hot water bathing in 40 degrees Celsius heat for 20 to 40 minutes alongside or immediately after training. Sauna exposure in 80-degree Celsius heat and 20% relative humidity or 40 ^{O}C for 20 to 40 minutes also either before or immediately after training. Restricting heat loss during regular training such as by wearing an upper-or full body sauna suit during training for 20-40 minutes. The recommendation is a minimum of 5 exposures over a 2-week period will get the body acclimatisation to heat (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018).

For every day that a trainer is not training in heat, their resting core temperature and heart rate have been shown to reduce by 2.5% per day. It is suggested for every 2-days absent from heat exposure the 1-day of adaptation is lost (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018). It is also noted that consecutive day live burns seem to exacerbate thermal strain (Schlader et al., 2017).

Other studies showed that increasing a fire suppression exercise from 15 minutes to 30 minutes increased the core body temperature by 1.5^{o}C (Hosler et al. 2016). When instructors acted as safety officers in live training exercises that averaged 40 minutes in duration, their core body temperature increased by 0.5^{o}C. New recruits or trainees with no previous fire exposure may be at greatest risk due as their individual heat intolerance is unknown, and they are unlikely to be heat acclimatised (Watkins, Gibbons, Dellas, Hayes, Watt, & Richardson, 2018).

As acclimatisation changes the body's ability to withstand heat exposure, it does so by reducing sodium loss and increases fluid loss, which can lead to earlier dehydration (CFOA, 2016). An acclimated person is able to work in hot environments for longer periods, but this advantage is lost within a week or two.

Wearable Sensors

One aim of this project is to identify and evaluate sensor devices that can monitor various physiological parameters related to heat stress. The purpose of the sensors was to gain information to assist with establishing protocols to minimise risk to trainers. Another aspect of this project is to identify and recommend recovery plans related to the limitation of wears, hydration plans, cooling strategies and rest periods.

There are a number of devices for monitoring physiological responses related to heat stress namely: Kenzen, Body Trak and the eq02-life monitor. However, the most reliable way to predict heat stroke is by taking the body core temperature which none of these devices do. They do however estimate body core temperature based on skin readings and this has been established as being relatively accurate.

The Kenzen device was developed for people working outside in extreme heat doing physical labour, not so much for firefighters wearing PPE gear (which impacts on sweating and cooling). The Kenzen software uses a personal profile to predict if the person will suffer from heat distress using the features of sex, age, sweat rate, hydration and heat susceptibility, and can sense ambient and skin temperature, heart rate, activity levels and motion metrics. They also have in development an illness detection system and also deep learning plus optimisation.

As this device uses artificial intelligence (AI) and hence the data parameters would not be based on acclimatised firefighters, which may mean there would be more false positives as acclimatised trainers can easily get their core body temperature at 38.5 ^{o}C degrees Celsius. The device might assume that the participant is near heat exhaustion. They have recently started evaluating their product with firefighters live fire situations according to Kenzen twitter account (https://twitter.com/kenzeninc). The Kenzen device is worn on the arm which would be underneath PPE which may impact on movability for the fire-fighter.

The application and research that was conducted by the Kenzen company was tested to meet industry-accepted standards meaning that on average there was only less than 0.3 degrees Celsius difference between their instrument and the gold standard methods of gastrointestinal pill for getting a core body temperature. Meaning that the core temperature accuracy was able to range from 36 to 40 degrees Celsius and environmental conditions ranging from 13 to 43 degrees Celsius. This device is well tested (albeit not in firefighting capacity) and is backed by well standard peer reviewed techniques (Kenzen, 2021).

The eq02-life Monitor is a device developed for firefighters, which means that it can tolerate live burn temperatures. The eq02-life has a lot more components that will allow for the device to measure more accurate measurements compared to Kenzen device components. The eq02-life has potential to monitor ECG, ECG waveforms, HR, R-R interval, Respiratory rate and respiratory waveforms, skin temperature, galvanic skin response, core temperature capsule/dermal patch, accelerometer, body position/movement, and oxygen saturation (eq02-life, 2022).

The eq02-life monitor is a vest monitor where the device is put in a slot into a vest that reads the users vitals, and this can be worn under PPE. This is more suitable than the Kenzen device which is worn on the arm.

Body Trak is another sensor device, and is very similar in the components to Kenzen, where Body Trak reads heart rate variability, $V0_2$ (Oxygen level), cadence/distance travelled and the stride rate (SPM), as well as calories burnt.

Body Trak in terms of its wearability is very different compared to eq02 life and Kenzen as the Body Trak sits on the ear and much smaller compared to the other two devices which makes the wearability much better for active work. However, wearing an earpiece on the ear under the helmet might be tight against the head of the wearer which will not be practical.

Body Trak devices use personal profiles like Kenzen and machine learning (neural network) to then predict if the person is close to getting heat stroke. If the person is then warned about through the earpiece.

The Oura ring is a sensor device worn on a finger so would be easier for the firefighters to wear as some of them already have their wedding rings on which they wear even in extreme temperatures under gloves. The Oura ring senses heart rate with high accuracy (98%). This means that the ring has a very accurate sensor so when it comes to monitoring the health of the wearer when engaging in training activities.

Parameters that Need to be Measured

We also considered building our own devices. We would have had to focus on sensors for heart rate, blood flow, skin sweat response and skin temperature. High heart rate, high sweat rate and high skin temperature are physiological responses indicating the wearer may progress to heat stress. With regard to skin temperature, anything higher than 40.6 °C if there is too much sweating then the heat cannot be dissipated normally from the body. When someone is suffering from heat stroke, they may have a rapid heartbeat and or low systolic blood pressure (Chen, Lin, Lan. & Hsu, 2018a). Having a heart beat greater than 60 and less than 99 beat per minute (bpm) is normal. Anything between 100 and 188 bpm is a normal exercise range and getting between 189 to 220 bpm is when it is too high. This is affected by age with maximum heart rate being calculated as 220 bpm- age. Having a skin temperature of between 36 to 37°C is normal, whereas getting between 38-40 °C is high and anything higher than 41 is dangerous (Chen, Lin, Lan, & Hsu, 2018b). These were the parameters that we would need to monitor which we need to take into consideration when developing our own device.

Anything we made would need to tolerate the heat in the Realistic Fire Training Building (RFTB) where temperatures reach over 250°C. It would need to be able to record data in this environment for a duration of around 10-20 minutes inside the RFTB multiple times in a day. The RFTB without any fire, would have an air temperature of about 50 degree Celsius and the device would have to store memory as transmitting out of the RFTB would be impacted as it is a metal structure.

To monitor ambient air temperature around the fire-ground we built our own device, and created a phone application to record activities, observations and qualitative data.

With some of the commercial devices there is a system that alerts the wearer that they are about to suffer from heat exhaustion which implies real-time supervision and monitoring. The Oura ring does not provide an alert system but the data can be put on phones so people can self-monitor. Anything we could build that could meet all of these parameters is likely to be larger than any of the commercial items.

The parameters that we are going to put our main focus on is the heart rate, breathing rate and skin temperature. An extra parameter will be to monitor ambient temperature/humidity.

Taking all the above into account we decided on the eq02 life sensor system as it has been tested under firefighter conditions (high heat), can be worn under PPE without impeding the work of the wearer, and will measure:

- Skin temperature
- Electrocardiogram
- Heart rate
- Breathing rate

A phone app was developed to record observations which are time-stamped to allow comparison with eqO2 data.

An external sensor for ambient temperature was also developed. For technical information on these developments see Appendix A.

Strategies for Cool-down

Most of the literature examining cool down strategies has been in the realm of high performance sport, where the aim is to get a competitive advantage (i.e. be faster or go further). These studies were also during activities where sweating and evaporation occurs (Schlader, Simmons, Stannard, & Mündel, 2011). Some of these studies examined the cooling effects of slushies versus fluids and found that consumption of slushies did temporarily lower core temperature but for short duration only and delayed the thermoregulation response meaning that athletes were able to push through the heat exhaustion (Jay, Morris, 2018; Naito, Haramura, MuraishiYamazaki, & Takahashi, 2020). Ice takes up more volume than water, so some studies found participants had difficulty consuming the equivalent fluid as ice, and there was more risk of stomach cramps. Ingesting slushies may also delay the thirst response - meaning that people do not realise they are overheating or are dehydrated (Choo, Peiffer, Lopes-Silva, Mesquita, Amano, Kondo, & Abbiss, 2019; Tan & Lee, 2015).

Most of the studies of cooling strategies using firefighters do so only after short bursts of activity such as 20 minutes and found that within 30 minutes of recovery, there was a slightly higher cooling rate for forearm immersion (buckets full of icy water) compared to a water perfused cooling vest or passive cooling using air conditioning, although the core temperatures at the end of the rest period were similar (Colburn, Suyama, Reis, Morley, Goss, Chen, Moore, & Hostler, 2011). Other studies found passive cool down in an air conditioned room at 15°C effective (Carter, 2007). In comparison with slushies, both cold water immersion (to navel) and slushie ingestion caused a faster rate of core temperature cooling when compared to passive recovery. There is some evidence that pre-cooling with slushies was more effective than forearm immersion or a cooling vest during rest periods (Watkins et al., 2018; Walker, Driller, Brearley, Argus, 2014).

Firefighting clothing (PPE) inhibits normal thermoregulation responses which can result in cardiovascular and thermal strain. Skin blood flow is increased and sweating occurs, but the sweat cannot evaporate leaving an increase in core temperature and heart rate. It was also noted that after 30 minutes with cooling and rehydration, most subjects' heart rate still exceeded 80p bpm and it is likely that a return to baseline or near-baseline status within 20-30 minutes recovery after exertion is unlikely (Colburn et al, 2011).

Water at temperatures between 10-15 °C is considered to be easier to drink, and there is a possibility that people may ingest less volume of cold drinks (i.e. 4°C) leading to possible dehydration (CFOA, 2016). Cold drinks can provide levels of thermo-comfort but may not result in consumption of as much fluid as needed. Vasoconstriction that may occur in the stomach may result in a slower rate of absorption. So the most effective cooling mechanism for all day training is by no means clear.

Summary of Parameters from Literature

The general parameters to consider about heat stress are:

- The body temperature fluctuates 0.8°C throughout the day
- Core temperature tends to be higher in the afternoon
- If you have been exposed to high heat in the morning, the core temperature gain in the afternoon will be greater

- Weight of wearing PPE adds to metabolic load and impairs ability to release heat (sweat).
- Physical activity adds to metabolic load (heat creation) – core temperature increases faster
- Ambient conditions (sources of heat i.e. hot, humid weather) adds to heat stress. Above 25 degree Celsius and/or high humidity
- Firefighting tasks can increase core temperature by 0.6-3.2^{o}C. Average is 1.5^{o}C for round 1 of activity and 1.8^{o}C second round.
- Firefighting tasks can increase heart rate up to over 90% of maximum. HR maximum rate is 220-age.
- General fitness is important for heat tolerance (low fat, aerobic health, age)
- Consumption of alcohol and caffeine (morning and day before heat exposure) impacts on heat tolerance by raising heart rate
- Medications impact on heat tolerance
- General illness, sleep deprivation, condition of skin (tattoos) impact on heat tolerance
- Personal heat acclimatisation increases heat tolerance
- Physiological responses to fire varies amongst individuals
- Fire service instructors who complete more than 9 heat exposures per month may be at a greater risk of ill-health and cardiovascular consequences.
- Heart rate and core temperature recovery after firefighting activities closely related to the time provided for rest. HR and Core Temperatures do not return to baseline until 50-80 minute post-firefighting.
- Intermittent work (2min work-rest cycle) has lower temperature increases compared to strenuous activities for 5-8 minutes.
- Lags of 6-8 minutes for peak core temperature to change indicating resting times needs to take this into account (more than 10 minutes)

Sources: Horn, G.P., Blevins, S., Fernhall, B. & Smith, D.L. (2013); Watkins ER, Gibbons J, Dellas Y, Hayes M, Watt P, Richardson AJ (2018); CFOA, (2016).

Methodology

The eqO2 sensors were worn by participants for the duration of normal firefighting training activity at the Emergency Response Centre in the months of February and March 2022.

A research intern was employed to assist with this study and observed the participants on each day of training recording duration of various activities and any relevant qualitative data. This included taking information on how much alcohol they had the day before, and their smoking habits and how they were feeling.

The participants wore the sensor device underneath their clothes and PPE and went about their duties as per normal training day. There were 120 hours of data collected including baselines studies where the tutors were doing office work and no PPE.

In figures 1 to 5 the trainees are putting out fires for an aviation exercise, and the tutors are acting as support and safety observers. The guest tutors are interacting directly with the students and assessing.

Figure 1: Day 2 Aircraft Training Exercise Wing Fire

Figure 2: Day 2 Aircraft Training Exercise Ground Fire

Figure 3: Day 2 Aircraft Training Exercise Roof Fire

Figure 4: Day 2 Aircraft Training Exercise Entering Aircraft

Figure 5: Aircraft Training Exercise

For the other days of data collection the activities included search and rescue training inside the RFTB which reached 250°C temperatures. The Wood Training tutors were safety observers and support crew and the Guest Tutors went into the RFTB to assess and supervise (figures 5 – 7).

Figure 6: Guest Tutor coming out of RFTB

Figure 7: RFTB with Dummies for Search and Rescue

The participants wore a harness (fig. 8) with the sensor device (fig. 9) in the pocket of the harness under their Level 2 PPE.

Figure 8: Harness and pocket for sensor - worn under clothes

Figure 9: Sensor device that is inserted into harness pocket

<u>Coolant Trials</u>

For the coolant trials the participant recorded baseline activities while engaging in 40 minutes of cross-trainer/weight lifting work that replicated the work of the instructors when working as support crew (short burst of high level activity then standing). For baseline this was done with no PPE. Then we conducted trials that involved pre-cooling using cold water (4°C) then slushy (0°C or less) and a combination of both while wearing PPE (Level 2) to see any impact if any, on core temperature and heart rate. The volume of fluid was kept consistent at ~650 ml precooling and at the rest times.

Trial #	Pre-activity	Activity	Rest	Activity	Rest 30 min
1	None **No PPE**	Light to medium activity 40 min + (less than 1 hour)	10 minutes Drink as you want (note volume and time)	Light to medium activity 40-1 hour	Keep sensor on – want to see how long to baseline
2	4 °C fluid **NO PPE**	Light to medium activity 40 min + (less than 1 hour)	10 minutes fluid	Light to medium activity 40-1 hour	Keep sensor on – want to see how long to baseline
3	4 °C fluid **PPE**	Light to medium activity 40min-1 hour	10 minutes fluid	Light to medium activity 40-1 hour	Keep sensor on – want to see how long to baseline
4	Slushy ~115g slushy **PPE**	Light to medium	10 minutes slushy	Light to medium	Keep sensor on – want to

		activity 40 min - 1 hour		activity 40 min -1 hour	see how long to baseline
5	Mix – slushy/fluid (make up to 650 ml volume) **PPE**	Light to medium activity 40 min - 1 hour	10 minutes mix	Light to medium activity 40 min -1 hour	Keep sensor on – want to see how long to baseline

An additional trial of 650 ml of slushie was done to see how long it took to eat it (same volume of the fluid).

Participants

Fire-fighter Trainers who are employed by Wood Training were the main participants of this study. They voluntarily participated in the study. Two guest Instructors volunteered to participate in the study while engaging in search and rescue instruction as well as four fire-fighting recruits engaging in fire-fighting training and being assessed.

For the purpose of privacy no data will be shown in the public report.

Results

Data was graphed, activities and observation data was aligned with biometric data and analysed to ascertain how close to capacity participants were in terms of heart rate, and any symptoms of heat distress that were obvious.

Estimated Peak Core Temperature °C	Trial Detail
37.3	No PPE - Baseline
36.9	No PPE – 4°C pre-cooling drink
37.1	No PPE – 4 °C pre-cooling & break 4°C
37.4	PPE - 4 °C pre-cooling & break 4 °C
37.4	PPE- slushy precooling & break
36.6	PPE – slushy and fluid mix – precooling & break

Table 1: Estimated Core Temperature Peaks

Note: digital thermometer had an error value of +/- 0.1°C.

Discussion

There are two aspects that have emerged from this study. The first is about recognising heat distress, the second is about physiological impact of long term strain on the body through regular exposure to live burns.

Taking all the heart rate data across the six days of data collection the tutor's heart rate reaches or nearly reaches their highest recommended rate (90% of capacity) daily during hot burn activities. Multiple consecutive days of exposure to live fire could mean personnel are regularly nearing their top physiological capacity. While acclimatisation has some protective impact against heat related injury the cost of this could be strain to the cardiovascular system. While repeated exposure to live burns builds heat acclimation and short-term protection against heat injury, excessive exposure may increase the risk of immunological disorders and cardiac issues.

Smoking and drinking alcohol the day before exercise also can impact on heart rate (elevation of 5 bpm for 2 standard drinks) as can drinking coffee. The average heart rates (median to median) rose by an additional 30-50 beats per minute from baseline. The literature indicates that an increase of 40 beats per minute is likely after a hot wear. The heart rate tends takes longer to recover to baseline after consecutive days of exposure.

The intern's heart rate increased an average of 14 bpm just wearing full Level 2 PPE in the summer sun, and so it is reasonable to calculate that an elevation of between 16 to 36 bpm is due to the exposure to fire, and the activity associated with the work. The Tutors are likely to be more acclimated to working in heat than the intern so the difference could in reality be more.

Skin temperature is a useful mechanism for monitoring as an estimate of core temperature. In general the temperature of the skin at the torso is 0.6-0.9 °C less than core temperature. Skin temperature is likely to fluctuate due to weather conditions, clothes and even time of day whereas core temperature is more constant and its role in thermoregulation is delayed.

Often the tutor's maximum skin temperatures close to heat stress parameters for people who are not acclimated, but are considered to be safe for those that are.

One tutor was showing signs of heat stress such as excessive sweating and cramps. As the tutor “had a few” the evening before, this may have been due to dehydration.

The Guest Tutors heart rates returned to pre-RFTB baselines relatively fast although the skin temperature was elevated. As a person who is likely to be heat acclimatised this temperature is not necessarily a sign of heat distress. Guest Tutor 2 had higher peaks of heart rate but also returned to baselines relatively fast and maintained a relatively stable temperature.

On student who entered the RFTB twice showed raised heart rate and skin temperature during his assessments activities. This shows the psychological impact on the physiology of the person who is not heat acclimatised. This student was likely in early stages of heat stress at the time of his last assessment. He indicated that they had not drunk much water during the day, and had alcohol the evening before (1 bottle of wine). Another student had increased breathing rate, and an elevated temperature and was possibly suffering early signs of heats stress after exiting the RFTB.

Drinking cold fluid appears be slightly more effective at keeping core temperature down during 40 minutes of exercise than just drinking room temperature water with pre-cooling possibly keeping skin temperature more stable (which may help with thermo-comfort).

Slushy did not appear to be any more effective than cold water, and was more uncomfortable to ingest. The trial of a similar volume of slushy (650g) the participant was not able to consume it all within the 30 minutes and it had started to melt. The participant felt unwell afterwards.

The most effective cooling strategy appears to be mix of slushy and cold water as the effect on oral temperature (proxy for core temperature). This also means it is less likely the participant will become dehydrated.

Recommendations

<u>General Wellness</u>

- Support fire-fighters to maintain their overall fitness (aerobic) for heart health
- Ensure awareness of risks of alcohol night before long days exposed to live fire especially in hot weather; also impact of smoking, caffeine, alcohol on heart health

- Consider warning students in fire training course outlines to minimise or eliminate alcohol up to 24 hours before fire training
- Plan for regular ECG, lung function tests, blood tests (immunoglobulins, IL-6, white blood cell count, inflammation markers) for tutors
- Plan for periods of rest – in particular rest day (no training, maintenance, office work) after working with defence force; rest periods in day minimum of 20 minutes (as it takes 10 minutes for thermoregulation to start)
- There is more risk of heat stress and other injuries in afternoon – schedule morning activities (start early finish early)
- Tutors should keep log of pre and post exposure temperature using ear thermometer.
- Any person above 39°C after rest period should not wear again that day, until core temperature returns to normal.
- Anybody with core temperature above 37.5°C start of day should not take part in hot fire training that demands physical activity.

Management

- Normal RFTB work tutors may have only have 2 "hot wears" a day as WT RFTB work already uses blind fold technique, smoke and lastly fire. This also minimises stress on students under assessment conditions.
- Using logs, monitor the amount of "hot wears" per month.

Hydration and Cooling

- Check the urine colour chart to monitor hydration level.
- Hydration is more effective before the event (has impact 4 hours after fluid intake). 500 ml two hours before heat exposure, 300 ml 15-30 minutes before, 200ml every 20 minutes when in hot environments, 1 litre within 30 minutes after heat exposure finished.
- If physical exercise is more than 1 hour - carbohydrate supplement in fluids (vit C based) advised. Isotonic drinks advised during lunch.

- Mix of slushy (115 g slushy made up to volume 650 ml with cold fluid) at pre-cooling and breaks appears to be the most effective at stabilising temperature.

Limitation of this Study

The purpose of this study was to ascertain some parameters to keep training staff safe while carrying out operational duties at the Emergency Response Centre. As such, the outcomes are not necessarily generalisable to other situations as they relate to the data collected from individuals and their unique physiology. This study was not meant for academic publication but for an internal report.

Literature indicates that the eqO2 device can accurately measure ECG and HRV (Akintola, van der Pol, Bimmel, Maan & van Heemst, 2016). Error rate for skin temperature was +/- 0.3°C. Error rate for digital thermometer was +/- O.1 °C.

The coolant study was also only conducted once – due to time limitations as the research intern was employed for a limited duration. The trials should be repeated to gain more data to give confidence in the outcome. The core temperature was also estimated. To be more reliable employing strategies for gaining core temperature would improve these trials.

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Appendixes

Data Collection App

The data collection app was written in react native, as this language would give the flexibility to create an apk for android phone or ipa for apple phones. This allows for easy versatility. The application follows a MVC (Model View Controller) model and the main functionally will be to edit, view, share or create notes.

When viewing notes, the app uses a flat list, iterates through an array containing the objects, retrieves the message, date and time, returns this to a flat list, then renders each element inside a new object component.

When creating notes, the app iterates through the current array to create a unique id to assign to the new note. The finished note is then added back into that array.

When editing, the app must retrieve and edit the correct note accurately. This is assured by the use of the MVC model.

For sharing, the app uses React Native Linking to open email applications that are download on the phone. This allows it to create an email that contains the notes and send it to anyone that might need a copy. When emailing, the data is processed into csv format. This is important because the eq02 life data is in csv format.

For storage on the phone, the app uses react native Async Storage. Maximum storage is not a concern for this app because it only stores four strings, the message, date, time and unique id strings.

The workflow of the application can be seen in the screenshots included below. In Figure 5 we can see the sample data that is being displayed is about to be sent, in the format of the csv file.

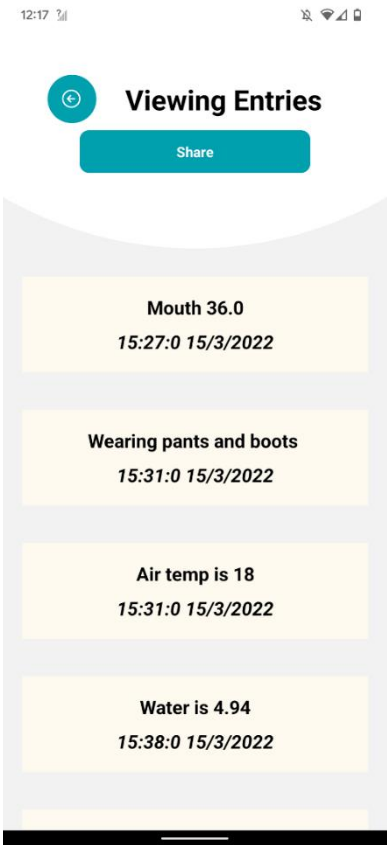

Figure 1 Notes app: View

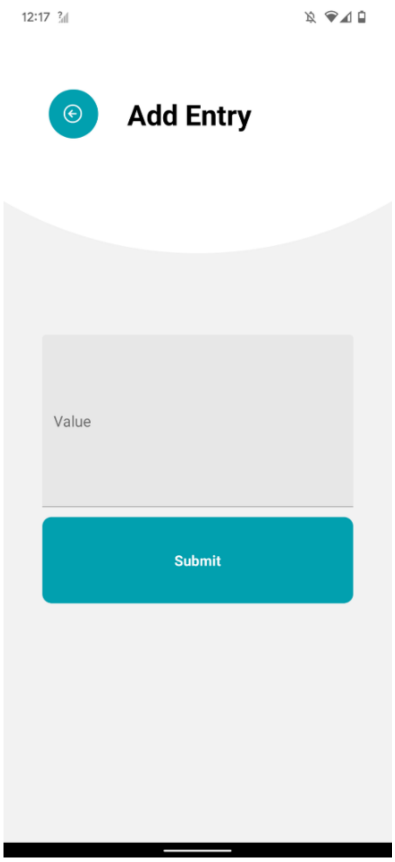

Figure 10 Notes app: Add

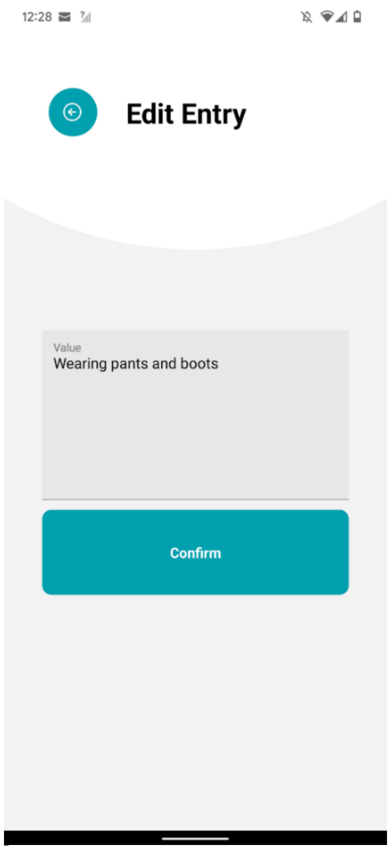

Figure 3 Notes app: Edit

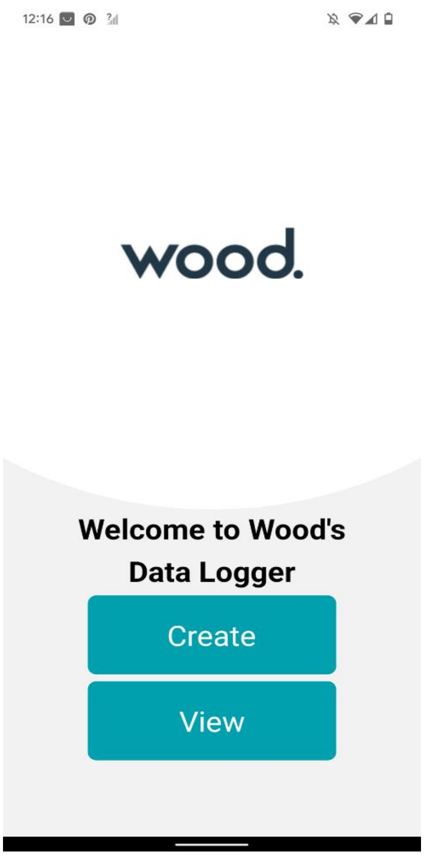

Figure 4 Notes app: Home

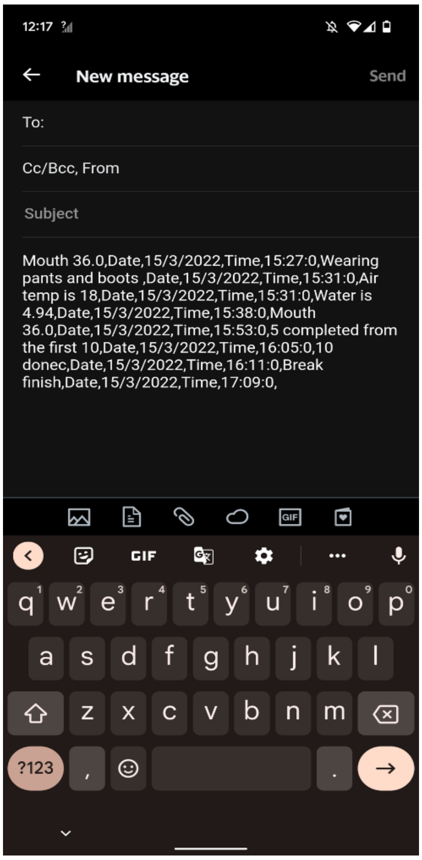

Figure 5 Notes app: Link Email

Pre-processing the Data

The data gathered during testing through the notes app and the eq02 monitors required pre-processing before results of testing could be analysed. This is due to the need to match the action notes for the day with the csv format data from eq02 life monitors. The action notes had extra commas, which meant it became hard to handle the data properly. A python script was developed that would remove all extras commas and return only the time and notes message.

Air Temperature

Our testing required air temperature to be accurately recorded throughout the day. The air temperature sensor needed to be able to function offline, as there is no WIFI in the fire training grounds. I used an Arduino uno, programmed in C++ including the Dallas Temperature, U8glib, OneWire libraries to create an air temperature that displays on screen.

Images below show the setup of the temperature sensor circuit.

In Figure 7, we have the layout of the board. The set up provides power from the Arduino uno to the OLED display and air temperature sensor. The circuit also includes wiring that takes the data from the air temperature sensor to be rendered on the OLED display.

Figure 8 shows the air temperature sensor and pluggable terminal which reformats the data from the sensor. The data from Figure 8 travels through to the board in Figure 7, and back out to display on the OLED screen shown in Figure 9 (showing the rooms air temperature is 18.75^{o}C).

Figure 6 Image of Arduino Uno

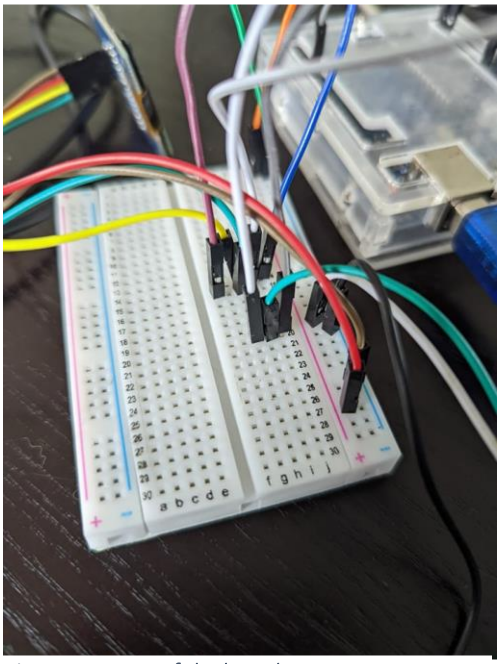

Figure 7 Layout of the board

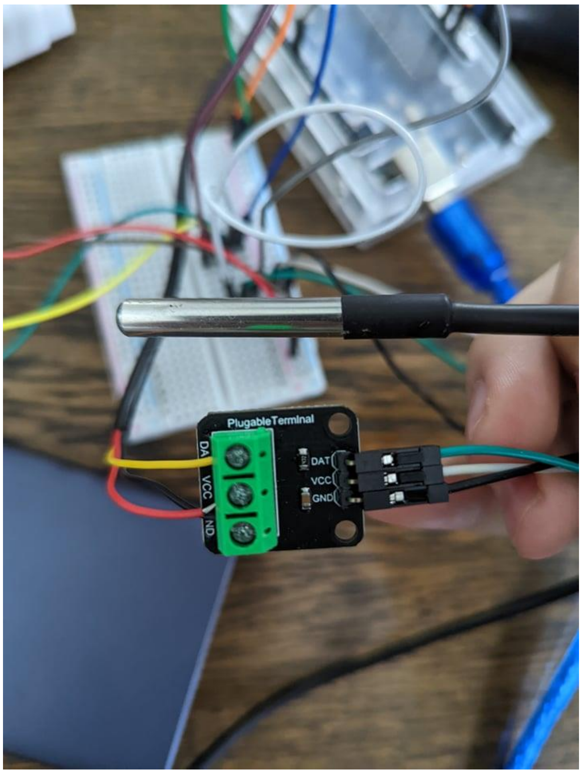

Figure 8 Air Temperature Sensor

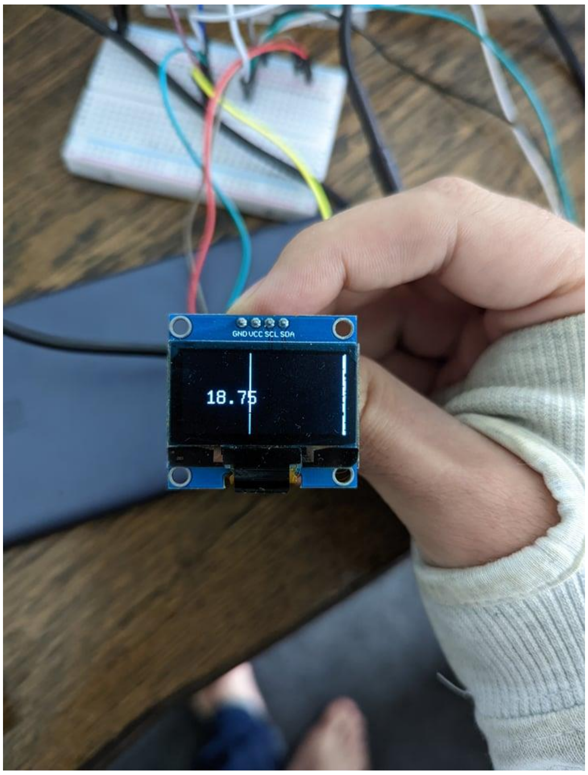

Figure 9 OLED Display