Influence of environmental temperature on motor control and motor learning: A DIY EMG investigation

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Master Thesis

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22nd August 2023

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Abstract

Living in Europe in the year 2022, we find ourselves in a significant energy crisis, which leads ordinary citizens to make sacrifices in terms of daily costs. One of these monetary concerns is the use of gas to heat one's work or home environment. Studies show that the temperature of the environment can have physical and psychological effects on individuals. This study aims to analyse and confirm previous studies on how the temperature of a room affects a person's psychological wellbeing and motor learning. In addition, this study investigates the effects of environmental temperature on motor control and muscle co-activation using a DIY technology.

This study analysed two conditions, a cold condition of 19 degrees Celsius and an ideal temperature condition of 23 degrees Celsius. The NASA TLX was used to analyse the stress and frustration levels of the participants. A DIY buzz wire technique and DIY electromyography (EMG) were used to analyse the effect of temperature on motor control and motor learning. The results showed a trend for participants in the ideal warmer temperature condition to have smoother movements during the buzz wire task, leading to better performance. However, this effect was not statistically significant and may have been confounded by some problems with the recording rate of the apparatus used for this experiment. In addition, this study confirms other studies on the positive psychological effects and reduced frustration levels when the ambient temperature is within ideal standards. In addition, this research has been able to analyse the benefits and problems of building your own setup for research.

1. Introduction

1.1. Co-activation and Motor Learning

Movement is a crucial aspect of human life. The ability to move our bodies not only gives us the ability to walk and manipulate objects but has allowed us to develop motor skills throughout evolution. Under the skin, movement is a complex interplay of muscles working in harmony through stability and co-activation mechanisms. Understanding how a person moves and identifying potential factors that may hinder the execution of specific movements are essential aspects of human motor control analysis. Research into the effects that can influence muscle control and stability is increasing, enabling the creation of an appropriate environment to promote motor learning. (Fitzakerley, 2011; Schmidt, 1975). When we talk about learning and movement, we often talk about stability, accuracy and coordination, the qualities that make it possible to complete a movement and reach its intended goal. These movement qualities are essential for completing a task and are often associated with 2 or more muscles.

When the muscles surrounding a joint are activated simultaneously to maintain joint stability, this is known as muscular coactivation. Muscular coactivation works through a group of muscles made up of agonist and antagonist muscles, allowing for correct motor control and stability of movement and joints (Latash, 2018). Antagonist muscles are found in pairs at all joints in the body, consisting of a driving muscle (agonist) and an opposing muscle (antagonist). Each muscle in the pair has a distinct purpose and is located in a specific area of the body (Latash, 2018). Antagonistic muscles have opposing actions and functions around a particular joint. When one muscle in the pair contracts to produce a specific movement, the antagonistic muscle relaxes to allow that movement to occur (Jones, and Round, 1990). When several muscles need to work together to complete a movement, they may exhibit coactivation to ensure synchronised and effective activity. This coactivation helps to provide stability and control to the movement (Ateş, Temelli, and Yucesoy, 2018; Latash, 2018). For example, muscles in the shoulder, arm, and wrist may exhibit coactivation during a difficult movement such as throwing a ball to ensure a smooth and coordinated movement. In addition, coactivation can also occur when opposing muscles are activated simultaneously to provide joint stability or precise control. This is often seen in activities that require precise control or when a joint needs to be stabilised. For example, coactivation of antagonistic muscles around the joint helps to maintain stability during a task that requires maintaining posture or when firmly grasping an object in the hand (Ateş, Temelli, and Yucesoy, 2018; Latash, 2018).

Movements can be either fast or accurate, which is known as the speed-error trade-off. The speed-accuracy trade-off is influenced by factors such as task difficulty, individual skill level and practice (Fitts, 1954). To improve accuracy, individuals may prioritise accuracy over speed in the early stages of learning a new motor skill (Zimmerman, 2011). Muscle coactivation and the speed-accuracy trade-off are linked, with slower movements resulting in greater accuracy and faster movements resulting in lower accuracy. By adjusting muscle coactivation appropriately, individuals can achieve the right balance between speed and accuracy, resulting in more efficient use of motor energy and similar outcomes (Fitts, 1954). Many studies have examined the stages of learning along with muscle activity patterns. According to this research, there is an initial increase in activity for all muscles, followed by a reduction in co-activation as learning progresses (Franklin, Burdet, Osu, Kawato and Milner, 2003). Darainy and Ostry's (2008) study extends previous research by demonstrating that the coactivation that persists after motor learning is adapted to the demands of the task, varying in amplitude in a systematic manner with both force level and direction of movement. As motor skill acquisition progresses, muscle coactivation becomes more selective and refined, focusing on the muscles required for the task (Hall, Schmidt, Durand and Buckolz, 1994).

Excessive coactivation, on the other hand, can be detrimental to motor learning, as it can lead to reduced movement efficiency and interfere with the activation of specific muscles (Latash, 2018). Therefore, having less muscle coactivation for certain tasks and movements, especially movements that do not require a high level of physical effort, may be advantageous in order to have a more fluid movement. Fluidity occurs in later stages of motor learning because muscle groups tend to be more efficient and require less energy (Lamontagne, Richards and Malouin, 2000). This is because when fewer muscles are activated at the same time, there is less interference and the possibility of unexpected movements or tremors. This allows for more precise and accurate movements by improving the control of the individual muscles involved in the task at hand (Latash, 2018; Lamontagne, Richards, and Malouin, 2000). Furthermore, it can be argued that less coactivation, i.e. activating only the necessary muscles to reduce energy expenditure, will help to reduce fatigue in movement performance. Finally, excessive coactivation in small motor tasks can lead to unwanted muscle interaction between the agonist and antagonist, creating and increasing resistance and reducing the range of motion, thus compromising the precision of movements (Lamontagne, Richards and Malouin, 2000).

1.2. Environmental temperature effects

Following the political events of early 2021, Europe was faced with a reduction in gas supply. This event has led the European Union to increase the cost of gas in order to find a way to compensate for the supply problem (European Council, 2022). The Dutch government has proposed that the Dutch population reduce the temperature of their homes and offices to 19°C (Hoogerwerf, and Eikelenboom, 2022). Changing someone's temperature environment can affect their productivity and well-being. Lang's (2004) study showed that temperature has a significant effect on productivity and typing errors. Specifically, when the temperature was increased from 68°F (20°C) to 77°F (25°C), errors decreased by 44% and typing speed increased by 150% (Lang, 2004). According to Lang's (2004) study, people perform better in daily activities when the temperature is between 22 and 24 degrees Celsius, making this temperature range ideal for performance. On the contrary, higher than ideal temperatures between 22 and 24 degrees Celsius can decrease cognitive performance and cause tension and dissatisfaction during motor activities (Lang, 2004). In addition, another study by Lan, et al, (2009) confirmed that room temperature has an effect on productivity and reaction time in simple motor tasks and at a neurological level. According to this study, participants had a slower reaction time when the room temperature was 19°C. Therefore, room temperature has a significant impact on an individual's productivity, comfort, body temperature and stress level while performing a task (Kakitsuba, and White, 2014; Vinkers et Al., 2013). The correlation between room temperature and stress is a topic of interest, especially in the context of the energy crisis faced by European citizens. Stress is related to the proper functioning of muscles and muscle mass in relation to ambient temperature.

Several studies have looked specifically at the effect of ambient temperature on muscle performance and the body's response to stress when investigating motor control and its relationship to stress and temperature. Animal studies have found a correlation between proper motor control and environmental temperature, which affects body temperature (Weinert and Waterhouse, 1998). Barnes and Larson (1985) show that temperature exposure factors can affect muscle function; therefore, to maintain force specification accuracy throughout exercise, some sort of correction mechanism must be used to compensate for temperature-related effects. This compensation is theorised to be related to a local or central neuromuscular compensatory mechanism that allows the individual to adapt their body temperature to their environment (Immink, Wright and Barnes, 2012).

Studies have shown that temperature affects muscular and manual performance, particularly at low temperatures (Provins and Morton, 1960). In addition, hand cooling has been shown to reduce finger and manual dexterity performance (Cheung, Reynolds, Macdonald, Tweedie, Urquhart and Westwood, 2008). The magnitude of the thermal stressor generated determines the risk of performance impairment. Research has argued that physiological and psychological systems can adapt to temperature effects within a tolerance zone, and that performance is only impaired when the temperature exceeds this adaptation zone (Hancock and Warm, 2003). However, little research has been conducted on how thermal conditions affect motor learning processes. According to Shephard (1985), when complex manual activities are performed in cold temperatures, training may require exposure to cold temperatures to allow for adaptation or acclimatisation. However, studies have also shown that low temperature in a training condition leads to muscular discomfort, even in the presence of strenuous and physically demanding motor tasks that have the function of warming up the body (Peiffer, Abbiss, Watson, Nosaka and Laursen, 2009).

Another effect of low temperatures is frustration in performing motor tasks. Cold temperatures have been shown in studies to increase feelings of annoyance and irritability in some people. According to Escobar, et al. (2021), people exposed to a colder environment (15.5 °C) reported higher levels of annoyance and irritation and general negative emotions than those exposed to a warm environment (32.2 °C), which was associated with high arousal and positive emotions. Another study by Hakim, et al. (2018) found that when people were exposed to cold temperatures, they rated ambiguous social situations as more unpleasant and frustrating than when they were exposed to warm temperatures. There are several reasons why cold temperatures can increase irritation and general negative emotions. One is that being cold can cause tension, and stress can increase feelings of irritation and impatience, making the person feel generally uncomfortable. Another claim is that being cold reduces cognitive capacity and affects judgement, which can make it frustrating to try to solve a problem or make a decision. As a result, temperature can affect cognitive processes such as memory and attention, both of which are essential for performing physical tasks (Hakim, et al., 2018). In addition, the influence of temperature on mood and stress levels can be seen. Research has shown that individuals are less anxious and happier under ideal temperatures, and consequently it may become more difficult to perform motor tasks as stress levels increase for individuals exposed to colder conditions (Escobar, et Al., 2021). Overall, while the impact of low room temperature on frustration, stress and well-being during motor activity varies from person to person, maintaining an ideal temperature between 22 and 24 degrees Celsius can help reduce the impact of temperature on cognitive function, mood and physiological responses, as well as stress levels during motor activity.

Several studies show that temperature also affects the body and muscle function, so it is another factor to be analysed in this experiment. The temperature of the environment can affect the way muscles work. For example, muscle viscosity may increase at lower temperatures, causing stiffening and reducing mobility. This effect could lead to changes in muscle activation patterns, as the muscles would have to work harder to achieve the same goal. (Shephard, 1985). However, muscles may become more elastic and easier to move at warmer temperatures. Muscle metabolism can also be affected by changes in ambient temperature. At lower temperatures, the rate of energy production in muscles may slow, resulting in a loss of muscular power and endurance (Peiffer, Abbiss, Watson, Nosaka and Laursen, 2009). Changes in muscle activation patterns may occur as muscles attempt to compensate for the decrease in force generation. Therefore, skin conductance, muscle mechanics and metabolic activity can all be affected by ambient temperature. Changes in temperature can affect both muscle activation patterns and the quality of electrical signals recorded by electrodes, with implications for both research and therapeutic applications. For example, colder temperatures reduce muscle force generation through stiffening and slower movements, whereas an ideal temperature allows the muscle to be more energy efficient and increases fluidity of movement, reducing the overall effort required to complete a task.

1.3. Electromyography

Electromyography (EMG) EMG technology is the gold standard for detecting activation of electrical activity in skeletal muscles (Ervilha, Graven-Nielsen and Duarte, 2012). This data can help identify muscle and nerve disorders such as muscular dystrophy, ALS and carpal tunnel syndrome. EMG can also be used to study muscle activation patterns during activities such as walking, jogging, or weightlifting, helping researchers understand muscle function and the effects of disease or injury (Di Girolamo, Pirri, Ajmone, and Ariano, 2018).
Surface electromyographic (sEMG) signals can be detected using electrodes inside a muscle or on the skin surface over the muscle. For this experiment, sEMG is used due to its greater distance from the recording site and the attenuation and distortion caused by the underlying tissue (Enoka, 2008). The skin-electrode interface consists of a multilayered anisotropic conductive medium (skin, subcutaneous tissue, and muscle) and an isotropic medium (the electrode itself) (Goldman, 1943). Two types of electrodes are used in EMG analysis: wet and dry. Dry electrodes are preferred due to their practicality, but require surface modifications

chemically, electrically, and mechanically to allow high-quality, low-noise recording of bioelectric events with modest amplitudes (Di Girolamo, Pirri, Ajmone, and Ariano, 2018).
In the current work, the electrodes were placed on two antagonistic muscles. The first muscle is the extensor digitorum, also called extensor digitorum communis (Figure 1A). This muscle is responsible for the extension of the wrist and fingers and the dorsiflexion (lifting) of the hand. It also helps to extend the wrist. The antagonist muscle to the extensor digitorum is the flexor digitorum profundus (Figure 1B), which is one of the deep muscles of the anterior compartment of the forearm (deep volar compartment). As the tendons of the flexor digitorum arise at or below the wrist joint, it is the muscle that acts as the primary gripping force of the hand. The extensor and flexor digitorum muscles work together to control the movement of the fingers and hand. When a person grasps something, the flexor digitorum tightens to close the fingers around it, while the extensor digitorum relaxes to allow the fingers to wrap around it.

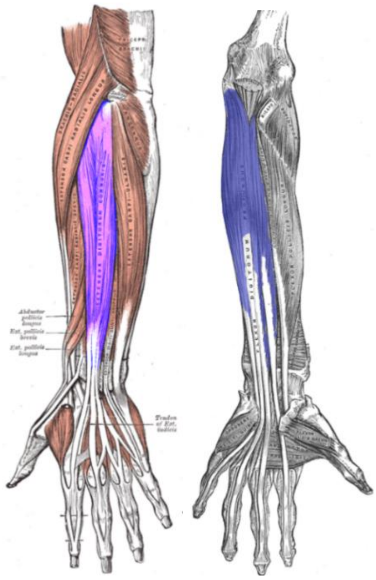

Fig 1. The 2 muscles decided to be analysed for this specific experiment (A) Extensor Digitorum Communis (B) Flexor Digitorum Profundus

1.4. The Current experiment:

This experiment aims to investigate the effect of ambient temperature on motor control and stability of antagonist muscles during coactivation activity within a simple motor task. The primary focus is to understand the relationship between temperature conditions and synergistic muscle coactivation during the learning process of the motor task. Specifically, this study aims to investigate how temperature affects the coordination of muscles as participants learn the movements of the motor task. Furthermore, the research will investigate the differences in synergetic muscle coactivation between ideal temperature conditions (between 22 and 24 degrees) and colder temperature conditions. By comparing these two scenarios, the experiment seeks to understand how muscle coactivation varies under different environmental temperatures during motor task learning.

Based on previous discussions and references (Lang, 2004; Franklin, Burdet, Osu, Kawato and Milner, 2003), it is expected that lower temperatures may lead to reduced muscle stability and increased stiffness, potentially resulting in more errors during the motor task. In addition, it is predicted that participants exposed to colder conditions will make more errors and show slower performance compared to those in ideal temperature conditions. In addition to motor control, the study will also look at the effect of environmental temperature on stress, frustration and overall workload for individuals engaged in the motor task. It is hypothesised that lower temperatures, which inhibit muscle movement, may lead to higher levels of frustration and stress compared to higher temperature conditions. Finally, the research also addresses the capabilities and limitations of a DIY technology used in the experiment. The findings from this research have the potential to contribute to future studies and improvements in the application of similar technology for motor control analysis.

2.0. Methods

2.1. Participants

Thirty-four participants aged between 18 and 35 years were analysed (M= 24, SD= 3.9), of whom 23 were female and 11 male. Prior to the start of the experiment, participants were asked to declare their dominant hand in order to attach the electrodes. Of the 34 participants, 3 were left-handed and 31 were right-handed. The 34 participants were randomly assigned to the two conditions: 1) 17 in the 24 degree Celsius room condition and; 2) 17 in the 19 degree Celsius room condition. Participants, who were part of the BMS faculty of the University of Twente, received an incentive to participate in the form of SONA points. In order to participate in the experiment, participants had to meet the following criteria: 1) no motor problems, 2) no alcohol consumption in the 24 hours before the experiment. Due to technical problems, the data from the first 4 participants could not be used for the final analysis, leaving a total sample size of 30 participants equally divided between the 2 conditions. The research protocol and procedure for this study were approved by the Ethics Committee of the University of Twente, no. 221474, and all participants gave their informed consent to participate in the study.

2.2 EMG set-up

This study implements DO-IT-YOURSELF (DIY) technology from the Ylab at the University of Twente in a controlled laboratory environment. The Ylab technology used in this experiment consists of both material and electrical components, each of which is critical to its operation. The final product of the construction of the experiment can be seen in Figure 2. The electromyography used for this experiment is rudimentary and was assembled by the researchers of this study. The decision to build an EMG, rather than use patented technology, was made to ensure the development and improvement of the experiment, as well as to ensure replicability for future experiments. Another important and necessary advantage of building an EMG was that it was possible to add relevant and necessary sensors for this experiment, along with function coding, to obtain more accurate and meaningful results for correlations. In order to analyse a simple motor task, a buzz wire task was chosen for this experiment, which not only can be personalised to the mean of this experiment, but is also easy to perform. This provides an easy and reliable activity for participants to collect EMG activity from. The device built for this experiment is non-invasive and constructed using a Cytron Raspberry Pico board, which allows even novice programmers to build reliable EMG technology that can be replicated in future experiments at low cost. The use of the Cytron Pico board not only makes it easy for novice users, but it is also open source. This allows a community of developers to work together to continually improve the board and its capabilities. The Cytron Pico board can be customised to meet specific needs as it is programmable. This gives users the ability to modify the EMG signal analysis methods and processing techniques, potentially producing more accurate and useful results. The Cytron Pico board was used with the Thonny Python programme to execute the programme and run the buzz wire structure. The Cytron Pico board used for this experiment used a micro-USB to record the sensor values at a frequency that varied from 48 to 133 MHz, with a resolution of 16 bits and a 3.3V supply. The Ylab code is available on GitHub (https://github.com/schmettow/YLab).

A Grove connector was used to connect the Raspberry Pico Board to two EMG sensors, which were connected to supra-cutaneous electrodes on the participants. A Grove connector was used to connect the Raspberry Pico Board to two EMG sensors, which were attached to supra-cutaneous electrodes on the participants. EMG sensors act as a link between the human body and the electrical environment. The sensor collects small muscle signals, which are then amplified and filtered before being sent to the Pico Board. The output voltage in standby mode is 1.5V. When the connected muscle is active, the output signal increases to a maximum of 3.3V. The use of the Raspberry Pico Board allows the integration of sensors useful for monitoring the temperature of the environment to make the experiment more reliable for understanding the effect of temperature on antagonistic muscles and movement control. For this reason, the DHT11 sensor for calculating room temperature and humidity was integrated via a grove connection. The DHT11 sensor allows measurement of the ambient temperature from 0 degrees Celsius to a maximum of 50 degrees Celsius with an accuracy of +/- 2 degrees Celsius. A final electrical component used in this experiment was the ADS1115, which allowed the connection and conversion of the values obtained from the second EMG detector, which could not be supported by the Cytron Pico board alone.

2.3 Buzz wire Task set-up

The basic buzz-wire setup consists of a wire, a handle with a conductive ring, and a lamp that lights up when the ring makes contact with the wire, accompanied by a buzzing sound. The buzz-wire task, known as a game, is used in this study to investigate simple muscular action and control. The addition of a Raspberry Pico board to the buzz-wire setup improves its motor analysis capabilities. The YLab has cleverly replaced the typical lamp-based display in the Buzz-wire work with the Raspberry Pico microcontroller. This microcontroller responds to the contact of the conductive ring with the wire by executing programmed sequences of code. The result is a mix of audio and visual information. This technical innovation opens the door to a more in-depth study of muscle control and movement patterns. The advantages of creating a DIY buzz-wire task include low cost, the use of inexpensive materials such as wood, plywood and copper wire, and creative freedom (Figure 2). The final decision on the circuit design, height, difficulty and handlebar circumference was based on the researcher's personal principles. The aim was to create a challenging task that allowed adequate wrist and hand movement for participants, making it a portable technology. However, DIY buzz-wire tasks have limitations such as limited durability and functionality. These disadvantages may require regular modification or replacement and may not provide the same level of functionality as commercially manufactured versions.

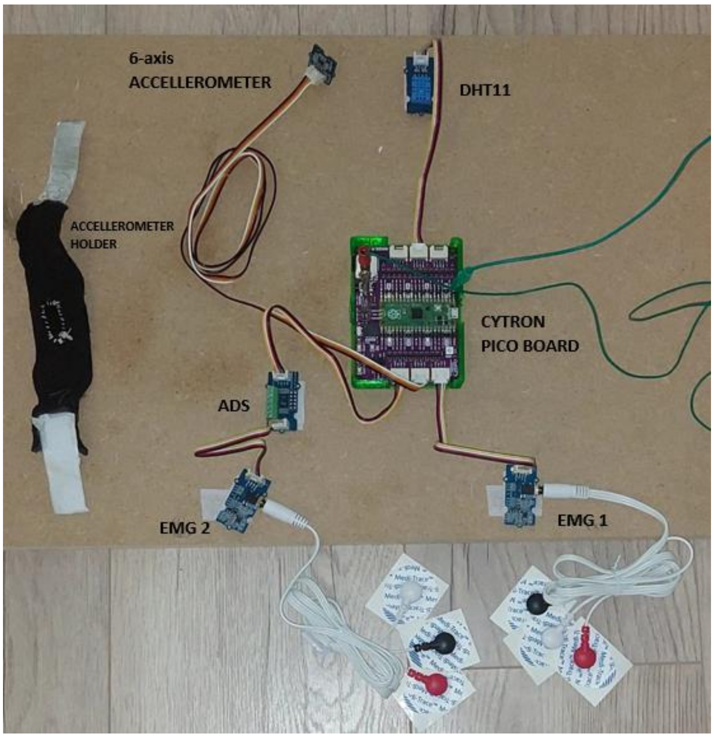

Fig 2. **(A)** Electrical components used for the experiment: Cytron pico board to run the python code, EMG 1 sensor which is connected to the extensor muscle to detect the electrical activity, EMG 2 sensor which is connected to the flexor muscle to detect the electrical activity, ADS1115 converter to allow the recording of the emg2, DHT11 sensor to detect humidity and temperature in the experimental room.

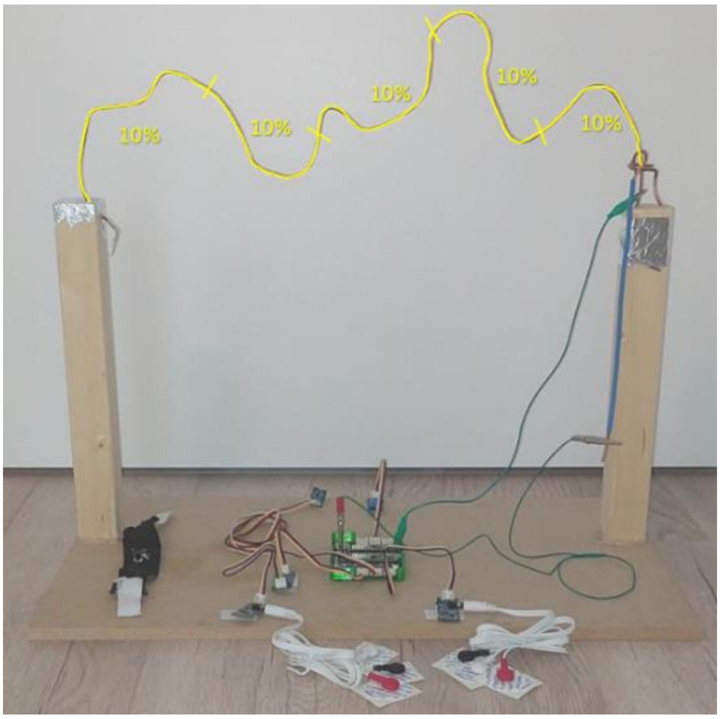

Fig 2. **(B)** Buzz wire task components, the task was elevated to ensure the correct movement of the wrist and minimise the movement of the elbow, on the picture the holding stick for the task can also be seen on the right. The task is divided in 10 equal parts for the data analysis.

2.4. Procedure

Participants were asked to present themselves in a laboratory room that had been pre-conditioned to the temperature of the participant's assigned condition. The gold standard for environmental temperature research is the use of a climatic chamber, but a DIY solution was chosen for this experiment. An electric heater was used to raise the room temperature, and opening the window was used to lower the room temperature, as the data collection took place in winter. The experiment had two conditions: 1) participants were placed in a room with a temperature of 18-19°C and; 2) participants worked in a room with a temperature of 23-24°C. The room temperature was constantly monitored by the researcher through the humidity and temperature sensor connected to the pico board, but also through a thermometer placed in the research room. In case of a change in the set room temperature, the researcher modified the temperature by using the heater or opening the window to ensure temperature standardisation. Before the start of the experiment, participants were asked to change their shirts in the room in complete privacy into a clean and disinfected T-shirt provided by the researcher. The same clothes were used for all participants in the experiment to ensure uniformity and standardisation. The clothing worn by participants during the experiment can affect their perception of the room temperature. Excessive clothing can cause overheating and sweating, while cold clothing increases core or skin surface temperature. Natural fibres such as cotton or wool regulate body temperature, while synthetic textiles retain heat and moisture. Standardisation of clothing is essential for accurate results. At the start of the experiment, each participant was given a cotton T-shirt to wear.

Participants were then asked to read and complete the informed consent form, which generally explained the aims and procedures of the experiment. It is important to note that, for reasons of bias, it was decided to omit the room temperature information from the explanation. This decision was made in order not to introduce a confounding variable into the experiment. The main concern with revealing the integration of the variable and the effect of room temperature was that participants might attribute their performance to the temperature and change their state of mind about the experiment, creating a bias.

Participants were then asked to complete demographic and general questions before being connected to the EMG technology. Participants were asked to shave their arm hair to remove any interference. Electrical noise from arm hair can interfere with the EMG signal. Both the static electricity generated by the hair and the movement or rubbing of the hair against the electrodes cause noise. It may also be more difficult for the electrodes to detect the EMG signal if there is arm hair between the skin and the electrodes. This could result in a weaker signal and a poorer signal-to-noise ratio. Electrodes were then placed on the participant's dominant arm on the two muscles of interest for this experiment. Participants were asked to perform the buzz-wire task for a total of 10 blocks of 5 trials each. Each trial corresponded to going from right to left and back to right of the maze wire (Figure 2). After 5 blocks, each participant was given a 15-minute break to stretch and relax briefly.

It was decided to use the NASA TLX (NASA, 1980) to analyse the level of stress and frustration associated with the task. The NASA TLX (1980) assesses workload along six dimensions: Mental demand: How much mental and perceptual activity was required; Physical Demand: How much physical activity was required; Temporal demand: How much time pressure was involved in the task; Performance: How successful were you in achieving the goals of the task; Effort: How hard did you have to work to complete the task; Frustration: How irritated, stressed or annoyed were you by the task? Each dimension is rated on a 21-point scale with anchors at the low and high ends. For example, the mental demand component ranges from 'low mental demand' to 'high mental demand'. Participants rate the workload of the task on each dimension by marking a point on a scale corresponding to their perception of the workload. The scores for each dimension are then weighted and combined to produce an overall workload score ranging from 0 to 100. A higher score indicates greater perceived strain. The NASA TLX is useful for identifying the sources of workload in complex systems and for assessing the success of workload reduction initiatives. Together with the NASA TLX, an affect grid (Russell, Weiss, and Mendelsohn, 1989) is presented to participants at three time points, before the start of the experiment, after 5 blocks, and after 10 blocks. However, the NASA TLX was only presented to participants after 5 and 10 blocks. At the end of the study, participants were asked to indicate the temperature at which they usually live, the strategy they used, and how they thought the temperature would have affected their performance. Participants' perception of temperature was also calculated on a scale from 1 (very cold) to 10 (very warm) at 3 points in time; before the experiment, after 5 blocks, and after 10 blocks. It is important to note that the time of each trial was manually reported using the timer function of the researcher's mobile phone, making it difficult to have an exact start and end time. Throughout the experiment, participants were asked to minimise the movement of the shoulder and elbow and maximise the movement of the fingers and wrist so that the EMG could detect the movements.

2.5. Data pre-processing

The YLab system is designed to produce only raw measures. The following steps were undertaken to prepare the data for the analysis. (http://rpubs.com/FedeGiusti/1046445). Much of this pre-processing involved manual input of each participant's trial time and calculating the 10-part trial (intervals). After calculating the time for each interval, trial and block it was necessary to calculate the coactivation index at interval and block level. The YLab system produces the following measures: errors, extensor values, flexor value, temperature and humidity. Unfortunately, the sampling rate was not constant, resulting in problems with missing data for analysis. Prior to the experiment, the maximum sampling rate of the YLab system was unknown and was later revealed to be lower than expected. We had initially configured a sample rate of 100Hz for each sensor, but the achieved sampling rates ranged between 50Hz and 100Hz across sensors. This variation in sample rates between 50 and 100Hz is substantial. An important analysis performed in this study was to analyse the missing and unrecorded data from the equipment. During the experiment it was noted that the equipment did not record data at the same frequency throughout the course of the experiment during the various blocks. Through an analysis of the NAs it was found that for the data the frequency of NAs is generally less than 1% for all variables, however, for the variable errors this percentage is 9.7% altogether for all the errors detected per participant. For some participants the quantity of errors not detected even goes from 15 to 21 %, making the analyses regarding the error rate not completely significant.

2.6. Data Analysis

2.6.1. Coactivation calculation

The buzz wire path that the participants have to follow during the task is complex and allows the main use of the two muscles intended for this experiment. However, a peculiarity of this experiment is that, depending on the relative section of the path, the use of one muscle may be more dominant than the other. As can be seen in Figure 2, the path is complex and requires multiple and different muscle movements during the completion of the task. Consequently, the movement of the agonist and antagonist muscle changes during the task depending on the task section. In order to be able to analyse the correct agonist during the movement, it was decided to divide the task into 10 parts and to include the agonist muscle used for each part in order to finally be able to analyse the coactivation index. The division into 10 parts was done by manually measuring the completion time of the participant's entire task. The total task for this experiment consisted of moving from right to left and back in the maze wire in Figure 2, so that the agonist and antagonist muscles were reversed when the participant moved from left to right. The muscles used for each percentage can be seen in Table 1 (Appendix I); if the movement was predominantly made with the extensor digitorum muscle, it is referred to as the agonist and the antagonist would be the flexor digitorum and vice versa. The division into 10 parts allows a more precise calibration of the coactivation index, but it is necessary to analyse several factors that can influence its calibration, such as the standardisation of the movements made by the participants. The decision to divide the task into 10 parts was taken in order to better understand the muscle activity along the buzz wire at different points. This allows precise information and changes in muscle activation to be recorded throughout the activity. However, the decision to divide into 10 equal parts brought advantages and disadvantages to the analysis, which will be explained later in this study. Although the participants were monitored to standardise their hand and wrist movements and starting position, the DIY technology has limitations in standardising the participants' posture and height, factors that can influence the primary function of the muscles and therefore the calculation of the co-activation index. The formula used by Ervilha, Graven-Nielsen, and

Duarte (2012) was used to analyse the coactivation index between the agonist and antagonist muscle.

$$Index = \frac{EMG_{ANT}}{EMG_{AG}} * 100$$

This formula can be used to calculate the coactivation between two muscles. According to this formula, if the result is closer to 100, it can be said that there is more coactivation. On the other hand, if the result is greater than 100, it means that the movement performed has a greater intensity for the antagonist muscle. Conversely, if the result of the formula is less than 100, it means that the movement is dominated by the agonist muscle. In general, if the results vary greatly from 100 during a task, there is less coactivation.

2.6.2. Model based approach

In order to have a clear and better between-subjects difference, the main model of this experiment is analysed using a linear mixed model to analyse the effect of temperature on the coactivation level. The participants' condition is the predictor variable for this model, together with the block the participants were in, and the outcome variable is the level of coactivation. In addition, to analyse motor learning, two linear mixed effects regression models were run, with the outcome being participants' error rate and response time, and the predictor variables being participants' condition and block. Finally, to analyse participants' speed and accuracy, a linear regression model was run with the predictor variables being time spent on blocks and participants' condition, and the outcome variable being error rate. To determine which temperature condition had an effect on the outcome variables, the marginal means of group performance was used using the “emmeans” package.

The survey allowed participants to explain their strategy and difficulties during the experiment, leaving room for qualitative analysis, with the aim of informing researchers for future experiments. In order to analyse these effects, a linear regression model was fitted with the predictor variable being the participants' condition and the time at which the survey was completed, and the outcome variable being the 6 dimensions of the NASA TLX. In addition, an analysis of variance was conducted to analyse the affect grid. For this analysis, the outcome variables were the level of arousal and the level of pleasant and unpleasant feelings, and the predictor variable was the participants' condition. Furthermore, the participants' temperature perception was also analysed using a linear regression analysis, with the predictor variables being the time of the survey and the participants' condition, and the outcome variable being the temperature perception. The analysis done for this experiment can be seen on http://rpubs.com/FedeGiusti/1046131 .

3.0. Results

3.1. Time and error analysis

The first data obtained from this analysis went to verify the speed of the participants during the execution of the blocks. Through a linear mixed-effects regression model, it was found that regardless of the condition in which the participants were, the execution time of the blocks decreased from block 1 to block 10, $F(9, 252) = 13.97$, $p < .001$, indicating a learning process. This learning effect can also be seen through the analysis of the error rate of the participants. Using a linear mixed-effects regression model, the results show that regardless of the conditions in which the participants were, the error rate decreased from block 1 to block 10, $F(9, 252) = 31.43$, $p < .001$. Figure 3 and Figure 4 show the previously explained effects on a block level for both conditions.

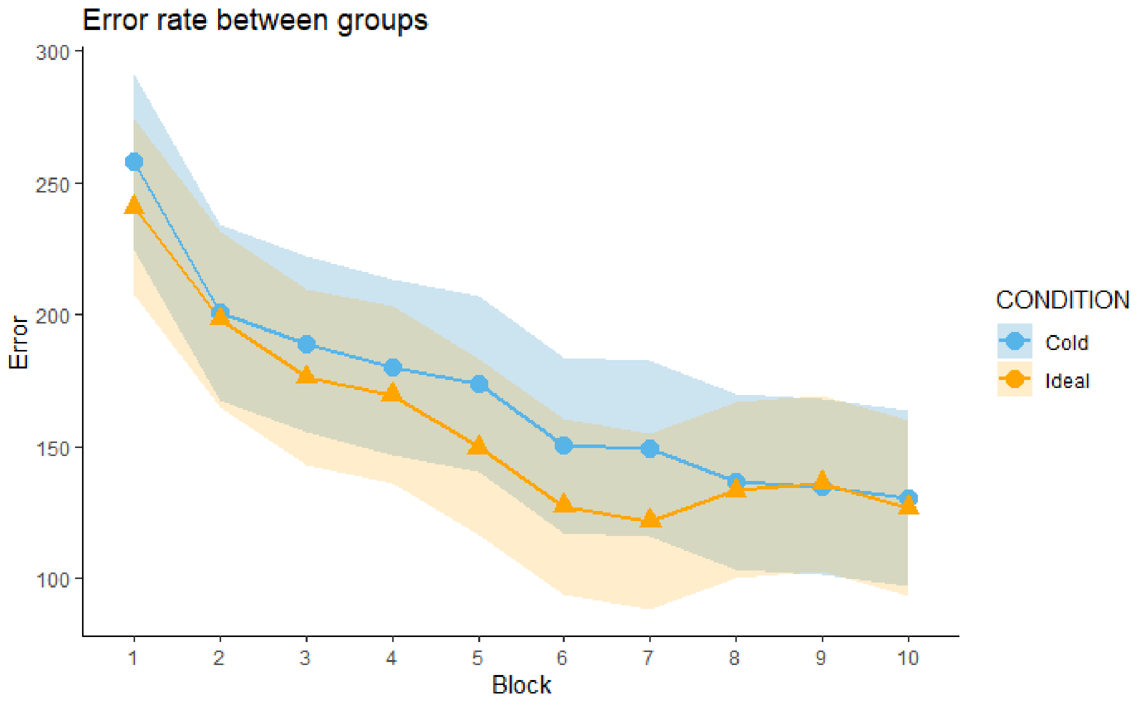

Fig 3. Raw error score per Block per Condition over the course of learning. The tendency of the graph shows that from bock 1 to block 10, participants made less error showing a learning behaviour.

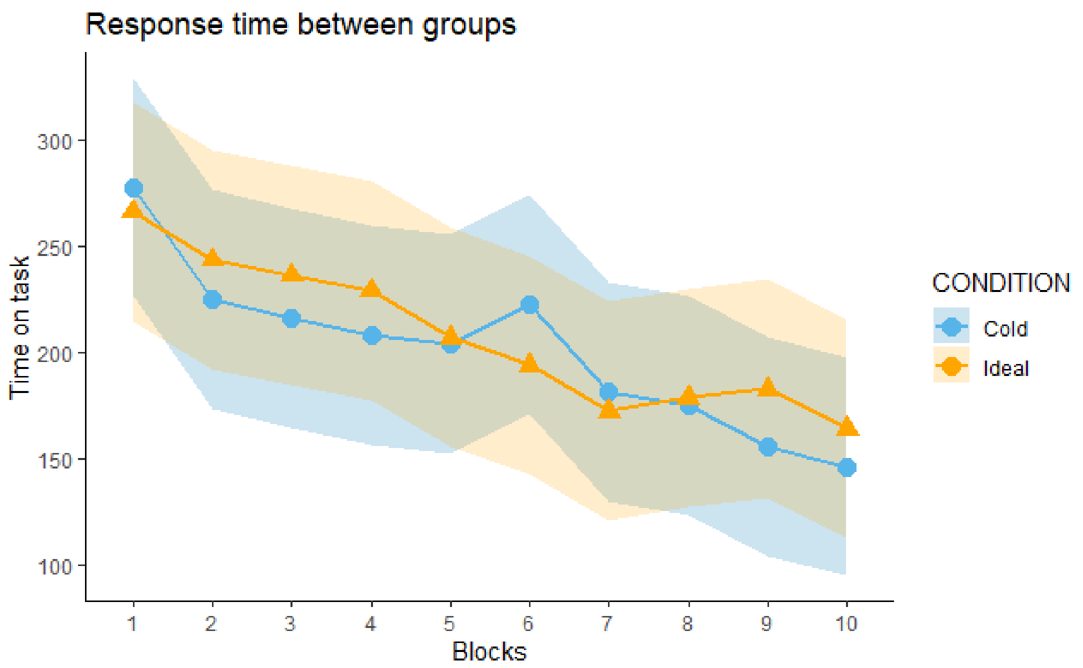

Fig 4. Response block time per Block per Condition. The tendency of the graph shows that from bock 1 to block 10, participants took less time therefore being faster.

The subsequent analysis had the intention of verifying the speed accuracy trade off. Through a linear regression analysis it was found that there is a significant effect of errors on the time taken to block, $F(1, 298) = 20.698$, $p < .001$. Afterwards, a post-hoc analysis revealed that the relationship was positive, indicating that the faster the participant was, thus the less time taken, the fewer mistakes were made, as can be seen in Figure 5. This effect is not influenced by Condition.

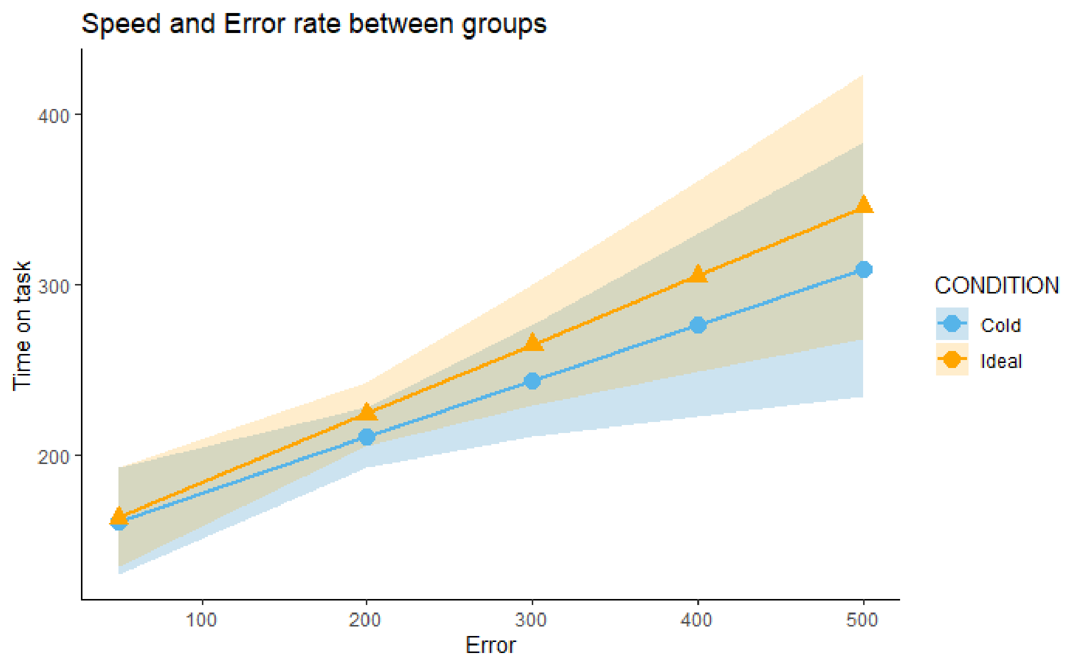

Fig 5. Error rate on Time on task per Condition. The tendency shows that less time spend on block (faster block performance) the less errors were made.

3.2. EMG Analysis

After calculating the coactivation index for each phase and subsequently averaging the coactivation index for each block, it was possible to analyse the effect of the temperature condition. The coactivation index per block for the participants in colder condition varied from a range value of 97.8 to 100.7, however for participants in an ideal condition, the coactivation index per block varied from a range of 97.8 to 173.1. A linear mixed model was used to investigate the effect of temperature on participant coactivation. Notably, our investigation uncovered two distinct tendencies. Initially, it was observed that the temperature to which participants were exposed exhibited a marginal, yet noteworthy, significance ($F(1, 235) = 3.36$, $p = 0.068$) in relation to the coactivation patterns. It is vital to note that the coactivation index was logarithmically transformed before to this study to guarantee proper distribution and manage possible skewness. Furthermore, the second marginally significant trend surfaced through an investigation into the interaction between the mean coactivation computed per block and the temperature condition ($F(1, 235) = 3.36$, $p = 0.068$). Following a post-hoc analysis, a notable discovery emerged: participants exposed to ideal temperature settings tended to demonstrate lower coactivation, resulting in more fluid movements, as contrasted to people subjected to cooler temperatures. This suggests that the logarithmic modification of the coactivation index contributed to the statistical integrity of these results.

Fluid movement implies that the coactivation levels can swing from a low variability from 100 meaning there is high coactivation, and high variability from 100 meaning there is less coactivation.

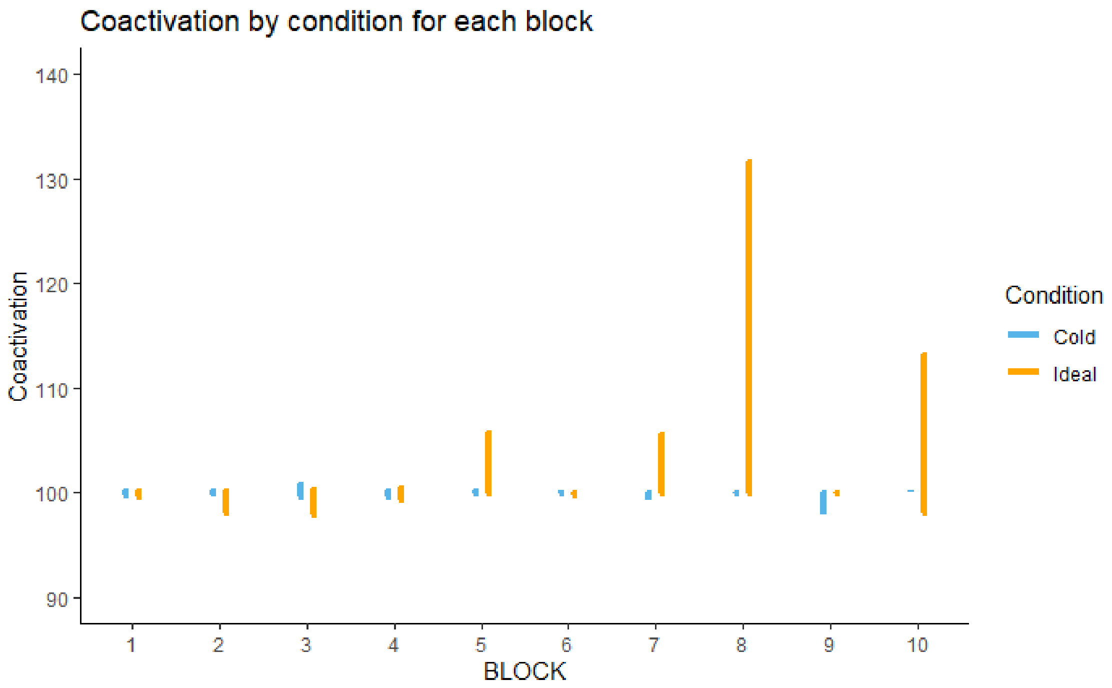

Fig 6. Visualisation of coactivation index per block divided per group, when the coactivation score is closer to 100, it has higher coactivation. Alternatively, it means one of the muscles is more prominent for the completion of the task.

3.3. Survey Analysis

Finally, the last analysis concerns the survey. The first analysis carried out was to analyse whether the temperature perceived by the participants corresponded to the condition in which they were allocated. Through a linear regression analysis, it was possible to analyse if there was an effect of the condition on perception. It was found that the temperature perception of participants after 5 blocks have a significant effect, $t(32) = 2.495$, $p = 0.018$, meaning the temperature participants are allocated correspond to their perception of temperature, and after 10 blocks this effect becomes a marginally significant trend, $t(32) = 2.031$, $p = 0.05$. Through a post-hoc analysis it was confirmed that the condition in which the participants were allocated corresponded with the perception of temperature. This effect can also be seen from Figure 7.

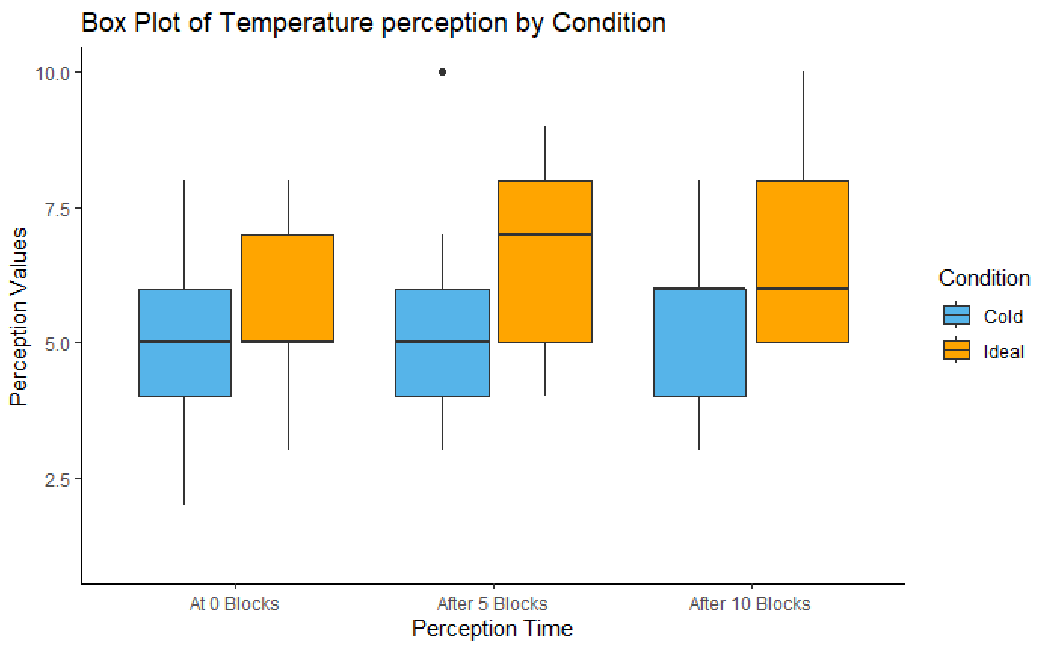

Fig 7. Temperature perception of participants according to their assigned condition. The perception is calculated on a scale from 1(really cold) to 10 (really warm), measured at three different timepoints.

The subsequent analysis concerns the affect grids. A visualization of the grid in form of heatmap with the results of the participants divided by condition is in Appendix I. Through an analysis of the variance between the two value axes and the condition in which the participants were allocated, it was found that regardless of the condition in which participants were allocated, the timepoint at which the grid was presented has an effect on the pleasant and unpleasant feeling axis, $F(2)=8.79$, $p < .001$. Through a post-hoc analysis it was found that after 5 blocks the participants tended to have more unpleasant feelings than at the other two time points. Furthermore, through the same analysis, a tendency was found on the effect of the condition of the participants on the axis of high arousal and sleepiness, $F(1)=3.11$, $p =$ 0.08. Although not significant, it was revealed that for participants in an ideal condition there was a higher, but not statistically significant, level of sleepiness in comparison to participants in colder condition.

Finally, the Nasa TLX survey was analysed to understand how the temperature affects the 6 dimensions. Considering that the Nasa TLX was presented to the participants at two timepoints, after 5 and after 10 blocks, a linear mixed-effect model was performed to see the effect of condition and timepoint per dimension of the Nasa TLX. The results show a significant effect of the timepoint of the survey and the condition in which the participants were allocated for the dimension of the effort, $t(32)= - 2.17$, $p = 0.04$. For this dimension it is also noted that the single effect of the ambient temperature had an effect, t(43)= 2.11, *p* = 0.04. With a post-hoc analysis it was possible to discover that after 10 blocks the effort demand of the participants is reduced and participants in colder conditions stend to have less effort demand than participants in an ideal condition (Figure 8). Moreover, participants tended to have more effort perception after 5 blocks, then after 10. Another dimension that has had a significant effect is the dimension of frustration. For this dimension, it was discovered that the timepoints and the temperature have a significant effect, t(32)= -2.14, *p*= 0.04. Through a post-hoc, it was discovered that after 10 blocks the participants tend to have less frustration than after only 5 blocks of practice. Moreover, participants in an ideal condition tend to have less frustration at both timepoints (Figure 9).

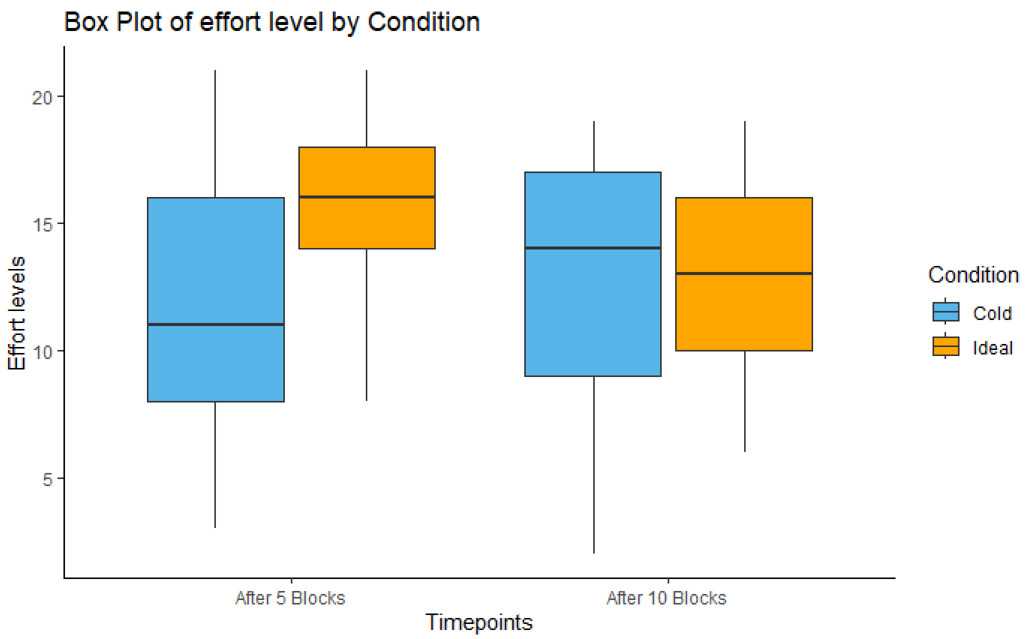

Fig 8. Visualisation of effort level for participants in both conditions in two different timepoints; after 5 blocks and after 10 blocks

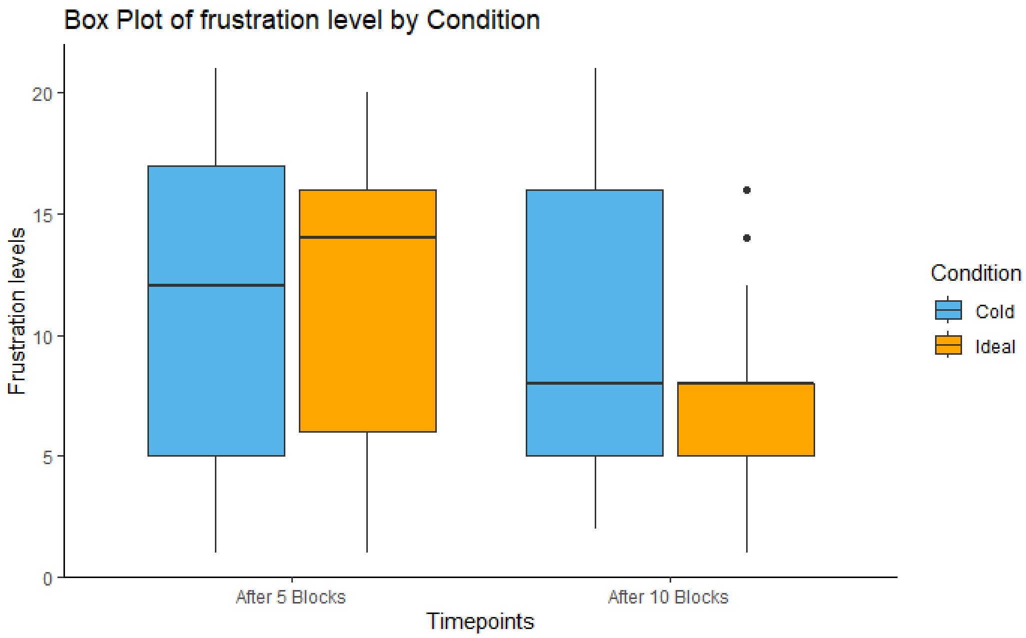

Fig 9. Visualisation of frustration level for participants in both conditions in two different timepoints; after 5 blocks and after 10 blocks

As regards the other dimensions of the Nasa TLX, it can be noted that there are trends which, however, are not statistically significant. First, it was found that there is a tendency for participants in an ideal conditions to have more mental demand than participants in a colder environment, t(44)=1.7, p = 0.09. Furthermore, due to the performance dimension, there is a tendency for participants in an ideal temperature environment to think they have had a better performance than participants located in an colder environment, t(32)=1.9, p = 0.06.

4.0. Discussion

The aim of this study was to investigate how ambient temperature affects motor learning, coactivation and muscle motor control. The following hypothesis was developed to guide our research: individuals placed in an optimal temperature condition of 23°C were predicted to have more fluid movements and less coactivation than participants in colder conditions. In addition, it was expected that participants would show less coactivation with practice, regardless of ambient temperature. In this section, the hypothesis will be explored in more detail and the main conclusions drawn from this research will be outlined.

The results show interesting trends, although they do not reach statistical significance. Given the nature of the do-it-yourself experimental methods, these findings are discussed to inform future research and improve our understanding. This study found that ideal room temperature leads to reduced muscle coactivation during the buzz wire task. Reducing coactivation allows participants to focus on using only the necessary muscles, improving accuracy and motor control. This can also aid skill acquisition and motor learning by helping to create unique brain connections and muscle memory for the task (Lamontagne, Richards and Malouin, 2000). The temperature of a room also affects performance (Lang, 2004). Lower levels of co-activation can result from relaxation, which minimises unnecessary muscle tension and involuntary muscle contractions. Physical comfort helps individuals to focus their attention and energy more effectively on the task.

Intense temperatures, whether hot or cold, can be unsettling and affect the body physiologically. The body naturally attempts to produce heat to maintain its core temperature when exposed to cooler conditions (Shephard, 1985). This can cause tensing and shivering of the muscles, which can increase coactivation and overall muscle activation. This phenomenon would explain the higher level of coactivation in participants exposed to the 19°C room temperature. A moderate temperature, such as 23°C, reduces these thermal disturbances, allowing people to concentrate better and minimising unnecessary muscle activity (Shephard, 1985). In addition, the results show that coactivation is not influenced by the participants' practice. As far as can be deduced from the results, the level of coactivation does not decrease from block 1 to block 10, as hypothesised in this experiment, and it is therefore necessary to reject this second hypothesis that practice has an effect on motor coactivation. Several factors could be involved in this result. Firstly, it could be argued that the practice was insufficient and that the result would have been statistically significant if the participants had been subjected to additional blocks of practice. Another possible explanation could be due to the do-it-yourself technology used in this experiment. It's possible that the techniques used to quantify coactivation are limited or lack the sensitivity needed to detect minute adjustments brought about by training. It is important to ensure that the testing methods used are reliable and able to adequately capture changes in muscle activation patterns.

Participants in the ideal condition tended to have less coactivation during the task, although this result was not significant and could have different explanations. A sense of overconfidence or complacency can also result from repetitive tasks and the same tasks and movements (Mamassian, 2008). This could lead to a loosening of motor control and a reduction in the perceived need for precision, which would increase errors. Furthermore, variables such as fatigue or boredom may have an impact on reduced performance in repetitive movements (Smith, 1981). Accordingly, the Affect Grid showed a tendency for participants in the ideal condition to feel more sleepy compared to participants in the colder condition. These elements can have a detrimental effect on cognitive, attentional and fine motor skills, which can lead to an increased risk of error. Although it may appear that repetitive tasks require less concentration or cognitive effort than novel tasks, the possibility of error still exists. Despite the repetitive nature of the activity, sustained attention, focus and purposeful engagement are still essential for accurate and error-free performance. Reduced speed may also lead to a loss of accuracy in motor control. Slower performance may affect fine motor activities that require precise movements or adjustments (Miyamoto, Wang, and Smith, 2020). This can lead to problems with accuracy, as the slower speed can interfere with the coordination and timing that are ideal for accurate execution.

4.1. Motor learning

In terms of motor learning, it was found that for both participant conditions there was generally a learning process with practice from block 1 to block 10, with fewer errors and an overall increase in speed. With practice, participants' motor skills improved as evidenced by the results, which showed a clear pattern of increasing speed and decreasing error rates. These results are consistent with previous research on motor learning, which shows that repeated practice of a particular activity leads to improved performance over time (Hird, Landers, Thomas, & Horan, 1991). The incremental mastery and refinement of the task demonstrates how participants can adapt and refine their motor coordination and control. This implies that individuals were actively learning and assimilating new motor patterns during the experiment. The 10 blocks all showed steady progress, highlighting the value of practice and repetition in the development of motor skills. The buzz wire task appeared to promote overall motor learning, as evidenced by the participants' improved speed and reduced error rates across the experimental blocks, regardless of the temperature condition in which they were placed.

Another interesting result found in this study concerns the speed-accuracy trade-off. Surprisingly, participants tended to make fewer errors the faster they performed the task. This result goes against the speed-accuracy trade-off. It is important to remember that the speed-accuracy trade-off is not always present and varies depending on factors such as task difficulty, individual ability and practice (Häusser et al., 2002). Individuals can increase speed while maintaining low error rates by improving motor control and motor learning, anticipatory skills, and decision-making techniques (Thura, Cos, Trung, and Cisek, 2014). However, repetitive tasks can be difficult due to their monotony and lack of novelty. As people become accustomed to the activity, they may lose attention and focus, leading to missed critical information and errors (Logan, 1990).

In addition, data analysis revealed a significant lack of participant error, potentially contradicting the speed-accuracy trade-off theory. Inadequate error detection systems can lead to biased data and erroneous conclusions that affect the dynamics of the DIY buzz wire task. As a result, the person may overestimate their ability and speed, believing they are performing better than they actually are. It is vital to ensure the reliability and accuracy of error detection systems to maintain the balance between speed and accuracy in such activities.

4.2. Nasa TLX

The results of the Nasa TLX effort dimension show that participants in both conditions have a higher effort rate after 5 blocks than after 10 blocks, which can be attributed to motor learning. In addition, participants in an ideal temperature of 23°C have a higher level of effort than those in a colder environment. This could be due to the cooler environment providing a more comfortable and productive environment (Roelofsen, 2002; Maula, Hongisto, Östman, Haapakangas, Koskela, and Hyönä, 2016). Another possible reason for this effect could be that, as explained at the beginning of this study, the participants' body temperature increased during the course of this motor task, which made the participants' temperature perception too warm in the ideal condition, thus reducing cognitive performance and increasing the effort needed to complete the task (Edwards, Waterhouse, and Reilly, 2007).

Accordingly, the results show that temperature perception increases significantly after 5 blocks for both participants and then adjusts and decreases after 10 blocks. There could be several reasons for these findings. Muscles produce heat when they contract and work while a participant is exercising, especially when performing a motor task (Knuttgen, Nadel, Pandolf and Patton, 1982). This metabolic heat production can lead to an increase in body temperature and affect temperature perception. In addition, during a motor task, the body increases blood flow to the working muscles to provide them with nutrients and oxygen (Knuttgen, Nadel, Pandolf and Patton, 1982). A rise in body temperature can result from the redistribution of heat caused by this increased circulation. However, with practice, the body becomes better at controlling its temperature and compensates for this effect. Regular exercise improves how well the body's thermoregulatory systems work, including how much sweat is produced and how efficiently blood flow is controlled to better dissipate heat (Bennett, 1984).

Continuing with the NASA TLX dimensions, another statistically significant dimension concerns frustration. The results show that the participants in the cold environment had higher levels than those in the ideal temperature, confirming the hypothesis of this study. The effect of temperature on the muscles could be the reason for this phenomenon. As mentioned above, cold conditions can cause muscle movements to become stiff. The physical consequences of cold environments can have an impact on the level of frustration. Muscle tension caused by the cold results in stiff movements and reduced dexterity (Shephard, 1985). The body tends to constrict blood vessels and limit blood flow to the extremities when exposed to colder temperatures, which can lead to reduced manual dexterity and slower movements. Therefore, participants in colder environments were more irritable when the cold made their movements stiffer or their activities more difficult (Monteiro, et al. 2022; Shephard, 1985). Being physically restricted can be irritating and prevent you from completing tasks. This dissatisfaction and frustration may be caused by the inability to complete tasks efficiently or by the extra concentration required to compensate for a dexterity deficit. Finally, the results show that other components of the NASA TLX did not significantly affect mental demands or performance. However, there was a tendency for ideal condition participants to report higher mental demands during the task, although this was not significant. In addition, participants in the ideal condition felt that they had generally done a better job of completing the task than those in the cold condition. Studies show that a comfortable temperature can improve cognitive function and alertness (Lang, 2004). This implied a higher level of cognitive involvement and attention to the task, suggesting that the participants may have experienced more mental demand.

The final significant result of the survey presented to the participants concerned the affect grid. From the results it is possible to understand that, in general, for both groups there is an increase in unpleasant feelings after 5 blocks, to then have reduced levels after 10 blocks. First, the participants learned to do the task through practice. It's possible that the first few blocks were particularly difficult, causing irritation, tension or, in extreme cases, pain. As they gained knowledge and familiarity with the work, their comfort and confidence increased and they experienced competence and mastery, resulting in more positive emotional consequences.

4.3. Limitation and future research

This experiment has encountered various challenges and problems throughout its course, but now with the aim of improving future research in the study of biochemical analysis through the use of DIY technologies. The first argument for the limitations of this experiment concerns the calculation and monitoring of the time taken to complete the task for each participant. As explained above, the time for each trial and block was manually recorded by the researcher using a stopwatch. This method, although partially effective, was later incorporated into the structure and code of the Cytron Pico board to make it more reliable and accurate, but unfortunately was not used in this experiment. Secondly, this stopwatch method did not eliminate the time taken by participants when they paused between trials at either end of the buzz wire task. However, the researcher's verbal motivation to the participant not to stop attempted to compensate for this problem. Another challenge in this experiment was the decision to analyse the path of the buzz wire by dividing the path into 10 equal parts. During the analysis, this 10-part division was calculated by dividing the total time spent on the trials into 10 equal parts. There are several problems with this approach. First, this procedure assumes that the participant completed each section at the same speed, which is not possible because the copper wire path in the task was intricately constructed differently for each interval section. Some parts of the maze wire required more articulated movements than other interval sections, making it more difficult for participants. On the other hand, this procedure does not take into account the small postural adjustments that participants made during the experiment, which slowed them down and led to errors during the task. With regard to the 10-segment division, the original intention of the experiment was to use a 6-axis accelerometer sensor to calculate the moment when the participants accelerated their movement and to be able to calculate the speed for each segment. The experiment faced standardisation problems due to the handmade sensor holders being moved and adjusted by the participants for their own comfort, and the loose bag in which the sensor was inserted, which caused the sensor to move and affect the results. These problems made the experiment more difficult for the participants and affected the results. In addition, the different handle of the buzz wire for each participant made it impossible to analyse and standardise the 6 acceleration axes. Some participants complained about the handmade sensor holder, which compromised their handlebar grip. For these reasons, it was decided to omit the 6-axis accelerometer results from this experiment, but unfortunately the handmade holder may have had an impact on the study results and participants' scores. Future research should focus on developing a more effective and stable method of applying the sensor to ensure usability, reliability and a comfortable experience for participants.

Related to this last point, another issue that arose in this experiment concerned the handlebars used for this experiment. In the qualitative questions of the survey, some participants expressed concerns and suggestions for improving the experiment. Some participants analysed the fact that holding the dumbbell in different positions or closer to the initial loop made the task more or less difficult. However, these experiments were sporadic and in the middle of trials, which compromised the standardisation of movements and therefore muscle activation. In addition, the handlebars were covered with an insulating plastic that became slippery with the heat of the hand, compromising grip and execution of the experiment. One participant suggested modifying the handlebars with a grip that would provide a better grip and make the experience more comfortable.

Another problem encountered in this experiment has already been analysed and concerns the lack of data collection during the experiment. As already explained, this problem was probably caused by the speed at which the participants performed the task. As some participants also explained, they preferred to go fast because they felt they would make fewer mistakes or because they didn't see any results when they went slower. This problem of data recognition may be caused by the fact that both the programme and the code used are DIY, but it may also be caused by corrosion of the materials. It was found that the copper wire oxidised throughout the experiment. This problem was expected as DIY technologies are generally less reliable and have less efficient material resources than licensed technologies. The final challenge, which may help future research, also relates to the number of participants used in this experiment. As explained, 30 participants were used for the analysis in this experiment. This sample is probably too small and has probably affected the results to the extent that they are not statistically significant.

5.0. Conclusion and implications

The results of this study allow us to answer the initial question of whether the reduction in the temperature of the working environment to 19°C, imposed by the government at this time of economic crisis, is healthy and has an impact on people's productivity and general wellbeing. This experiment found that at an ideal temperature of 23°C, people tended to experience less frustration and effort in a simple motor task. From the point of view of coactivation and motor control analysis, this experiment did not produce significant results, but there was a tendency for participants to have smoother and more fluid movements at an ideal temperature, and therefore better performance. Despite this tendency, the alternative hypothesis that temperature has an effect on motor control must be rejected.

This study could still be useful for researchers to learn more about how environmental variables affect motor control and learning by examining how room temperature affects these processes. This study investigates the effect of environmental factors on motor learning and stability, with the aim of improving training rooms and rehabilitation facilities to create the best learning environment. The importance of the study lies in understanding the relationship between ambient and room temperature and muscle control. In addition, the experiment used handmade technology, with the aim of driving future improvements by analysing problems and limitations, resulting in accessible, reliable and durable technology for all.

Appendix I

Table 1 - Table of agonist and antagonist muscle depending on percentage.

PERCENTAGE	AGONIST	ANTAGONIST
10	extensor	flexor
20	extensor	flexor
30	flexor	extensor
40	extensor	flexor
50	flexor	extensor
60	extensor	flexor
70	flexor	extensor
80	extensor	flexor
90	flexor	extensor
100	flexor	extensor

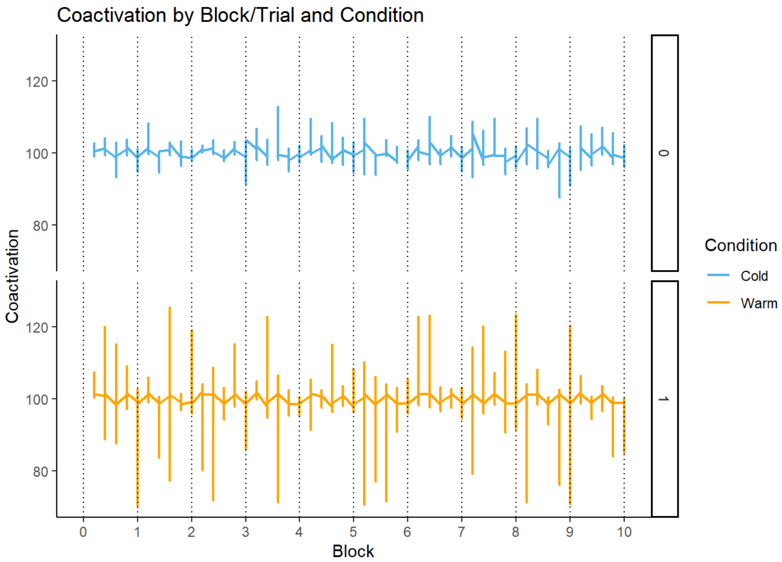

Fig10. Representation of coactivation per trial, divided by condition.

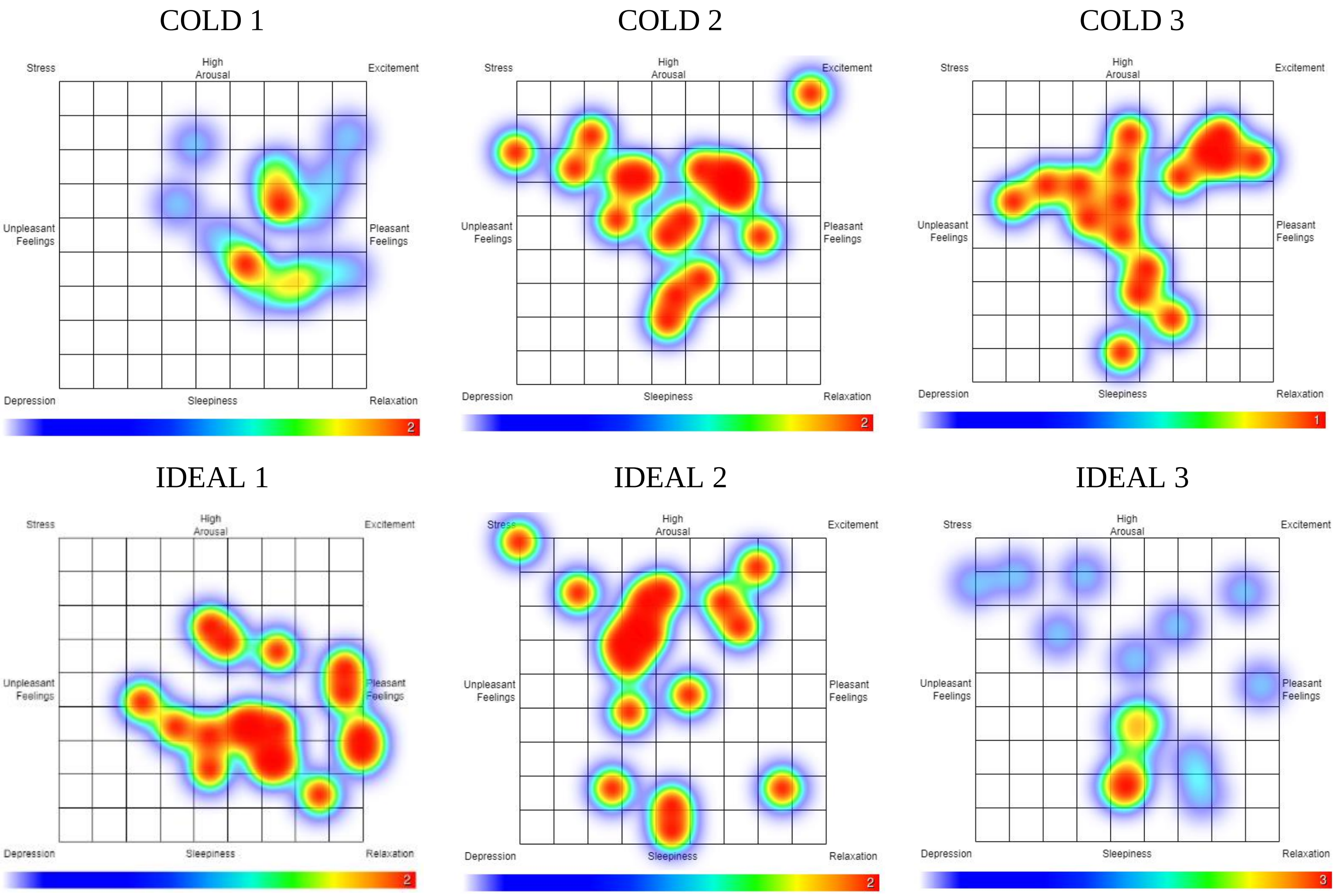

Fig11. Visualisation of state of mind grid divided by Condition of participants and timepoint before the experiment, after 5 blocks and after 10 blocks.

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