Parting the Clouds: Moving Towards an Affordable Natural-Lighting Solution

16019243

N. Appleton

Supervisor: Matthew Studley
BEng Robotics

Designing a modular, human-centric lighting system
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Faculty of Environment and Technology
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Chapter 1

Introduction

1.0. Let there be Light

"*God said, 'Let there be light,' and there was light. God saw that the light was good, and he separated the light from the darkness. God called the light 'day,' and the darkness he called 'night'. And there was evening, and there was morning — the first day.*" ~Genesis 1:3-5.

Since the dawn of life itself, we have been exposed to the natural light of the sun, and the distinct separation of day and night. However, our modern, fast-paced lifestyle no longer allows for such long periods of time being wasted and unproductive in darkness.

As the literature reveals more and more ways in which this divergence harms our well-being, it seems that a serious re-think of our environments - and how we light them - is required.

1.1. Gap in the Market

Light has been shown to have serious ramifications on many facets of life: excess blue light in the evenings causing sleep deficiency; lighting affecting lifestyle-related diseases; insufficient blue light exposure being a risk factor for depression and other mood disorders; and plenty more that are discussed in chapter 2.

Chapter 2.7 outlines why the existing products attempting to solve this problem are not appropriate, and thus why a new solution must be developed.

1.2. Aims and Objectives

This project set out to try to develop an affordable, modular, broad-application natural lighting solution.

1.2.1. Aims

There were 2 main aims that the device set out to achieve: 'To produce an affordable device that replicates the visual solar spectrum as closely as is feasible' and 'to validate the device by measuring the output spectra across the day'.

Initially, further aims included developing the device as a product by improving user experience through user interface, web apps, and other expanded functionality. This would have been researched using qualitative methods such as opinion surveys to assess the interest in the device in the consumer market. These aims were set out as stretch goals that could be undertaken when the two main aims had been completed.

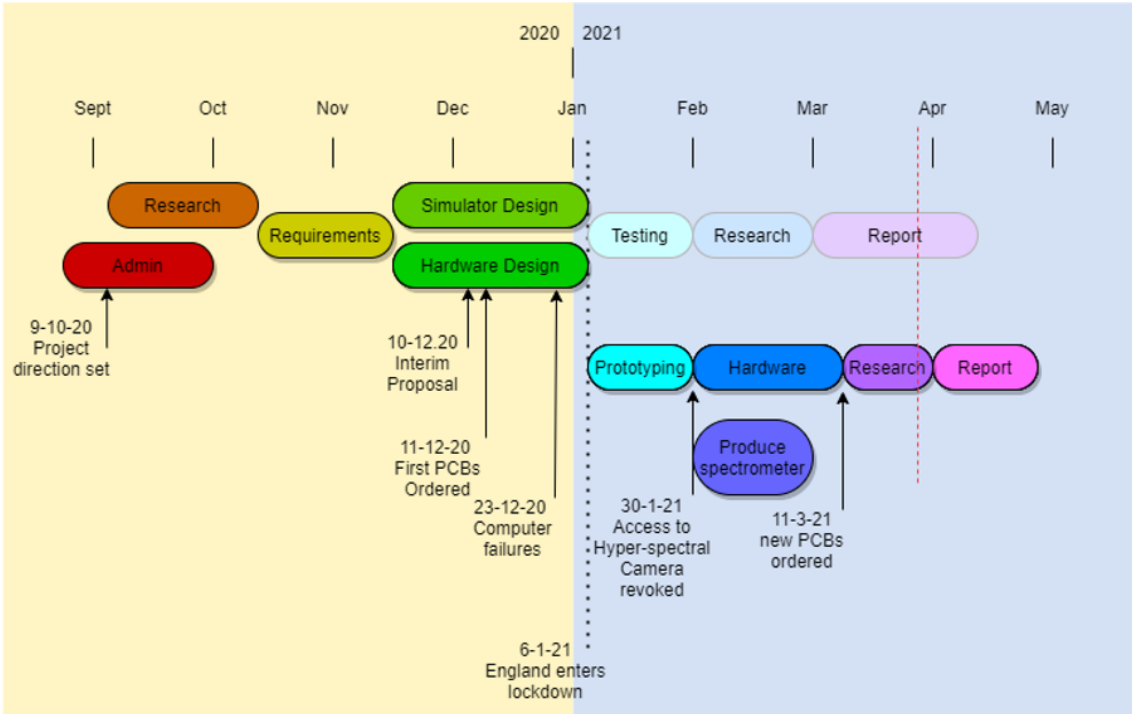

Figure 1.1: *How the lockdown in England affected the objectives of the project. Reasons for the changes are discussed later in the document.*

1.2.2. Objectives

The objectives used to achieve the aims have been dynamic throughout the project. The initial plan of producing and testing 2 rounds of Printed Circuit Boards (PCBs) before using these to validate the spectral outputs was heavily influenced by the pandemic. See Fig 1.1.

Both N. Appleton and V. Halenka were involved in the design of the hardware, as it was a useful device for both areas of research. The success of these devices was assessed against the requirements specification (Appendix A.1 and is discussed in chapter (REF).

One of the most important aims of the project from the beginning was the development of the simulator. This allowed for a contingency for that spectral measurements to be obtained even in the absence of physical hardware. The simulator was also used to explore the desired outputs of the device and how they could be achieved.

1.2.3. Scope

Keeping the scope of the project relatively flexible was an important factor due to the pandemic. Designing the hardware, which was scheduled to be done by February, was severely impacted by the lockdown that began on the 1st of January 2021.

Due to the "modular" construction of the aims, the qualitative, product-based research and much of the usability development had to be left for future research and development. In removing these aims from the project, it allowed the primary objective to be successfully achieved.

Had the pandemic not had such a profound effect, the main aims would have likely been completed earlier, allowing for progression to the secondary research goals. However, going into the project, there was no way to know how the year would pan out. Using this dynamic scope worked very well and allowed the successful completion of the primary area of research.

1.3. Project Management

AGILE Kanban The project was approached using a Kanban-style AGILE workflow, using the $ClickUp^{TM}$ project management software to organise tasks, subtasks, Gantt charts, meeting minutes, relevant literature and more. Using just one piece of software to organise all of this reduced the friction and chance of errors. For example, when updating Gantt charts, the Kanban boards and tasks are automatically updated to reflect these changes and vice versa.

Weekly meetings Both weekly supervisor meetings, and weekly meetings between the hardware developers took place to ensure that all areas of the project were progressing as planned. Alterations to the scheduled work could be discussed and approved at these meetings, further reducing the friction when needing feedback. Minutes of these meetings were made on the $ClickUp^{TM}$ software and copies were printed and pasted into the project logbook.

Logbook The logbook has been used as a hard-copy of all the digital documents that were produced throughout the project including interviews, requirements documentation, meeting minutes, invoices, design documentation and Gantt charts. All work has been logged to ensure data is not lost and the project could continue even in the event of the researcher being replaced.

Gantt Charts The project plan Gantt charts were updated on a monthly basis to ensure their relevance and to take into account the most up-to-date information. These updates happened in meetings between the development team to allow timescales to be discussed before implementation. All Gantt charts are displayed in appendix A.2.

Time Constraints As with any project, there have been some strictly imposed time constraints throughout the year. Weekly supervisor meetings meant that there was always a two-way stream of information so as to put less importance on each meeting.

It was important that the experimentation could be completed by the end date of the project, and that at least initial results could be gathered before the progress review that took place at the end of March.

Contingencies From the beginning of the project, a focus has been placed on creating effective contingencies to ensure that the main experimentations would give results. This has been especially true within a hardware-based project during the pandemic. The flexible aims have been discussed earlier, but many other contingencies were put in place. Building a simulator was a big priority to ensure that results could be gathered in the event of failure to obtain hardware.

Risks and Mitigation The project has been focused on de-risking throughout by front-loading the highest-risk tasks to ensure that, in the case of failure, objectives can still be met. For example, hardware development happened early on in the project to allow time to overcome any of the issues that arose.

This method of risk identification and mitigation proved extremely effective during the pandemic, when many of the unwanted outcomes came to pass.

The risk-assessment and resources forms have been kept up-to-date throughout the project to ensure that a safe working environment can be guaranteed. Few changes were made to these documents as the initial copies were good reflections of the risks and resources required.

Reflection The successful completion of all the main outcomes of the project is a testament to the good planning that has been observed from the beginning.

The continued planning and de-risking, alongside the effective use of supervision, have ensured that all the primary aims were achieved within the timeframe. This, in turn, allowed the adherence to milestones and deadlines, including the progress review. Contingencies played a large role in delivery of the project, and are discussed further in chapter **??**.

Mitigating any potential risks through the use of the risk-assessment (Appendix A.3 early in the project allowed for progress to be made safely and appropriately.

The Engineering Council's UK-SPEC has been consulted throughout the project and a spreadsheet has been kept up to date containing relevant evidence of each competency. This has helped to keep the project relevant to engineering professionalism and personal development. The logbook has been used as the main repository for all of the relevant documentation, minutes, notes and technical details. Using this, alongside $ClickUp^{TM}$ for planning tasks and time management, has streamlined the workflow, allowing for much more efficient use of time.

Overall, the management of this project has been executed excellently and, despite the pandemic, all changes to circumstance have been overcome (more in chapter **??**).

Chapter 2

Existing Work

2.1. Lighting

2.1.1. Introduction

Many people do not realise how much time they spend in unnatural lighting conditions. In 2001, a study published in *Nature* magazine found that the average American spends more than three quarters of their time inside (Klepeis et al., 2001). More recent studies have put this number as high as 90% (Opinium, 2018), and when most buildings do not get adequate sunlight in the day, the time spent under man-made light sources can be significant. Furthermore, after dark, almost all buildings are lit artificially; very few people around the world do not spend their nights in lit environments.

Falchi et al. (2016) found that 86% of the World's population, and 99% of the US and European population live under "light polluted" skies. The world uses so much light, that one third of humanity, 60% of Europeans, and 80% of North Americans cannot see the Milky Way.

2.1.2. History

It wasn't always this way. For only the most recent 1.5 million years - a blink of the evolutionary eye - have humans been able to harness the power of fire to extend the usable time of day (J. A. J. Gowlett and Wrangham, 2013). It is important to note, however, that fire does not try to emulate daylight; fires lit after dark were used for cooking and as a social space (J. a. J. Gowlett, 2016).

This was until Michael Faraday's contributions to science allowed Davy to produce the first functional electric light: the arc lamp (Knight, 1998). Since that fateful day, humans' relationship with night has grown increasingly distant. In 1878, Swan presented the first incandescent lamp, patented by Edison in 1880 (though it is believed that others were developing this technology concurrently) . These bulbs are very inefficient; the peak wavelength is determined by the temperature of the gas in the bulb. In order for visible emission to occur, very high temperatures must be achieved - and still the majority of the light will be infra-red (IR) and not visible to the human eye (Montoya et al., 2017).

The next widely adopted innovation was discharge lamps such as sodium lamps and fluorescent tubes, as many Correlated Colour Temperatures (CCTs) could be achieved. A Compact Fluorescent Tube (CFT) could directly replace an incandescent bulb using the same fitting.

While LEDs gained widespread popularity

in the early 21st century (Matsumoto and Onuma, 2020), the first visible light LED was produced back in 1962 by Nick Holonyak (Holonyak and Bevacqua, 1962), based on the even earlier LEDs of Oleg Losev from 1927 (Zheludev, 2007). It wasn't until 1995 that a non-red LED was produced, solving the issue of monochromasity of LED technology (it was blue) (S. Nakamura, 1995).

Once white LEDs could be produced, it led to the "Third Revolution" of indoor lighting (Montoya et al., 2017), and now LEDs are ubiquitous in modern life. New LED technology continues to be developed, such as the Organic LED (OLED), which is cheaper and offer better colour rendition. OLED technology has only recently been applied to indoor lighting (Phelan, 2018), although there are some promising developments in the field (Bender, Marchesan, and Alonso, 2015). However there is still some way to go before OLEDs replace LEDs in artificial lighting technology.

2.1.3. Energy Consumption and Environmental Considerations

Incandescent bulbs are not efficient. in fact, they are banned from being sold in the EU because they are so inefficient (EU, 2012). However, this does not mean they are all bad, they actually have many benefits: firstly, they produce light much more similar to firelight than modern lighting; they are also not hazardous, something which cannot be said for fluorescents and LEDs, which also require higher resource depletion to create (Lim et al., 2013). But LEDs use 85% less energy and last 50 times longer than incandescents (Mottier, 2010). This is significant when considering that 20-40% of most buildings' power consumption is from lighting alone (Pérez-Lombard, Ortiz, and Pout, 2008), accounting for as much as 10% of all power consumed in Europe (Bertoldi, Hirl, and Labanca, 2012). Considering this, and that LEDs can theoretically convert 100% of electrical energy to visible light (thermal regulation is key) (Jordan, Hutter, and Oppermann, 2012), it is clear why the wide-scale adoption of LED technology has been so rapid (Matsumoto and Onuma, 2020).

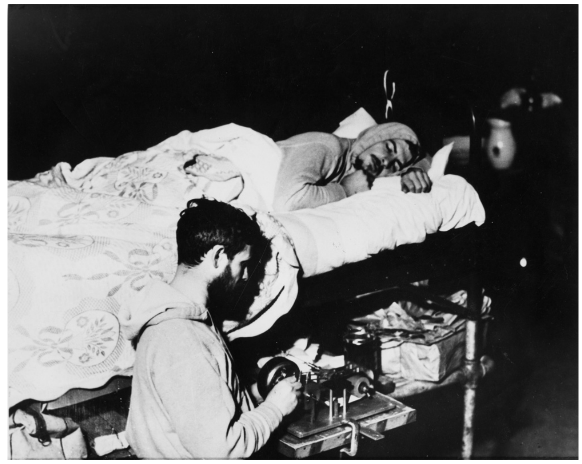

Figure 2.1: *Nathaniel Kleitman (foreground), donning an impressive beard, measures the sleep of Bruce Richardson (University of Chicago Photographic Archive, 2021).*

2.2. Circadian Rhythms

2.2.1. What is the Circadian Rhythm?

In 1729, the French scientist Jean-Jacques d'Ortous de Mairan used plants kept completely in the dark to determine that their diurnal cycles were not caused by external light stimulus, but rather were regulated by some endogenous (internal) clock (De Mairan, 1729).

Amazingly, it wasn't until 1938 that someone repeated this experiment on humans. Dr. Nathaniel Kleitman was a professor of of Physiology at University of Chicago who was later

Table 2.1: *The 5 potential factors for circadian entrainment (Charles A. Czeisler et al., 1981)*

	Factor
I.	Knowledge of time of day
II.	Light Dark cycle
III.	Social Contacts
IV.	Timing of food availability
V.	Scheduling of bed rest and activity

to discover Rapid-Eye Movement (REM) sleep; he is known as the father of sleep research. Together with his PhD student, Bruce Richardson, and a pair of metal beds, they descended into Mammoth Cave in Kentucky for 32 days without any natural lighting stimuli. They found that their sleep-wake cycle did not corrupt into sporadic bouts of sleep, but rather stayed at a periodic length of around 26 hours, undeniably longer than the 24 hour day. This showed that humans have an internal time-keeping system that lasts about (*circa*) one day (*dian*); they named it the circadian rhythm (Kleitman, 1987).

Siffre (1964) repeated this experiment, delving himself into a cavern for 2 months, and discovered much the same results. Meanwhile, Von Aschoff and Wever (1962) kept participants in a sealed cellar for 8-19 days, also discovering a circadian rhythm of over 25 hours.

As circadian rhythms are not 24 hours long, they need to be synchronised daily, and thus must rely on a periodic stimulus to entrain them, ie. to keep them synchronised with the 24 hour day. There were 5 factors that were thought could contribute to this entrainment of the circadian rhythm, as shown in Table 2.1.

Factor **I** (knowledge of time) was shown to be insignificant (J. N. Mills, 1964). Factor **II** (light-dark cycles) is the most powerful in many animals and plants, but Aschoff et al. (1971) concluded that this effect was too weak in humans, and that factor **III** (social cues) must be our central stimulus, or zeitgerber.

However, when inspecting the facilities used for these experiments, Charles A. Czeisler et al. (1981) realised that the researchers "*permitted the subjects to use kitchen, bathroom, bedside and desk lamps as sources of self-selected light during the 'dark' phase of each cycle*", prompting a reassessment of the role of light in the entrainment of human circadian rhythms, concluding that light-dark cycles have a "*direct synchronising effect*" on human circadian rhythms. They then went on to publish the landmark study titled *Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle* (C. A. Czeisler et al., 1986).

2.2.2. Melatonin and Melanopsin

The circadian rhythm is controlled by a part of the brain called the Hyperthalimus (Stephan and Zucker, 1972). Specifically, in the Suprachiasmatic Nucleus (SCN), located above the optic nerve (Welsh et al., 1995). The SCN sends signals to the pineal gland (Cassone, 1998; Borjigin, X. Li, and Snyder, 1999) which is responsible for the production and regulation of melatonin.[1]

Melatonin is known as the sleep hormone, or to some: the "chemical expression of darkness" (Reiter, 1991), and builds up throughout the evening and is essential for sleep onset (J. Arendt, 2003).

In 2000, a novel Opsin was found in the human eye (Provencio, Rodriguez, et al., 2000).

[1] There is much intrigue and mystery around the pineal gland, with many believing that it is where conciousness is generated in the brain (Bob and Fedor-Freybergh, 2008). René Descartes referred to the pineal gland as the "seat of the soul" (Lokhorst, 2020).

An opsin is a light-sensitive protein that exists in the visual cells in the eye and is what converts the energy from photons of light into electrical signals that are sent to the brain (Terakita, 2005). It was soon discovered that the action spectrum of this new opsin, malanopsin, did not match any of the action spectra of the known visual cells (rods and cones), implying there was a new cell that we were not yet aware of (Thapan, Josephine Arendt, and Skene, 2001).[2] This cell was found to be the intrinsically photosensitive Retinal Ganglion Cells (ipRGC) (Berson, Dunn, and Takao, 2002), the signals from which are what keeps the SCN entrained, but to not contribute to conscious vision (Berson, 2007). This explains why some blind people have circadian rhythms that can be entrained with light, as discussed in the review by Allen (2019).

2.2.3. Blue Light

It has been established that light is of great significance in circadian regulation, and that "moderate illumination" of around 500 lux (Laakso et al., 1993), or even "room light" of less than 200 lux (Gooley et al., 2011) can cause a phase shift in the circadian rhythm. Furthermore, due to the action spectrum of the ipRGC, blue light causes a much larger effect than longer-wavelength light (Lockley, Brainard, and Charles A. Czeisler, 2003).

The effect of blue light is so potent, that even one second pulses of blue light through closed eyelids are enough to suppress melatonin production (Mariana G Figueiro, Bierman, and Mark S Rea, 2013), thereby dramatically affecting sleep.

There are a few existing solutions attempting to tackle this problem. For example, the use of amber glasses can filter out blue wavelengths before they reach the retina, and have been shown to improve sleep when worn in the evenings (Kimberly and Phelps, 2009).

2.3. Health Implications

In a meta-analysis, Sanchez-Barcelo et al. (2010) discuss the potential effects of melatonin in a host of situations, including *"ocular diseases, blood diseases, gastrointestinal tract diseases, cardiovascular diseases, diabetes, rheumatoid arthritis, fibromyalgia, chronic fatigue syndrome, infectious diseases, neurological diseases, sleep disturbances, aging and depression [as well as being] used as a complementary treatment in anaesthesia, hemodialysis, in vitro fertilization and neonatal care"*.

2.3.1. Cancer

We've known for a long time that total visual blindness is protective against many types of cancer (Hahn, 1991; Feychting, Österlund, and Ahlbom, 1998; Flynn-Evans et al., 2009). It has also been observed in many studies that flight attendants are more likely to develop breast cancer, as summed up in the meta-analysis by Tokumaru et al. (2006). This effect was also observed in night-shift workers, shown in two large reviews of the existing evidence (Kolstad, 2008; Stevens, 2009). It is also known that the circadian rhythm has a cancer-suppressing effect (Fu and Lee, 2003) and that circadian disruption is a promoting factor for lung cancer (Papagiannakopoulos et al., 2016). An extensive meta-analysis even found that chemotherapy toxicity correlates to when it is taken, lead-

[2] Interestingly, melanopsiin has been found to be much more similar to invertebrate opsins than they are to visual mammalian opsins (Provencio, Jiang, et al., 1998). This, as well as the fact almost all animals produce melatonin, shows it is a truly ancient part of our biology (Davies, Foster, and Hankins, 2014).

ing to the entire field of chronotherapy (Focan, 1995; Dallmann, Brown, and Gachon, 2014).

The correlation of circadian regulation and cancer is so well recognised that even the WHO classes night-shift work as a class 2A carcinogen (WHO, 2013). However, even those not engaging in abnormal working hours may have an increased risk; Stevens et al. (2014) blames electric lighting directly as the cause of breast cancer being the leading cause of cancer death among women worldwide.

2.3.2. Diabetes

Although 415 million people worldwide live with Type II Diabetes, it is a preventable and reversible disease (Fung, 2018). Type II diabetes is a lifestyle disease, mostly caused by diet, whereby insulin resistance is built up such that blood sugar can no longer be absorbed by cells. A contributing factor to this is melatonin, which has been shown to aid blood glucose homoeostasis (Bouatia-Naji et al., 2009). Melatonin receptors influence fasting glucose levels (Prokopenko et al., 2009) and when completely removed, can even induce insulin resistance (Contreras-Alcantara, Baba, and Tosini, 2010).

Another study found that social jetlag - the jetlag-like effect of inconsistent waking times, ie. waking up later at the weekend - is a risk factor for obesity, itself the largest risk factor for Type II Diabetes and a host of other health issues (Roenneberg et al., 2012)

2.3.3. Seasonal Affective Disorder

Seasonal Affective Disorder (SAD) is caused by a lack of light in the winter months when the sun is lower and takes a shorter path across the sky (Charmane I. Eastman, 1990). It has been long considered a fact that bright light helps alleviate the symptoms of SAD (Magnusson and Kritbjarnarson, 1991; lee et al., 1997; Charmane I. Eastman et al., 1998), but this has actually been quite a controversial topic, with others claiming that the placebos in these studies were not adequate, and that the anti-depressant effect can be attributed to placebo effect (C. I. Eastman, M. A. Young, and Fogg, 1993). A comprehensive meta-analysis found that only 13% of studies published between 1975 and 2003 were adequate in their methods (Golden et al., 2005). The meta-analysis also highlighted the importance of dawn simulation, which performed better than both bright-light and placebo effects significantly Avery et al. (2001).

2.4. Cortisol and Attentiveness

Melatonin is essential for sleep, building throughout the evening and peaking in the middle of the night. Similarly, Cortisol - produced in the adrenal gland - helps us wake up, and peaks around mid-morning. This is known as the Cortisol Awakening Response (CAR) and is, of course, also regulated by the circadian rhythm (Fries, Dettenborn, and Kirschbaum, 2009).

Cortisol is the hormone of wakefulness and alertness and it has been shown that a higher spike in morning cortisol is correlated with better cognitive performance (P. D. Evans et al., 2011), and general daytime cortisol improves alertness (Chapotot et al., 1998). It is clear, then, that we want to maximise the CAR, which can be done through exposure to short-wavelength (blue) light after awakening (Mariana G. Figueiro and Mark S. Rea, 2012). Dawn simulation has also been shown to improve the CAR - more so than just blue light - as well as improving melatonin regulation, increasing well-being, mood and cognitive performance (Gabel et al., 2013).

It is also well documented that cortisol is a large contributing factor to mood disorders, especially bipolar disorder (A. H. Young, 2004). A study by D. Sit et al. (2007) found that *"Women with bipolar illness are highly sensitive to morning bright light treatment"*, following this up a decade later with a double-blind placebo controlled trial that found that 68.2% of the bright light participants had their bipolar disorder go into remission, compared with only 22.2% in the placebo group (D. K. Sit et al., 2017).

2.5. Mood and Lighting

Lighting arrangements affect how we perceive spaces (Durak et al., 2007), with the general finding being that daylight-style LEDs are the most comfortable during daytime hours (Cajochen et al., 2019). It is also known that red ambient lighting is more relaxing than blue (Laufer et al., 2009), and that blue causes more stimulation that red (S. Schweitzer et al., 2016). Pulsating orange light has also been shown to be even more relaxing (Wan et al., 2012), it seems as though this could have a link to the fact it is a closer approximation to firelight.

Full-spectrum lighting has been thought to improve cognitive performance and mood states (Berry, 1984). However, this is somewhat controversial and likely to be a placebo effect (Veitch, Gifford, and Hine, 1991).

2.6. Summary of Literature

Over the past 150 years, electric lighting has gone from a pipe-dream to an everyday necessity, increasing the length of the productive day.

"Light affects our sleep more powerfully than any drug"

(Charles A. Czeisler, 2013)

Alongside these developments, circadian science has been driving forward, from observations of the nature of free-running circadian rhythms to the discovery that light has profound affects upon them. Blue light's effect is especially powerful and is becoming more and more ubiquitous as our technology advances. As Charles A. Czeisler (2013) says in his landmark perspective piece entitled *Casting the Light on Sleep Deficiency: "Technology has effectively decoupled us from the natural 24-hour day to which our bodies evolved"*.

This decoupling is dangerous for many aspects of our health. Not only is sleep important for all aspects of health and well-being, melatonin itself has a promising effect on many diseases including type II diabetes, SAD, cancer, and many others. Cortisol, melatonin's sister hormone, is also essential for a healthy life and promotes attentiveness, alertness and cognitive function.

Looking to the past for answers, we see that the output spectra of more outdated technologies such as incandescent bulbs are far more appropriate for evening use than the more modern fluorescent tubes and LEDs. But these older technologies are far less energy efficient. On the other hand, the adoption of more energy efficient technologies should not come at the expense of human health (Boyce, 2010) due to excessive blue light exposure - which has also been shown time and again to damage our eyes in excessive quantities (Ueda et al., 2009; Kuse et al., 2014; Niwano et al., 2014; Marek et al., 2018; M. Nakamura et al., 2018).

Blue light is not all bad, though. Its effects on SAD, bipolar disorder, and cognitive ability show that it is all about giving our body the right light at the right time of day. Some people already strive for this by using blue light blocking glasses or RGB LED bulbs that can be set to change colour. These technologies are flawed, though: glasses are an inconvenience to wear and RGB LEDs only approximate perceived colours by combining red, green and blue, thereby ensuring there is more short-wavelength light that is desirable (Gilewski, 2018).

This has led many to believe that an overhaul in the lighting used in the built environment is of paramount importance, with many papers calling for immediate action (A. R. Webb, 2006; Boyce, 2010; Grose, 2014).

2.7. Existing Solutions

An analysis of existing solutions was undertaken early in the project to understand what already exists in this field. The products could be generalised into 4 categories:

2.7.1. Wake-Up Lights

Ranging from £20 to £200, these products usually come in the form of an alarm clock with a built in light to wake up the user with a simulated dawn. With many varying features across the models, most contain an FM radio.

These lamps are used as a bedside light and are not appropriate for lighting a whole space. As they are focused on morning light, many use inappropriate spectra to be used before going to sleep.

While these devices utilise an artificial dawn - shown to have many beneficial effects - there are few studies on these devices themselves.

2.7.2. Bulb Replacements

Various forms of smart-light exist on the market currently, most notably the Philips Hue. this can be set to fade to warmer light in the evenings and brighter light during the day to encourage winding-down and focus respectively.

However the basis of these are very much visual entertainment, not circadian entrainment. Using RGB LEDs, they are less than ideal for use before bed and need serious modifications to automatically change temperature.

These bulbs are expensive, too. For a starter kit including the base unit and just 4 bulbs, Philips charge almost £200.

Circadian bulbs also exist. These are fitted to dimmer circuits and change temperature instead of dimming. BIOS lighting have a natural spectrum bulb that can be used both in day and night. However, these require manual adjustment throughout the day and require dimmer circuits to be installed.

2.7.3. Industrial Circadian Lighting

There are many companies offering bespoke services to fit circadian lighting systems into office spaces and warehouses. However these are very expensive and not appropriate for home installation. Furthermore, as they are designed for business environments, many of these solutions do not account for later evening light that can aid with sleep onset.

2.7.4. Software Based

Windows, OSX, iOS and Android all now have built in blue light filters that can be turned on to limit the amount of blue light that the screen emits. The intensity and time that it comes on can usually be adjusted by the user. Specialist software such as f.lux can also be used for this purpose but with greater flexibility.

2.7.5. Discussion

All of the devices discussed here have one other feature in common: as they are all LED devices based on providing a visual cue and are not designed based on the evidence in the literature at the forefront (perhaps with industrial solutions as the exception), the spectra of these devices can be questionable.

Also, none of these products are designed to become dim enough to be used late at night. They are all for use leading into the evening, but once the user is in bed, these become insufficient solutions.

2.8. Implementation

The ideas discussed in this chapter were used to inform the requirements specification (Appendix A.1). The output spectra of the lamp will have to be respectful of biological considerations: no light produced within the melanopsin action spectrum during the evening, but high blue light in the morning. Dawn simulation must be achievable on the device to gain many of the benefits.

The existing solutions have shown that the device must be low cost, and fully automated to bridge all of the shortcomings of the current devices. The device should also be simple to install and not require additional technology such as a smartphone.

Chapter 3

Methods

3.1. 4 Phases

There were 4 major phases to the project: idea generation, project setup, development and research. Each of these phases was approached in a different way in acknowledgement of the differences of each.

3.1.1. Idea Generation

Phase I of the project was the time in which to identify a problem that could be addressed.

The initial idea was a running aid for use by natural movement specialists. Qualitative techniques were used to identify whether this would be an applicable solution to the lack of training aids for natural-running coaches. Interviews were conducted between February and September 2020 and many world-renowned athletes and trainers were consulted. These interviews were semi-structured and took approximately 45 minutes to complete over video call, and were recorded for later processing, anonymisation and interpretation; consent forms were signed by each participant confirming that they had read the information sheet provided and understood how to withdraw their data, copies of these can be found in Appendix A.6.

The outcome of this process was that the industry being investigated was not in need of such a device to aid running coaching. The interviews did, however, highlight that almost all of the participants believed that some form of natural-lighting system would be beneficial for their clients and others.

Once the direction had been fixed towards the natural-lighting system, the analysis of the current state of the market was undertaken. The results of this informed what the aims and objectives of the project would be, and a summary of the findings can be found in chapter 2.7.

3.1.2. Project Setup

Once the direction of the project had been identified and confirmed as a suitable project, the groundwork began to create a solid foundation that the rest of the project could be built upon.

The risk assessment, security form, resources form and requirements document were all completed during this phase (See appendix A) to ensure that the project could be undertaken safely, securely, and with an effective and sustainable use of resources. The initial project plan was also compiled to give structure to the two semesters of work (Appendix A.2.1). This initial plan was drafted with the knowledge that it would change over the course of the project in the monthly reviews. Laying out an achievable but optimistic plan ensured that the project hit the ground running and began in the most effective way.

Before development began, the requirements documentation was drafted. This took place in a meeting between the two hardware developers and 45 functional and non-functional requirements were determined. This 3 page document was then adjusted to create a hierarchical structure to aid the ease of understanding and allowing sub-requirements to visually link to multiple parents. The final version of this document can be found in Appendix A.1.

This phase was also used to identify the equipment that would be required to take measurements of the device, including gaining access to a hyper-spectral camera that could be used to record the output spectra. Meetings took place with Professor Darren Reynolds to arrange how access could be given. Meetings also took place to determine how the collaboration with V. Halenka would proceed; the physical design of the device would be split, but further usage and development of software was to be left to each researcher individually.

3.1.3. Development

This is the phase in which the device was actually produced. The tools required to capture the data that would be used to assess the results of the project were developed.

The initial schematics were created before producing the first PCBs. However, due to the lockdown in England beginning on the 6^{th} of January, these PCBs could not be retrieved. For this reason - and the university rules against soldering without the on-campus facilities - a breadboard prototype was made to approximate the final device and test all the functions. This prototype was used as the main device for the purposes of gathering data later in the project.

Once it had been confirmed that the breadboard prototype functioned fully and correctly, a new set of PCBs were ordered, this time with high confidence of them working. More about the specifics of the hardware can be found in chapter **??**.

Alongside the hardware development was the production of the simulator; created in LabVIEW, it was designed to approximate the spectral output of the device to be used to develop the spectra that would be implemented without having to have constant access to the measurement facilities.

Measuring the actual device was also made significantly harder due to the lockdown. Access to the hyperspectral camera was revoked in line with the stay-at-home order. An alternative method for recording the spectra had to be found. Many potential solutions were discussed with machine vision specialists, but many of the proposed solutions were applicable as they could not capture the entire spectrum.

A spectrometer that could achieve full visible-spectrum range was produced (as discussed in chapter **??**) which could be used to gather the spectral data from the device.

The approach employed during this phase was results-driven, de-risk oriented approach to ensure that problems were handled quickly and effectively wherever they arose. This meant that from early in this phase, the ability to create data for the purposes of the study could occur, in one form or another.

3.1.4. Research

The final phase of the project, the results were gathered using the methods discussed below. The simulator was calibrated using measurements from the spectrometer to ensure that the graphs that it output were close to the true spectral output of the device. This meant the spectra that would emulate the solar output could be created in software, saving the time that would need to be used to implement them on hardware and measure the outputs.

The spectral data needed to be extracted from the spectrometer images before it could be used. For this, the Tracker Physics software was used in which a line profile could be drawn across the spectrum to determine the relative power of each point. However, the software required the calibration function to be manually loaded into each image to be extracted.

To streamline this process, another LabVIEW program was created, based off code generated from National Instrument's Vision Assistant. This allowed dozens of images to be converted in seconds once the calibration had been done in Tracker Physics.

3.2. Research Methods

3.2.1. Methodology

The research was undertaken with quantitative techniques such that numerate analysis could be done on the data. This allowed for concrete analysis of many of the aims and requirements, employing a logical approach to the assessment of the success of the project.

By collecting quantitative data, the device can easily be compared to other devices within the same field; this way, the results of this study can be immediately put into context of the real world.

3.2.2. Data Collection

Four spectra were created and assessed: morning (MN), afternoon (AN), evening (EV), night (NX). These spectra were created using the LabVIEW simulator to calculate the LED values required to produce them. The created spectra were then implemented on the device and measured again with the spectrometer to ensure accuracy.

The simulator was then used to create Spectral Power Density (SPD) graphs that were analogous to the physical outputs, and could be binned at any wavelength increment. Only the visual spectrum was considered due to limitations in the measuring equipment.

A lux meter was then calibrated using a known source and used to calculate the luminous flux of the device which could then be expressed in $\mu W cm^{-2} nm^{-1}$, the standard units for luminous flux used when comparing lighting spectra.

Reference datasets were gathered from fluxometer.com (f.lux Software LLC, 2020) for the solar irradiance spectrum throughout the day, as well as a firelight spectrum for the night, and a sample of standard lights for comparison of results. f.luxometer was chosen as it carries a wide range of open-source spectra including many solar spectra. The curators of this data ensure that it is of high quality, and all their work is backed up by a large body of research.

3.2.3. Methods of Analysis

After the spectra had been normalised, they could then be compared using Matlab where the Spectral Angle Mapper (SAM) was used to

Photoreceptor	Photopigment	Unit of Measure
Short-Wavelength (S) Cones	cyanolabe	Cyanopic lux
Medium-Wavelength (M) Cones	chlorolabe	Chloropic lux
Long-Wavelength (L) Cones	erythrolabe	Erythropic lux
intrinsically photosensitive Retinal Ganglion Cells (ipRGC)	melanopsin	Melanopic lux
Rods	Rod Opsin	Rhodopic lux

Table 3.1: *5 Photometric measures that effect cause circadian and neurophysiological responses in humans (Lucas et al., 2014)*

determine the similarity of each spectrum to its respective reference spectrum suing a spectral angle error metric (Kruse et al., 1993). This was repeated for the other lights so comparisons could be drawn as to how effective the device is at mimicking the solar irradiance spectrum. The SAM is given by:

$$cos^{-1}\left(\frac{\sum_{i=1}^{nb} t_i r_i}{\left(\sum_{i=1}^{nb} t_i^2\right)^{1/2}\left(\sum_{i=1}^{nb} r_i^2\right)^{1/2}}\right) \tag{3.1}$$

where: t =test spectrum, r =reference spectrum, nb =number of bands

The Colour Rendering Index (CRI) was also tested using the standard techniques (C. Li et al., 2012). This is the ability for the light to correctly illuminate certain colours; a low CRI means that colours illuminated by this light would not look accurate to their true colour. This analysis was also conducted on the comparison illuminants.

Photometric measures that effect the circadian rhythm were also examined, with the effects of the light on each of the 5 photopigments (listed in Table 3.1) being quantified as per the techniques laid out by Lucas et al. (2014). These responses correspond to how the light will affect the circadian rhythm and other neurophysiological effects within the users. Comparisons of the effects of standard lights and the produced device are drawn to understand whether this is an improvement on existing solutions.

These techniques were selected as they would answer the questions as to the relevant performance of the device as stated in the requirements document (Appendix A.1). The quantification of these factors has been approached in the ways most relevant and have scientific backing in the fact that they are broadly used in the literature.

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Glossary

AN afternoon. 15

blue light Short wavelength, high-energy - usually below 550nm. 1, 8, 9, 10, 11, 12

CFT Compact Fluorescent Tube. 5

CRI Colour Rendering Index. 16

EV evening. 15

ipRGC intrinsically photosensitive Retinal Ganglion Cells. 8, 16

L Long-Wavelength. 16

luminous flux the perceived power of a light source, measured in lumen. 15, 34

lux the SI unit of illuminance, measured by luminous flux per unit area. Equivalent to $lumens/m^2$. 15

M Medium-Wavelength. 16

MN morning. 15

NX night. 15

PCBs Printed Circuit Boards. 2, 14

S Short-Wavelength. 16

SAM Spectral Angle Mapper. 15, 16

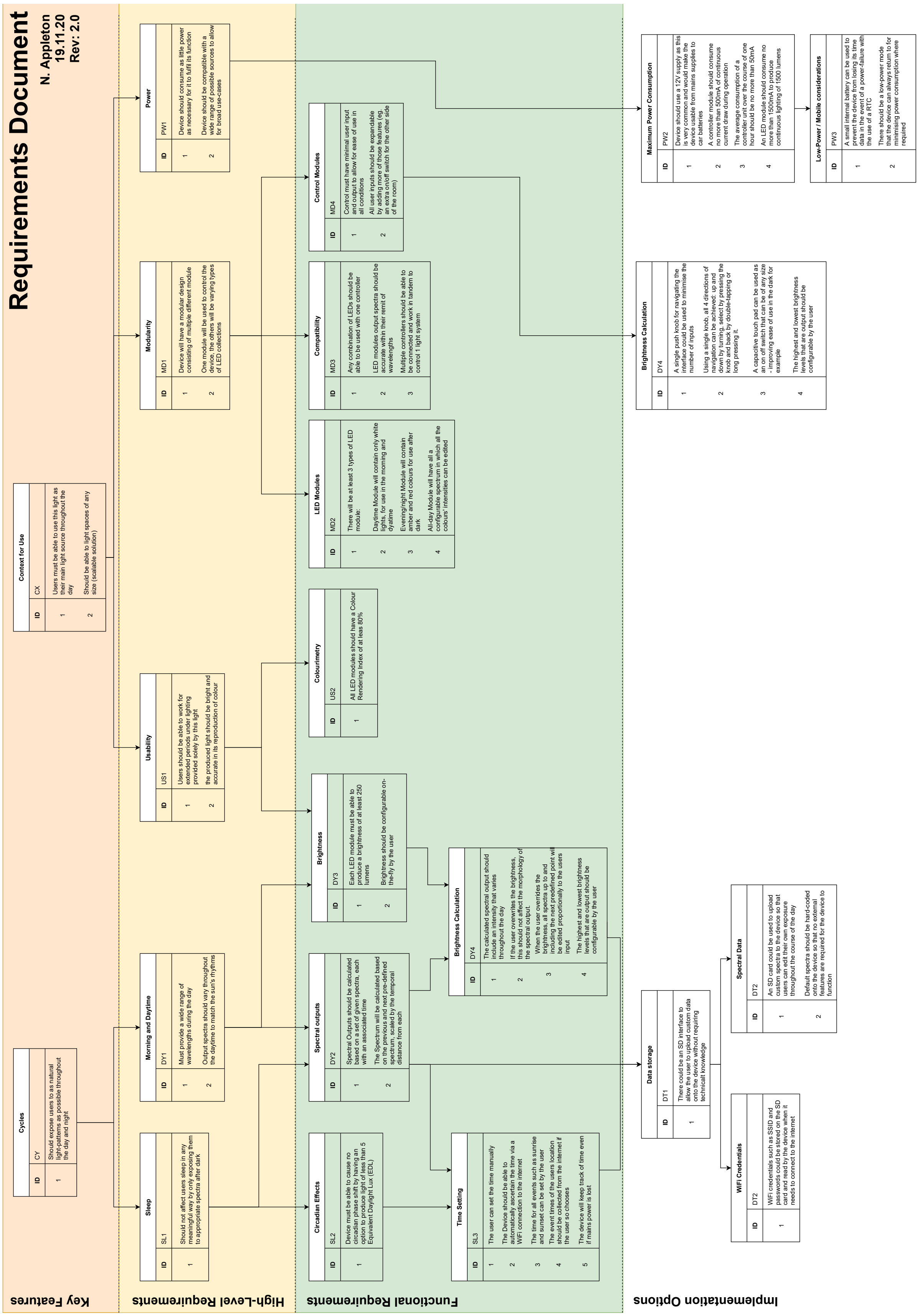
solar irradiance spectrum the spectrum output by the sun as measured from the surface of the earth. 15, 16

SPD Spectral Power Density. 15

Appendix A

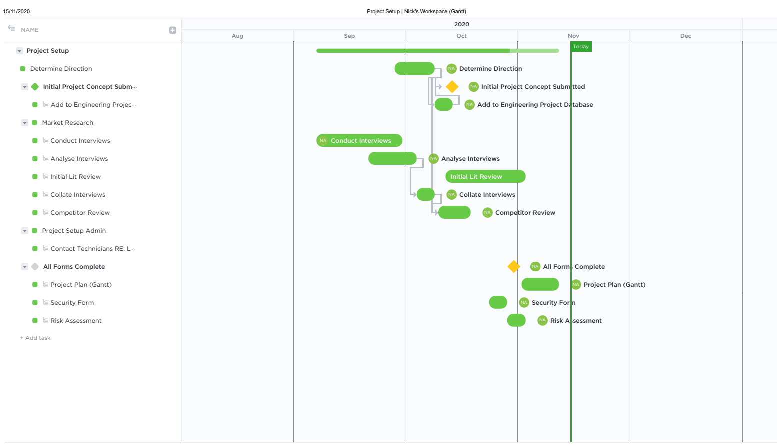
Project Documents

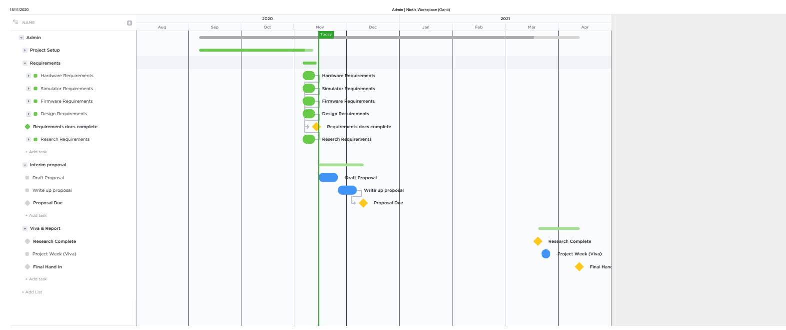
A.1. Device Requirements



A.2. Gantt Charts

A.2.1. Nov 15th 2020 (initial)





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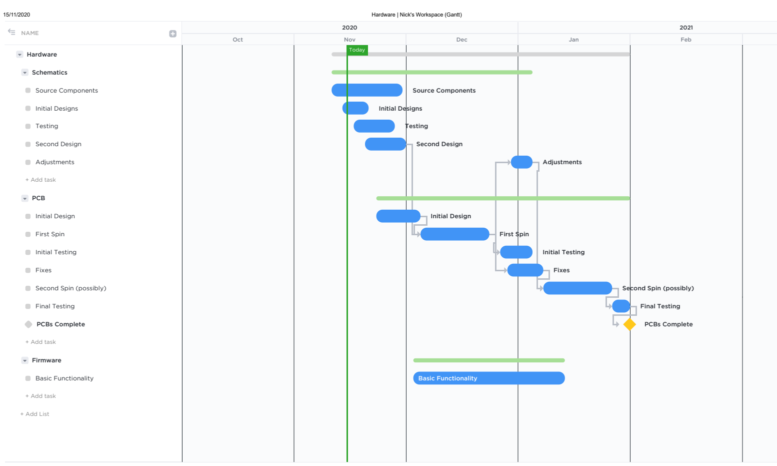

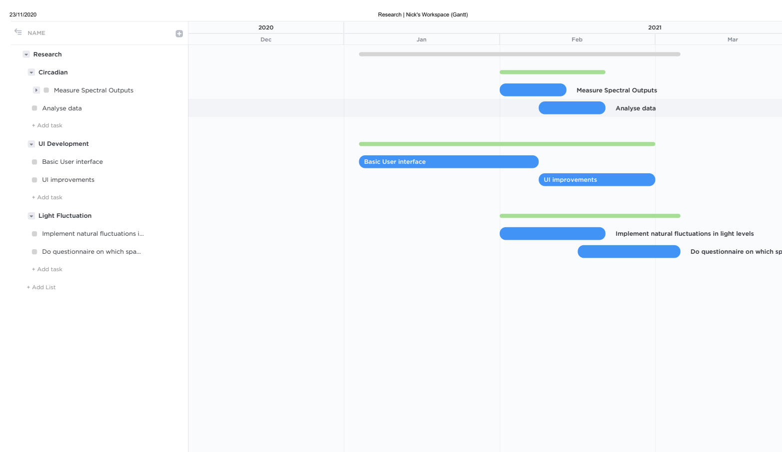

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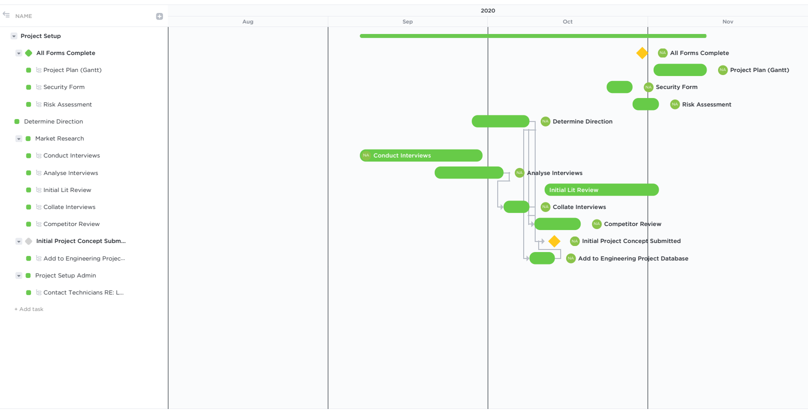
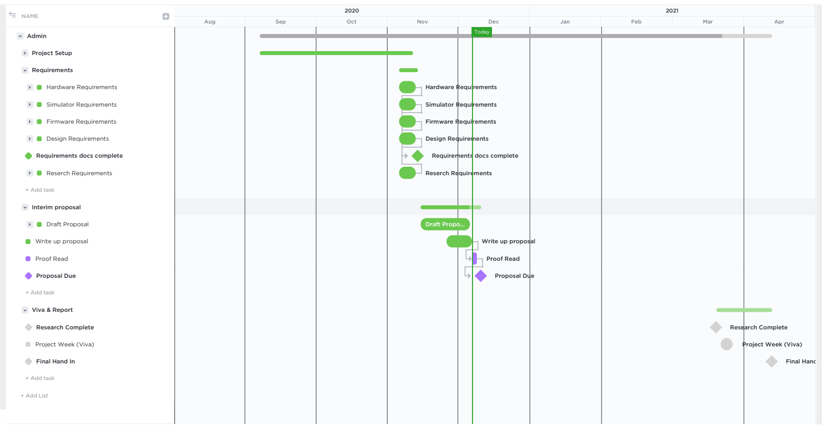
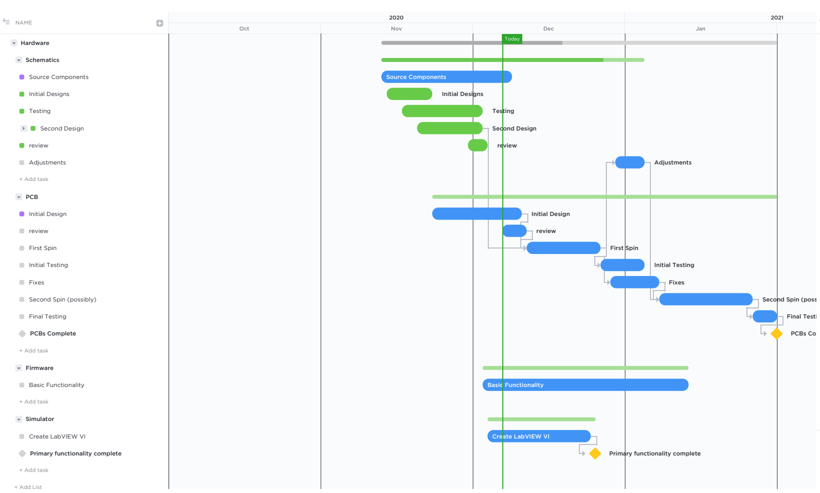
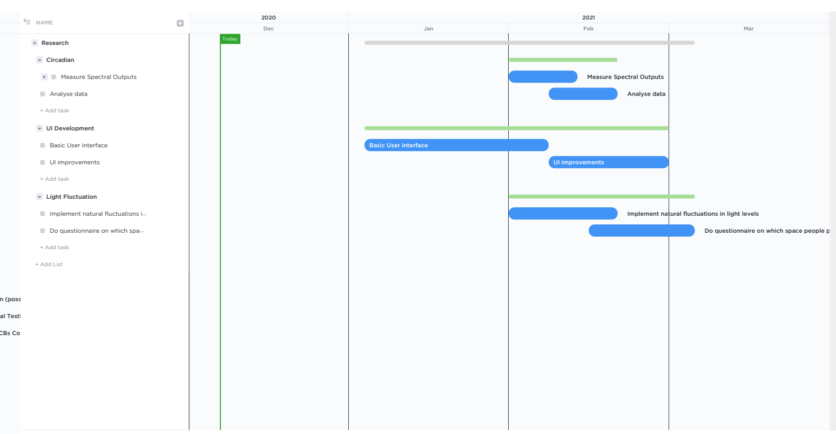
https://app.clickup.com/2605241/v/g/f/17128849 1/1

A.2.2. Dec 12^{th} 2020

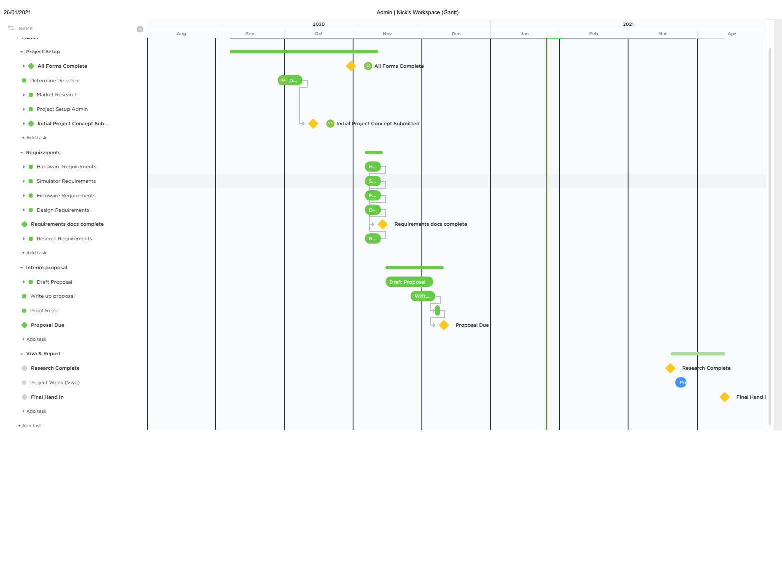


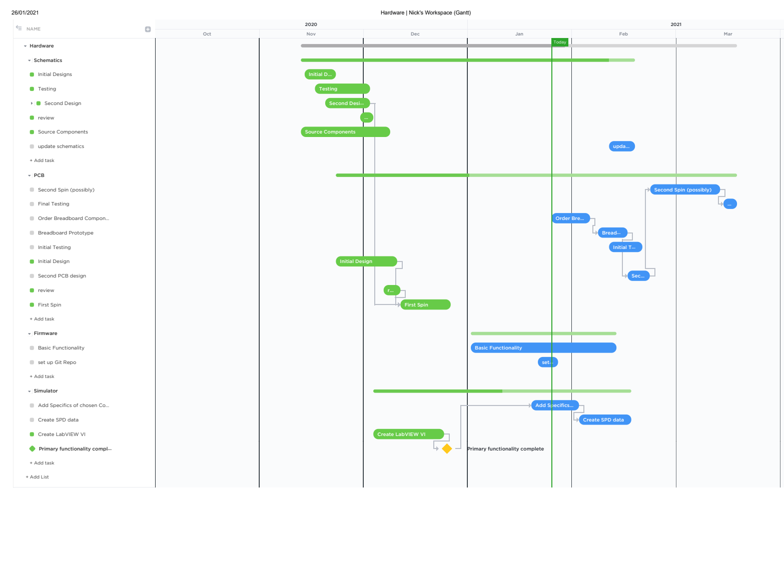


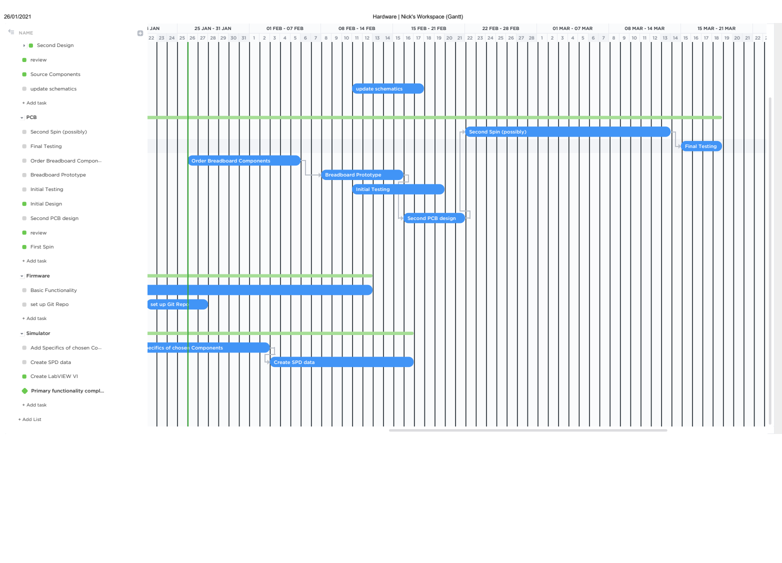


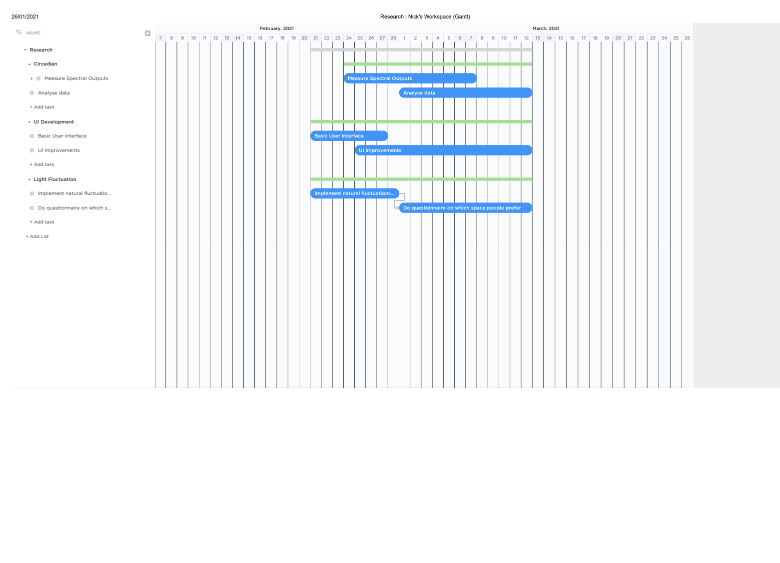


A.2.3. Jan 26^{th} 2021

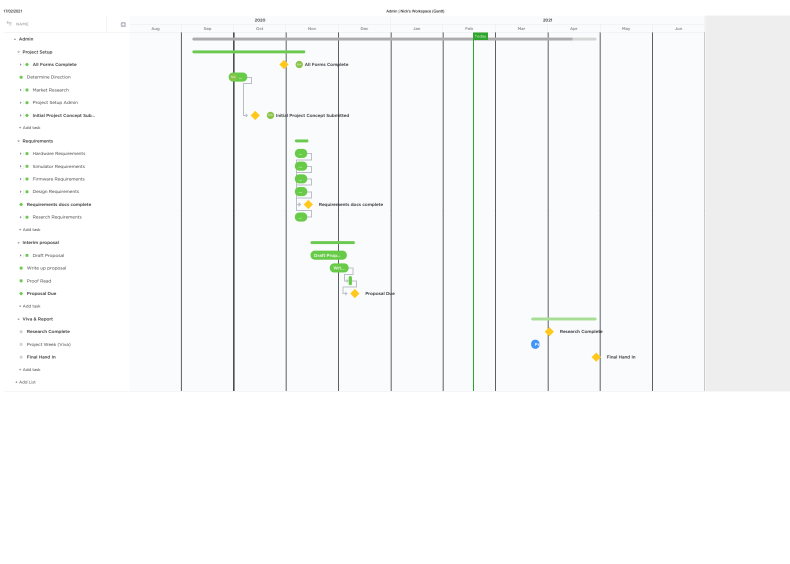


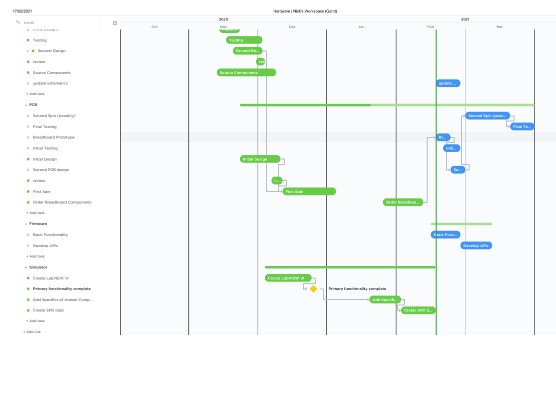


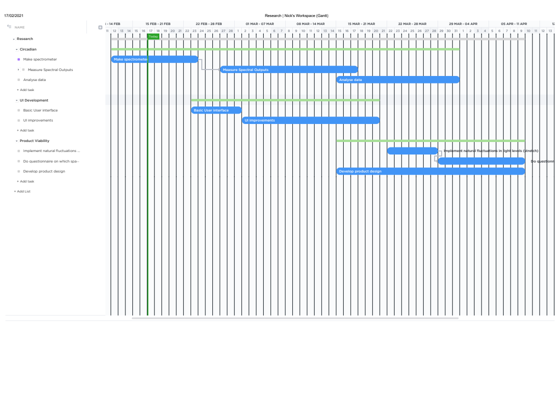




A.2.4. Feb 17^{th} 2021

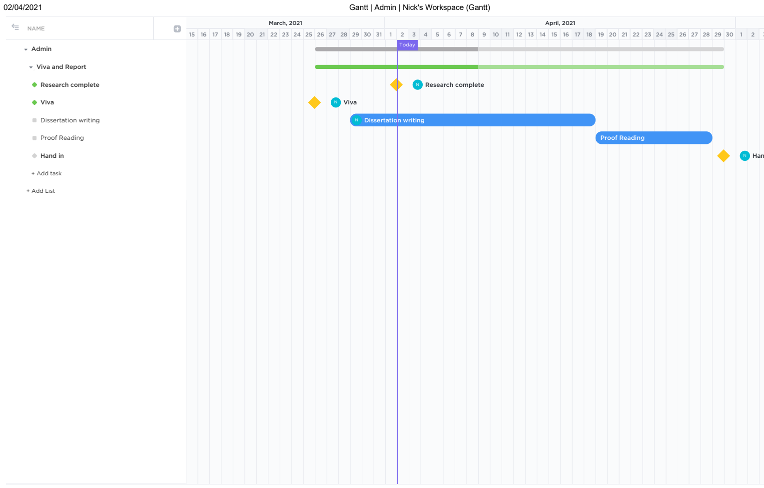






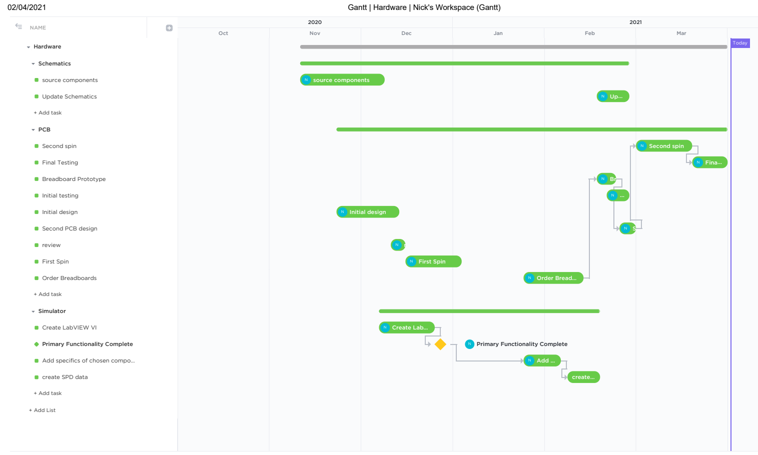
A.2.5. Apr 2^{nd} 2021

02/04/2021 Gantt | Admin | Nick's Workspace (Gantt)



https://app.clickup.com/4713725/v/g/4fv7x-15?pr=8846896 1/1

02/04/2021 Gantt | Hardware | Nick's Workspace (Gantt)



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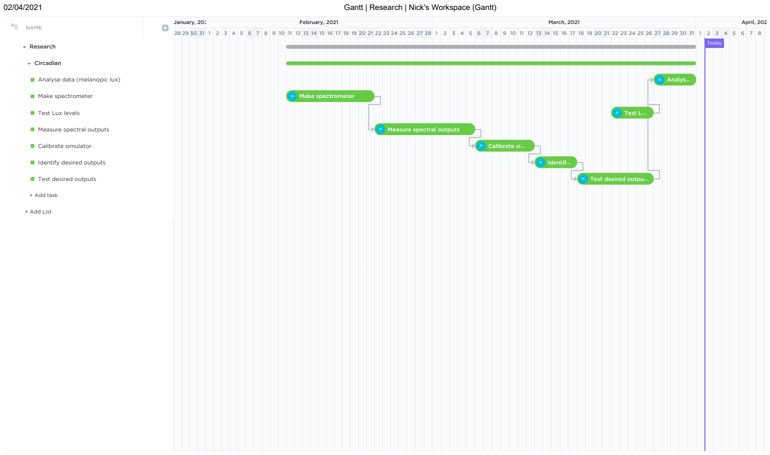
02/04/2021 Gantt | Research | Nick's Workspace (Gantt)



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A.3. Risk Assessment

University of the West of England BRISTOL

GENERAL RISK ASSESSMENT FORM

Without exception

Describe the activity being assessed: Producing a natural-cycle based lighting system	**Assessed by:** Matthew Studley	**Endorsed by:**
Who might be harmed: Nick Appleton (NA) **How many exposed to risk:** 1	**Date of Assessment:** **02/04/21**	**Review date(s):**

Hazards Identified *(state the potential harm)*	Existing Control Measures	S	L	Risk Level	Additional Control Measures	S	L	Risk Level	By whom and by when	Date completed
Potential use of Lab equipment	Existing risk assessment including mitigations	3	2	6	Keeping a clean workspace and ensuring that equipment is used properly and switched off when not in use	3	1	3	NA - consistently	Ongoing
Covid-19 Risk from face-to-face meetings	Government and University rules and guidance	3	3	9	Conducting all meetings online without exception	3	1	3	NA – Every meeting	Ongoing
Soldering: very high temperature, hand-held iron		2	3	6	Make sure to store the iron in the holder when it is not being used. Minimise the number of sessions spent soldering, while not allowing any rushing to occur.	2	2	4	NA – all soldering	Ongoing
High-power electronics pose an electrocution risk		4	2	8	Whenever handling electronics, wearing a grounding bracelet connected to an anti-static mat and earthing point to discharge any potentially harmful electrical surges. Testing the device with lower power inputs.	2	1	2	NA – whenever handling electronics	Ongoing
Isolation from working from home and related stress		3	3	6	Implement stress-relief measures and ensure that overworking doesn't occur by time-boxing various tasks and implementing effective project-management strategies. Seeing peers (when the covid restrictions allow).	2	1	2	NA – Always under evaluation	Ongoing

A.4. Resources

Dissertation Project Resources Form

Name: Nicholas Appleton Student ID: 16019243

Supervisor: Matthew Studley

[If you are carrying out a desk-based study and/or are only using the library or ITS facilities available at UWE, the faculty's risk assessment procedures will sufficiently cover your activities. In these circumstances, you should identify this on your risk assessment form, which you should attach - along with this form - to your Interim Research Proposal.]

Please sign below to confirm your request for resources.

Student: ………………………………………………………………… 02/04/21

Supervisor: ………………………………………………………………………….

Further Resources – *what else will you need?*

R-Block workshop	☐	Laser cutting	☐
N-Block workshop	☒	Large format printing	☐
3D printing	☐	Miscellaneous	☐
Labs:			
Structures	☐	Car/flight simulator	☐
Materials	☐	Engine test bays	☐
Composites	☐	Robotics	☐
Hydraulics	☐	Dynamics	☐
Wind tunnel/aero	☐		

If you have ticked any of the above, please fill out a risk assessment of your activities.

Have you spoken to a technician? Yes x Not yet ☐

Materials - *outline the materials required for your project:*

Electronic components

- *LEDs*
- *SD card*
- *Alphanumeric Display*
- *Input and Output ports*
- *PCBs (printed and placed – including components)*
- *Optical Encoder*
- *RTC module*
- *Spectrometer equipment*

A.5. Security

Engineering Design and Mathematics

- **UK Engineering Council Guidance on Security**

Security is an important consideration for any project and in any workplace. UK SPEC provides guidance on security and outlines how it expects professional engineers to conduct themselves with respect to security. This guidance is split into six key principles. Your task is to visit the UK SPEC security page and read through the tips provided for each principle.

Using the tips on the webpage provide at least one example for each of the six principles that you can directly link to your project or that should be considered in the role of Professional Engineer. Then summarise your findings in the comments box below.

The link is https://www.engc.org.uk/security

- How would you adopt a security-minded approach to your project?

- be responsive to changes in the operating environment, including the impact of changes in use of the asset or system, its wider connectivity and emerging threats and vulnerabilities. With the current situation with working from home and potential changes to the working environment, this will be relevant to how I consider security.
- remember that security risk assessment is an aid to professional judgement, not a substitute for it. I will continue to assess any and all security risks throughout the project to ensure that any risks are neutralised as quickly as possible.

- What should you consider in order to apply responsible judgement and take a leadership role?

- working with other professionals to ensure informed, proportionate, holistic judgements. When I am working with other professionals – eg. When using equipment like a hyper-spectral camera – I will strive to ensure that we both are remining security minded throughout the work
- being prepared to challenge assumptions and proposals. If when working with one of these professionals, they do something that could potentially cause a security risk, I will certainly be prepared to challenge them and stop them from presenting those risks.

- How will you ensure that your project complies with legislation and codes, while understanding intent and prepared to seek further improvements?

- be aware of, and comply with, the security-related laws in countries where they operate or where their products or services will be used. As I will be developing a prototype product, I will ensure that I am aware of the relevant laws and will comply with them entirely when developing my product.
- be open-minded and avoid using regulations to facilitate complacency. By constantly evaluating the security risks, I will ensure that I am constantly staying on the ball, and not becoming complacent.

- How do you ensure good security-minded communications?

- adopt appropriate measures to protect sensitive information when it is communicated, used and stored, both within and beyond their organisation. Whenever sharing information, I will ensure that it is done in a secure way, and I will communicate when it needs to remain secure.
- recognise the persistent nature and accessibility of information published on the internet or otherwise made publicly available. Before making any information publicly available on the internet, I will ensure to conduct a thorough review of the content and redact or not publish any sensitive information.

A.6. Interview Documents

Consent Form

Walking Back to Nature: Developing an Unobtrusive Device to Measure Kinetics and Kinematics of Gait

This consent form will have been given to you with the Participant Information Sheet. Please ensure that you have read and understood the information contained in the Participant Information Sheet and asked any questions before you sign this form. If you have any questions please contact a member of the research team, whose details are set out on the Participant Information Sheet

If you are happy to take part in an interview, please sign and date the form. You will be given a copy to keep for your records.

- I have read and understood the information in the Participant Information Sheet which I have been given to read before asked to sign this form;
- I have been given the opportunity to ask questions about the study;
- I have had my questions answered satisfactorily by the research team;
- I agree that anonymised quotes may be used in the final Report of this study;
- I understand that my participation is voluntary and that I am free to withdraw at any time until the data has been anonymised, without giving a reason;
- I agree to take part in the research

Name (Printed)…………………………………………………………………………..

Signature…………………………………………………. Date…………………….

Information Sheet For Interviewees

Project Title: Walking Back to Nature: Developing an Unobtrusive Device to Measure Kinetics and Kinematics of Gait

You are being invited to take part in this research project. Before you decide to do so, it is important you understand why the research is being done and what it will involve.

Please take time to read the following information carefully and discuss it with others if you wish. Ask the research student if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

The researcher (Nicholas Appleton) can be contacted at nicholas2.appleton@live.uwe.ac.uk

The project supervisor (Matthew Studley) can be contacted at Matthew2.Studley@uwe.ac.uk

Thank you for your time.

What is the purpose of the project?

This project aims to develop a small, unobtrusive device that can be used by natural movement specialists (Physiotherapists, Personal Trainers, Rewilding Coaches, etc.) to measure the motion and forces involved in a person's gait. By using minimal hardware and flexible materials, the device can be used to measure the true function of the foot - unlike devices on the market currently which require restrictive shoes to function. The purpose of this interview is to capture requirements sought by professionals in the movement industry.

Why have I been invited to take part?

As a professional in the movement industry, we are interested in gaining your views and opinions on what is important in a device as described above. You may also be asked about your experiences as a movement specialist where these are relevant to the research. The purpose of these questions is to gain an understanding of what requirements are necessary to the potential users of the device.

Do I have to take part?

You do not have to take part in this research. It is up to you to decide whether or not you want to be involved. If you do decide to take part, you will be given a copy of this information sheet to keep and will be asked to sign a consent form. If you do decide to take part, you are able to withdraw from the research without giving a reason until the point at which your data is anonymised and can therefore no longer be traced back to you. This point will take place 4 weeks from the date you signed your consent form. If you want to withdraw from the study within this period, please write to N. Appleton (nicholas2.appleton@live.uwe.ac.uk). Deciding not to take part or to withdrawal from the study does not have any penalty.

What will happen to me if I take part and what will I have to do?

If you agree to take part you will be asked to take part in a video interview that will last between 20 minutes and an hour. The interview will be recorded and saved using a unique identifier that will be used to re-identify you if you choose to withdraw from the study within the period. Once the requirements capture has taken place, the video recording will be deleted.

What are the benefits of taking part?

By taking part in this interview, you are helping to develop a tool that could be used to help people regain their natural movement and improve their health. The device will be created around specifications built from the information you provide in this interview.

What are the possible risks of taking part?

We do not foresee or anticipate any significant risk to you in taking part in this study. If, however, you feel uncomfortable at any time you can ask for the interview to stop.

What will happen to your information?

All the information we receive from you will be treated in the strictest confidence. All the information that you give will be kept confidential and anonymised. Voice recordings will be destroyed securely immediately after anonymised value extraction. Your anonymised data will be analysed together with other interview and file data, and we will ensure that there is no possibility of identification or re-identification from this point.

Where will the results of the study be published?

Results of the research will be part of the student's undergraduate dissertation. You will not be identified in this piece of work. If you wish to be given a copy of the resulting dissertation, please indicate so on the consent form.

Who has ethically reviewed this project?

This research has been ethically approved by Matthew Studley of the Department of Engineering, Design and Mathematics.

What if I have more questions or do not understand something?

If you would like any further information about the research, please contact in the first instance:
N. Appleton nicholas2.appleton@live.uwe.ac.uk

Thank you for agreeing to take part in this study.

You will be given a copy of this Participant Information Sheet and your signed consent form to keep