Developing an affect-sensitive Turrellian lamp designed to improve mood.

Towards multimodal affect-sensitive computing and devices.

By

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Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and the requirements of the degree of Master of Science in the Faculty of Engineering. Furthermore, this paper has not been submitted for any other degree or examining body. Except where indicated by specific reference in the text, the work is entirely the author's own work. Work done in collaboration with, or with the assistance of others is indicated appropriately. Any views expressed in the dissertation are those of the author, Humphrey David Whitefoord Curtis.

SIGNED: .... DATE: 10.09.20

Executive Summary

This thesis describes the development of the Turrellian lamp - a multi-modal affect-sensitive lamp designed to improve mood. The Turrellian lamp is the first smart lamp designed to improve mood, which utilises tightly synchronised body sensors and a self-journaling application to gauge users' affective signals.

However, the Turrellian lamp fundamentally differs from other smart-lighting internet of things (IoT) devices - because it is the first device to be tethered to users' affective state and offer mood enhancement utilising research from colour psychologists Valdez and colleagues.

Inspired by the work of lightscape artist James Turrell, the Turrellian lamp is designed to bridge the gap between mindful applications and smart lighting systems – improving users' day-to-day quality of life. The Turrellian lamp was initially tested in a pilot study versus a control lamp, namely a Phillips Hue smart bulb. Key results from the pilot study in chapter 11 find that:

- Four out of six participants (67%) self-reported direct improvements in mood, which they directly attributed to the Turrellian lamp.
- The biometric data collected reports that five out of the 6 participants (83%) physiologically improved towards their desired positive emotional state because of the Turrellian lamp lighting.
- The Turrellian lamp outperformed the Phillips Hue smart bulb in all user experience (UX) Attrakdif questionnaire categories - scoring significantly higher in hedonic qualities and stimulation.

The main contribution of this thesis is the Turrellian lamp itself. However, additional contributions to the key research areas of affective-science and multimodal human computer interaction (MHCI) include:

- Insights from affective science - most notably embodied and scaffolded approaches to improve future MHCI research in chapter 3.
- Light sequences and methodologies based off Valdez and colleagues findings to best improve users mood according to Russell's circumplex emotion model in chapter 4.
- A thorough review and critique of open-source and publicly available multimodal hardware used throughout research in chapters 7 and 8.
- Conclusions from creating an open source, low cost and novel MHCI architecture, which can recognise users affect in chapter 10.

Dedication and acknowledgements

I would like to first and foremost thank the incredible help and support of my supervisor Dr Paul O'Dowd throughout these difficult pandemic circumstances. His advice, thoughts, tireless work and weekly meetings helped immensely in writing this thesis and successfully executing the entirety of the project - I always learnt a huge amount from his insights.

Additionally, I would like to thank the support of fellow MSc student Nathan Cubbitt for lending LEDs, offering plenty of experienced micro-controller advice for this project and suggestions for improvement.

Also, I would like to thank Brian Shareland for his masterful help with woodwork materials and supporting the construction process of the prototype Turrellian lamp. Furthermore, the support of Robbie's Media for providing hardware supplies during the difficult Coronavirus circumstances.

My parents for their huge unwavering help - especially with providing financial support for the project and allowing me to work at home throughout the pandemic. Lastly, I would like to thank Carys Williams for just about everything else and countless constructive discussions regarding the project.

COVID-19 STATEMENT

For the Covid-19 statement, I will discuss the unforeseen issues faced by the project as a consequence of the pandemic. Firstly, I will consider the key structural issues and then secondly, briefly consider personal issues caused by the pandemic.

Structural issues

- **Hardware supplies** - Disruptions from China meant computer hardware supplies were difficult to acquire and limited the modalities of the lamp. For instance, a GSM monitor never delivered from the manufacturer in China. Additionally, basic computer hardware pieces from key suppliers such as Adafruit or Pimoroni sold out due to surplus demand or took longer to deliver - slowing down the lamp construction process.

- **Laboratory conditions** - The closure of Bristol's computer laboratories meant that all development of the lamp software and hardware had to occur at home in London. This was obviously tricky as I had no in-person support, help and guidance. Furthermore, I lost key tools such as a 3D printer and soldering equipment.

- **Experiment setup** - The projects' pilot study participants were not assembled normally. I worked with a commercial partner and used 6 of their employees all of whom were offered a £10 Amazon voucher for participation. In normal circumstances, random members of the public would be sampled for better data, more participants would be used and vouchers would be avoided so as to prevent any forms of implicit bias. However, in the difficult circumstances it was the best pilot study I could achieve and I am delighted to have collected initial data concerning the effectiveness of the Turrellian lamp.

Personal issues

- **Home conditions** - Working from home in London without laboratories for developing software and hardware was challenging. Additionally, I shared a bedroom with my younger brother who participated in online learning for primary school, which obviously provided another challenge. These conditions for producing the Turrellian lamp were not ideal.

- **Family challenges** - My mother runs a small independent business which faced great strain during the pandemic and my father was made redundant. This did not directly impact the Turrellian lamp, but as the study was self-funded obviously resulted in cuts for hardware materials, I left Bristol prematurely and took up supportive work for my family.

- **Part-time work** - Coupled with the demands of the project, I worked for free for my mum - supporting her business wherever I could mainly with IT, SEO and other free consultancy. Additionally, I regularly helped my younger brothers with their online study and classes.

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CHAPTER 1

INTRODUCTION

1.1 Context

No aspect of mankind's mental life has more meaning to the quality of our present existence than emotions [191]. Quite simply, emotions have the capacity to make life worth living or ending [191]. With the advent of computers and wearable devices - scientific research into affective computing has markedly increased. Affective computing is the study of systems and devices, which recognise, process, simulate and interpret human affects [168–170]. Conversely, traditional computers serve as more rigid tools and do not respond to their users affects.

Since Rosalind Picard's, notable paper and book on affective computing in 1995 [167] – much research has been established towards developing affective computers [193], systems [145], interfaces [71] and robots [12]. Equally, the exponential increase in transistors on silicon integrated circuits (microchips) i.e. Moore's Law - has supported much innovation in affective computing technology [126, 192].

Resulting in affect-sensitive computer systems that can increasingly embed themselves into the fabric of our everyday living spaces and project the human user into the foreground [158]. Indeed, these affect-sensitive and multimodal devices have the capabilities to understand their users intentions without the keyboard or mouse and instead solely from users emotions automatically [158, 203].

For instance recently, prominent human computer interaction researchers Pantic et al. have established the term affect-sensitive multimodal human computer interaction (MHCI or HCI2) – specifically computing, which can understand and respond to natural and autonomic modes of human communication such as emotion automatically via analysing a range of human modalities [158, 159]. Naturally, these devices or interfaces offer a better alternative to the traditional computer keyboard and mouse - by enabling users to intuitively control their devices through

(b)

(a)

FIGURE 1.1. (a) Web application used by participants in pilot study to control lamp. (b) Image of the final 6 feet tall Turrellian LED lamp emitting a peaceful green hue ambient light.

behavioural signals and without the frustration or inconvenience of traditional computer requirements [158, 168].

In this envisioned future, referred to as “ambient intelligence” - humans will be increasingly surrounded by intelligent multimodal computer devices that can anticipate our daily needs [158]. For instance, cars may automatically pull over if a driver becomes drowsy, our favourite music may be played by speakers when we come home weary after a long day at work and smart watches may prompt us with notifications to remind us to meditate when we are feeling stressed [158, 159, 203].

There are significant advantages to these empathetic and multimodal computers, interfaces and machines. Chapters 2 and 3 will discuss evidence from MHCI research which finds that they are more human-like, usable, efficient and effective [148, 159]. Consequently, these multimodal affect-sensitive computers and devices have the capacity to significantly improve users’ day-to-day moods, emotions, routines and overall quality of life [168–170].

Spectrums of coloured lighting diffused by an internet of things (IoT) lamp has been chosen as the most appropriate medium to explore enhancing the mood of users. This is because different spectrums of lighting have been proven to have a non-invasive range of health and emotional

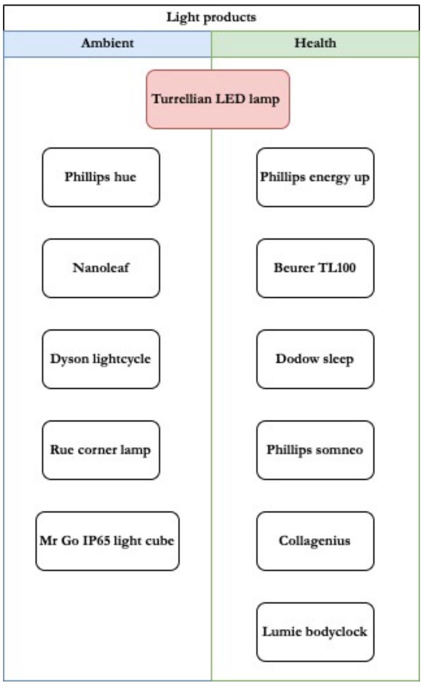


FIGURE 1.2. Figure depicts taxonomy of commercially available light devices - most fit into two categories of health and ambient centric.

benefits from improving concentration [108] and sleep [51] to even alleviating depression [102, 103] and migraines [2].

Additionally, there is a growing popular market of IoT lighting devices designed to treat specific health disorders or on-command calibrate suitable environmental ambiences for their users [68]. Therefore, there is undoubtedly value in adding more to this IoT lighting market by building a device which automatically enriches the environment resulting in improvements in users' mood (see figure 1.2).

1.2 Map of project paper

This thesis can be successfully broken down into four parts:

I. **Literature review:** In this section, I define affect sensitive MHCI, critically taxonomize recent contributions to the field. Before juxtaposing the research with recent relevant insights from affective science.

II. **Design approach and prototyping:** Here I discuss the context for the Turrellian lamp, colour psychology and the groundwork for successful delivery of a pilot prototype.

III. **User experience testing:** This section focuses on evaluating and user experience testing the pilot Turrellian lamp prototype.

IV. **Outcomes:** Results from user experience testing are collected, statistically analysed and evaluated. Thus the outcomes will contribute towards further MHCI research and future prototypes of the Turrellian lamp.

1.3 Introduction to James Turrell

As the device-namesake, James Turrell's artwork has been a dominant influence in this research. Turrell emerged as one of the foremost artists associated with the Light and Space movement of the 1960's [1, 21]. His art encourages a state of reflexive vision that he calls "see yourself seeing" wherein we become aware of our own senses, emotions and of light as a tangible substance [15].

Particularly, Turrell's work explores the immateriality of light – building on the sensorial and emotional experience of space and colour. His oeuvre, phenomenological lightscapes feature technically advanced LEDs, which are configured by computer programming. Collectively his innovative and photographic techniques enable light and its spectrum of colour to have a physical presence and fully immerse the space.

These expositions and spaces engage viewers – capturing the limits and wonders of human perception prompting an incredibly transcendental and emotional experience. As Turrell aptly notes, "my material is light, and it is responsive to your seeing" [1]. This physical engagement with light and colour strongly inspires the aesthetic design of the Turrellian lamp.

In this sense, Turrell's work, particularly his expositions focusing on the Ganzfeld effect, hones visitors' senses by deliberately removing elements of perception and enabling colour to fully inhabit and immerse the space [72]. Notably, art curator De Lima Greene notes that, Turrell's "pieces enact not just an emotional response to colour but a sharpening of all of your perceptual faculties. After you have spent some time looking at a Turrell, you walk out and pay attention to how even an ordinary lightbulb casts light upon the wall" [66].

Specifically for the project, Turrell's work serves as inspiration because the Turrellian lamp is keen to produce a positive emotional response through immersive coloured lighting for its users - thus capturing the emotiveness of Turrell's lightscapes. Additionally, Turrell's work demonstrates that lighting is a sensory medium, which can be adapted by hardware and computer programming to provide captivating ambiences in any environment. Having discussed Turrell, now I will consider the lamp itself.

1.4 The Turrellian lamp

This thesis describes the development and testing of a new IoT device, the Turrellian lamp, which inspired by the phenomenological works of Turrell and a wide range of research initially outlined above within light, colour and affect-sensitive MHCI is used to improve user's mood and quality of life.

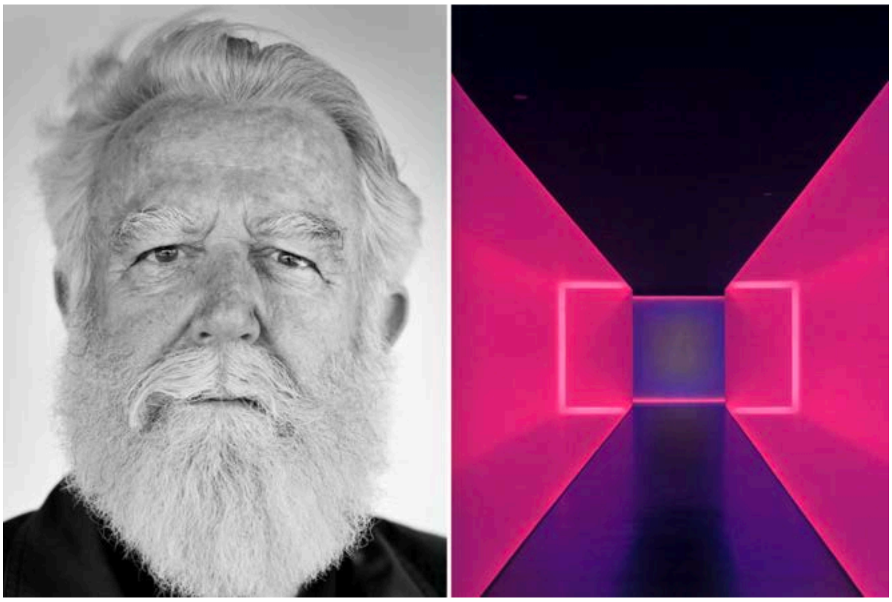


FIGURE 1.3. A portrait of artist, James Turrell coupled with a picture of his installation, the Light Inside - a pink light corridor exhibited at the Museum of Fine Arts, Houston, 1999.

Particularly, the Turrellian lamp proposes an enhanced sensory experience to benefit users mental-wellness, cognition and emotion – few appreciate the significance of appropriate lighting and the subconscious effect of coloured lighting on mood [106, 153]. Therefore the lamp aims to subtly expose users to appropriate colours and hue profiles of lighting to enrich their present mood and cognition. The potential of this is based on detailed research from colour psychologists Valdez et al. [153, 216], which is discussed in more depth in chapter 4.

The Turrellian lamp will be operated from a web based application which encourages journaling and daily self-reflection. Data from the application will be coupled with the physiological signals of the user enabling the lamp to recognise and improve the users mood. Furthermore daily reflection and journal writing has tremendous therapeutic benefits for mental health and mood, this is discussed in greater detail in chapter 6.

Conventionally, individuals have become accustomed to the importance of music for their quality of life – people everyday use radios, phones or even music streaming platforms to play their favourite songs and playlists [34]. Surprisingly, in contrast, ambient environmental lighting has been broadly overlooked due to its imperceptible nature and perceived lack of importance. However, like music, ambient environmental lighting holds significant importance for individual's mood, health and general cognition as found from research conducted in elderly care homes [106] and light therapy research within hospitals [99].

With this realisation, more recently, there has been growing demand for smart IoT light devices, lamps and lighting systems [68]. Typically, these devices fit into two key categories (see figure 1.2). In the first category, the light devices are designed to be manually calibrated by users to provide ambient lighting on-command. In the second category, the light devices are designed to provide "health" functionality to treat disorders such as seasonal affective disorder (SAD), sleep disorders and even dementia.

In contrast to these categorised rival devices, the Turrellian lamp is the first IoT lighting device to use insights from affect-sensitive computing to work synonymously with its users' affective state (both conscious and subconscious) based off an innovative application and physiological data - thus offering mood enhancement through coloured lighting. Furthermore, the Turrellian lamp has the capacity to operate automatically. The goal of utilising insights from disparate fields such as ambience research, psychology and affective computing in the form of the Turrellian lamp is threefold for users:

1. To positively impact user's cognition, affective state and mood through non-invasive coloured lighting.

2. To encourage users to become committed to self-reflection and journal practices – amplifying their daily routine with appropriate lighting and fostering improvements in mood.

3. To provide a low-demand and open source computer architecture for IoT devices, which is sensitive to users affect and offers multimodal human computer interaction.

Researchers within MHCI and affective computing have focused on the delivering a wide variety of devices and applications such as more usable operating systems [203], driver-less car design [89], healthcare [211], education [118], marketing or advertising research, video games [54], robots [12] and even mirrors [8]. However, as of yet limited research has sought to utilise affective computing for building an ambient RGB LED lamp with open source software and hardware. This is surprising considering much has been established concerning the influence of lighting and colour on users' moods and emotions [9, 64, 85, 98, 116, 223, 226].

1.5 Hypotheses

Specifically, I have formulated two central hypotheses for the project. The first hypothesis centres on quantitative data collection – precisely collecting data on users physiological and thus emotional data rendered in the presence of the Turrellian lamp. In contrast, my second hypothesis focuses on qualitative evaluation and user feedback from an Attrakdif survey versus a Philips Hue smart bulb control lamp:

1. Participants physiological readings will be notably altered by the Turrellian lamp's light changes and move closer to physiological readings coherent with a good mood. Participants will be able to recognise the affective change as a positive shift towards a better mood.

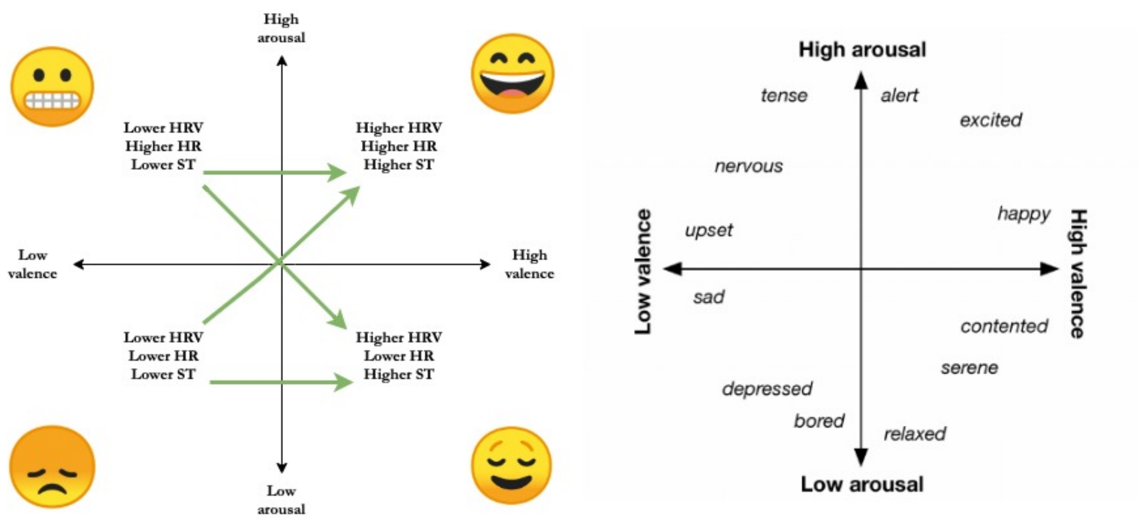


FIGURE 1.4. The left PAD model and green arrows denotes that participants will be pushed by the Turrellian lamp lighting into the right two quadrants - associated with higher heart rate variability, adequate heart rate and higher skin temperatures. The right PAD model denotes the associated emotions with each quadrant [182].

2. The Turrellian lamp will score higher in all UX categories than the rival Phillips Hue smart bulb from feedback collected by the Attrakdif questionnaire.

To improve mood according to Russell's circumplex model - there are broadly two good mood quadrants, which users can cognitively enter. These are the far right two quadrants of the bipolar axes between valence and arousal. Consequently, to improve mood the lamp aims to push users into the two desirable quadrants via light patterns:

1.6 Engineering design process and user experience testing

For this project, I decided to use an engineering design process in which I would develop a 'demo' prototype for pilot experimentation and UX testing with participants because of the the importance of users' personal affective experience with the lamp [172]. I envisaged that collaboration with participants within a pilot study would help provide useful data and research concerning the devices effectiveness and ease of use. Furthermore, it would enable necessary improvements to be made to the interface and Turrellian LED lamp for future research.

I worked with test subjects remotely over Skype - observing their relationship with the device, the usability of the interface and reflection from the Attrakdif questionnaires. Additionally, a Phillips Hue control lamp was employed with test participants for direct comparison to determine the effectiveness of the Turrellian lamp. Testing on the 3-4 August 2020 was conducted to provide feedback and results on the lamp. Due to the constraints of the Coronavirus pandemic

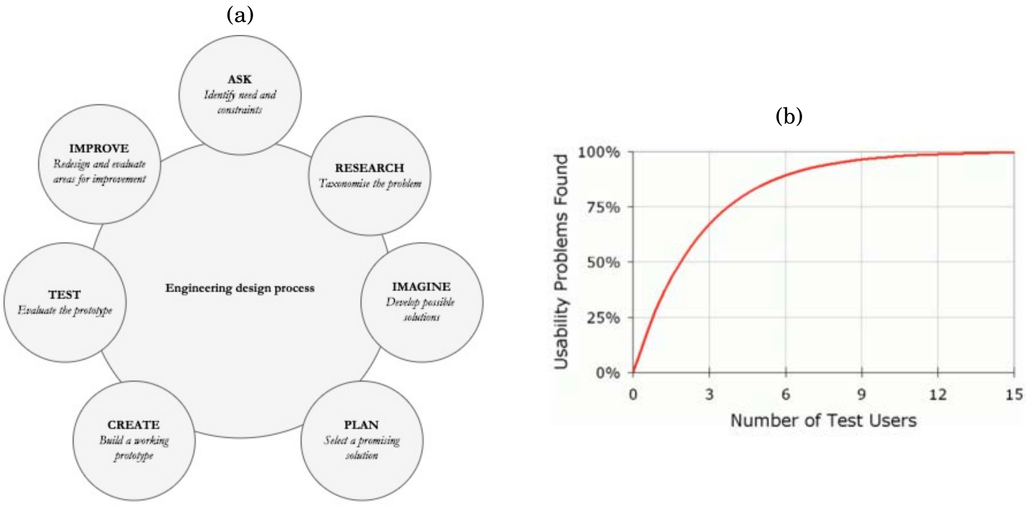


FIGURE 1.5. (a) Diagram of the highly iterative engineering design process used for creating the Turrellian lamp prototype for pilot study [172]. (b) Figure of Nielsen's usability model which finds that 5 users is the absolute number for testing designs for over 85% of UX problems [151].

and consequent issue of using a large number of test subjects safely. Instead of engaging in a high number of test candidates, I adopted Sun Microsystems researcher, Nielsen's model which encourages small pilot studies of about five people for finding most significant design problems [151].

1.6.1 Project aims and objectives

The project core aims are twofold. Firstly, developing, testing and evaluating a prototype product and application which enriches the current IoT smart-lighting market. Secondly, to contribute to burgeoning academic research and discourse within affect sensitive MHCI via providing criticism of current approaches, contributing a novel solution and offering pathways for future research.

In order to achieve these aims the seven objectives of the project are as follows:

1. To situate this study within the field - thorough a definition and critical taxonomy of existing affect sensitive MHCI systems and literature.

2. Critique current MHCI approaches and offer insights from affective science, particularly embodied and scaffolded emotion to improve future MHCI research.

3. Explain the design approach and research foundations of the Turrellian lamp and evaluate competitor devices.

4. Develop a fully functioning prototype – equipped with integrated hardware, physiological sensors, LEDs and a graphical user interface (GUI) controller.

5. User experience test the functioning prototype and collect initial physiological results and UX questionnaire data.

6. Analyse results and offer clear pathways for future research – so as to continue successful development towards affect-sensitive multimodal computer devices.

7. To integrate multiple learning concepts studied within the MSc - web development, C, Java, version control, academic research and computer architecture design into a commercially viable prototype.

Chapter 2

Affect-sensitive MHCI

This chapter situates the proposed Turrellian lamp within the existing MHCI academic literature. In this chapter, I firstly clearly define affect-sensitive MHCI and its specific position within the broader research area of affective computing. Afterwards, I secondly contextualise with a taxonomy of the modalities and various approaches of prominent MHCI researchers. Lastly, I thirdly critically evaluate the differing approaches with respect to developing the Turrellian LED's affect sensitive system architecture.

Rather than providing an exhaustive literature review of all research regarding affective computing – I focus on literature concerning automatic and multimodal analysis of spontaneous affective behaviour. Indeed, this specific multimodal literature is most pertinent for developing devices and systems such as the Turrellian lamp. However, for readers interested in more exhaustive surveys of affective computing, please refer to: [77], [159], [187] and [214].

2.1 Definition

Affective computing is the study and development of systems and devices that can recognise, interpret, process and simulate human affects [167, 168]. Originating with philosophical enquiries of the mind, this modern branch of computer science was defined within Picard's 1995 paper [167]. However, the focus of this research paper is affect-sensitive MHCI – a smaller subset of affective computing.

The term affect-sensitive MHCI originated more recently under a paper written by prominent researchers Pantic and Rothkrantz in 2000 [158, 159]. MHCI focuses on next-generation human computer interaction (HCI) designs, which are capable of recognising users affective state – to become more human-like, usable and effective [158, 203]. Therefore, affect-sensitive MHCI differs

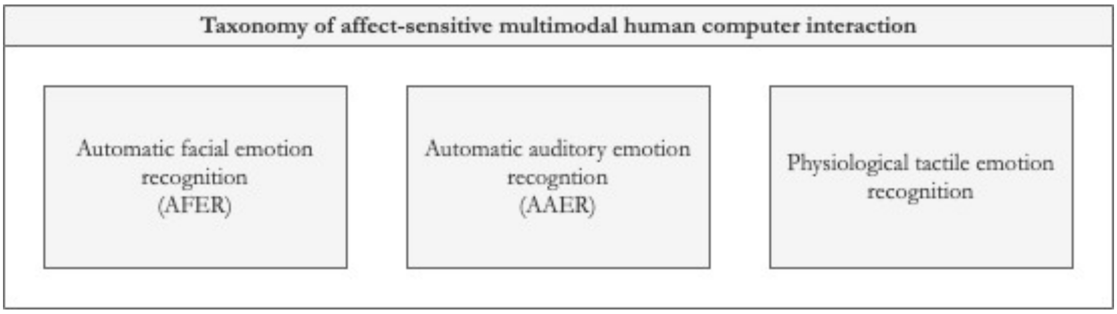


FIGURE 2.1. Taxonomy of the three core domains of MHCI.

from broader affective computing because it is specifically focused on interpreting and processing the emotional state of users to thus improve man-machine interaction [158].

To ensure systems are multimodal, affect-sensitive MHCI designs will monitor multiple non-verbal modalities [158, 159]. For instance, facial expressions, body movements, vocal and physiological reactions to automatically determine the affective state of the user. Certainly, this ability for computers to convincingly respond to their users current emotion - neatly replicates a cornerstone of human-to-human communication [160].

Indeed, in face-to-face communication and interaction human beings socially process affective social signals with little conscious effort [158, 159, 203]. Affect-sensitive MHCI computer designs thus envisage understanding their users affective state in a similarly automatic way [159]. With this definition of MHCI - now I look to address MHCI in far greater depth and literature relevant to the MHCI system of the Turrellian lamp.

2.2 Taxonomy of approaches and significance of field

As alluded to in the chapter introduction, there has been tremendous divergence in the modalities and methodologies employed by MHCI researchers designing affect-sensitive computer systems [159]. Consequently, the three core human interactive modalities (sight, sound and touch) and non-verbal interactive signals (facial expressions, vocal expressions, body gestures and physiological reactions) have not been researched equally mainly due to dislike of invasive physiological sensors and preference for non-invasive technology.

Currently most MHCI research has been preferentially invested into facial expression recognition and auditory speech analysis [77, 159]. These modalities are logically most desirable due to their non-invasive nature. Indeed, a non-invasive camera or microphone can succinctly automatically document users vocal or facial changes and automatically deduce the underlying changes in a user's affective state [159].

Additionally, the two modalities of facial and vocal expression most neatly mimic natural forms of human social and emotional communication, which depends on auditory and visual facial

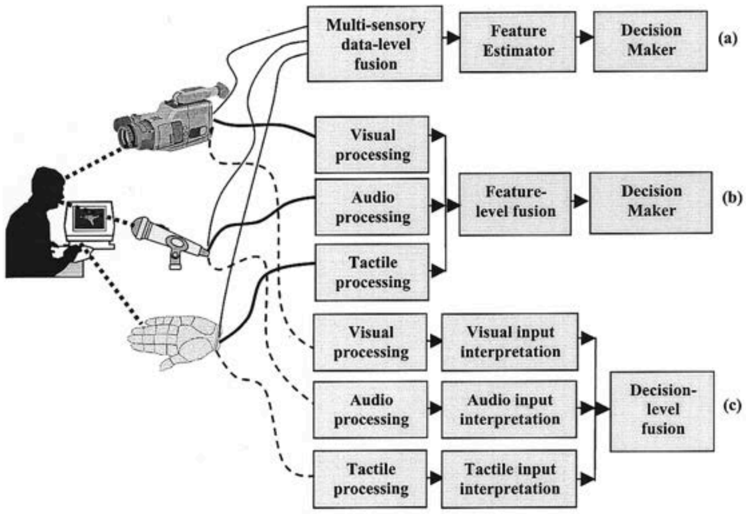


FIGURE 2.2. Fusion of an ideal MHCI architecture taken from Pantic et al. [159]. (a) Data level fusion of raw sensory data. (b) Feature level fusion combines features from individual modalities. (c) Decision level fusion combines data from different modalities at the end of analysis.

signals and channels [159]. For example, we view mouth expressions to interpret if another party is smiling denoting happiness or the sound of guttural sobbing will usually preclude another party's sadness [159].

In contrast, physiological reactions and bodily gestures require the use of intimate physical sensors for tactile processing of users changes in affective state [96, 119]. Often experiment participants have labelled these physical sensors as uncomfortable and mildly irritating [96, 119] resulting in less preference from MHCI researchers for physiological based architectures.

Despite the three different modalities used by MHCI, there is broad consensus amongst MHCI researchers that a fusion of the three core modalities (sight, sound and touch) will lead to the most sensitive and functional MHCI architecture [158, 160]. Indeed, an architecture which utilises and processes all three modalities automatically – will have the most comprehensive pool of data concerning its user's current affective state.

Providing machines with emotional intelligence will improve many existing computer systems, devices and architectures. Despite this, I accept that some machines are still useful serving as rigid tools [168]. However, there are many cases were computers monitoring for emotional state could be very useful - for example, a device which monitors vehicle drivers for inattention or tiredness. Furthermore, initial research finds that affect-sensitive machines have been found to be more natural [144] and trustworthy [16], which reduces user frustration, improves productivity and overall quality of life. Indeed, affect-sensitive MHCI computer designs already have a wide variety of beneficial applications in multiple fields as noted below:

- Elderly care - to provide 24 hour support to help pre-existing nurses and monitor care home occupants physical and emotional needs to raise their quality of life - this is especially important within ageing developed populations.

- Healthcare - to improve healthcare services by assisting and monitoring patients emotional and physical needs. Not only this, but affect-sensitive MHCI devices can assist and aid people with autism.

- Marketing and advertising research (e.g. Real Eyes and Landsec) - to determine if the the marketing was offensive or successful.

- Lie detector for security (e.g. Neurodata lab) - to help with legal cases and security.

- Monitoring for inattention (e.g. Affectiva) - to help prevent accidents caused by inattention particularly during driving.

- Better understand ourselves - research into affect-sensitive MHCI has greatly improved our understanding of emotion and human-focused emotional research.

- Reduce user frustration - to help improve operating systems to make computers more accessible and easier to use.

- Video games - to improve video games to make them more arousing and adaptable for example, adjusting difficulty levels based on frustration.

- Education - to ensure students are in the optimal emotional learning state - this can enable teachers to devise specific lesson plans and better support students psychological health.

Certainly, automatic MHCI designs unequivocally offer much application across a variety of different fields. In much the same way, the domain of this thesis - the Turrellian lamp will utilise an MHCI architecture to improve users quality of life through automatically adjusting coloured lighting and serve as a viable product for pilot studies like commercially available MHCI systems. Additionally, the lamp can be used across multiple environments - including care homes, retail and education to help improve ambience and mood. Furthermore, the findings from this open source research can be extended to support other MHCI computer architectures and designs. Now, I will describe the latest research within the three dominant modalities: automatic facial emotion recognition (AFER), automatic auditory expression recognition (AAER) and lastly, physiological (tactile) approaches - from describing each in turn, I will synthesise the approaches with the Turrellian lamp architecture.

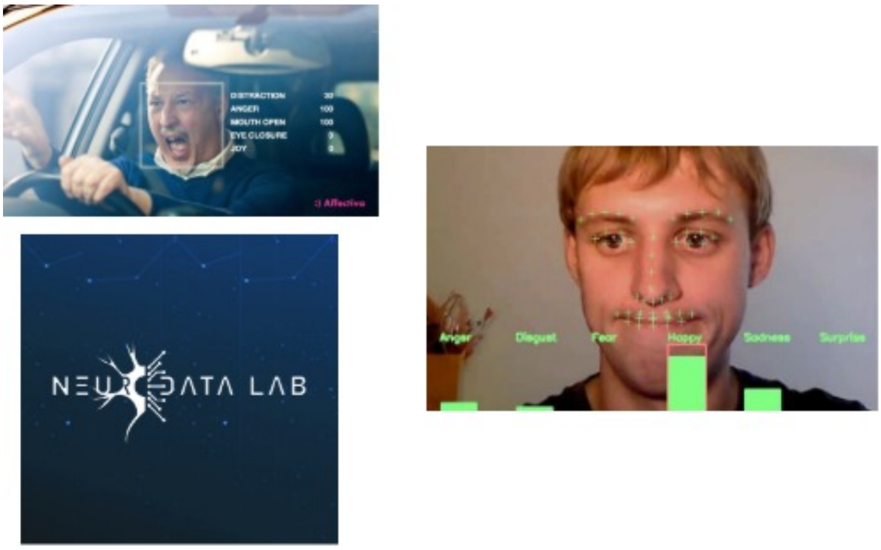


FIGURE 2.3. Firms involved in MHCI from left - Affectiva (left above), Neurodata lab (left below) and Real Eyes (right).

2.3 Automatic facial emotion recognition (AFER)

Utilising facial recognition for automatic recognition of emotion (AFER) has become the most prominent methodology for designing affect-sensitive computer systems and architectures [158–160]. However, the Turrellian lamp will not use AFER and support a camera within its system architecture because of two core reasons - (1) AFER architectures have very high entry costs and (2) AFER methodologies involve immense sophistication. Consequently, for the Turrellian lamp this is highly impractical within the given time-frame and without a team of researchers. Nonetheless, to date, there have currently been numerous academic papers and start-up companies using AFER methodologies. Additionally, as a part of this project it is worth discussing AFER approaches because my project seeks to thoroughly taxonomise MHCI literature and future evolution's of the Turrellian lamp may utilise AFER approaches.

Historically, facial expression analysis to determine emotion was originally professed in 1862 by French researcher Duchenne who focused on the elector-simulation of individual facial muscles as responsible to produce facial expressions [46]. This methodology for determining emotion via facial expression, was further enshrined by the tremendously influential work of Darwin and his book entitled, *The Expression of Emotions in Man and Animals* [38]. Darwin's work comprehensively accounts variation in facial expression and emotion [45].

More recently, this methodology centred on facial expression has been further extended by the prodigious work of psychologist Paul Ekman. Ekman's research boldly suggested that the six basic emotions namely anger, fear, disgust, happiness, and surprise are universally transmitted through prototypical facial expressions [43, 44]. Furthermore, utilising the groundwork of anatomist

Hjorstjo, psychologists Ekman and Friesen produced the Facial Action Coding System (FACS) to codify and taxonomize facial expressions into 32 Action Units (AUs) and 14 additional Action Descriptors (ADs) [32, 47].

Today, it is widely accepted that facial expressions serve as an essential nonverbal means for human beings to communicate emotions [159]. Consequently, several AFER approaches have been developed by MHCI researchers designing affect-sensitive computer systems through visually measuring users' facial expressions [235]. Firstly, the message judgement approach, which aims to directly determine the meaning conveyed by a facial display such as being happy, angry or sad [131]. Whilst secondly, the sign judgement approach, which in contrast aims to specifically study the physical signal used to transmit the message instead – for instance, raised cheeks, nose wrinkles or jaw drop [131, 231].

Both approaches are based off Ekman's original psychological research [47]. Message judgement computer vision systems categorise facial expressions into the six basic emotion categories [208, 231]. Conversely, sign judgement computer systems most commonly utilise Ekman's latest edition of FACS [131]. Both models are incredibly different and offer a range of advantages and disadvantages. Sign judgement systems offer a more accurate system for MHCI researchers because they are more comprehensive and objective – every facial expression is comprehensively described as a unique combination of AUs and ADs [131].

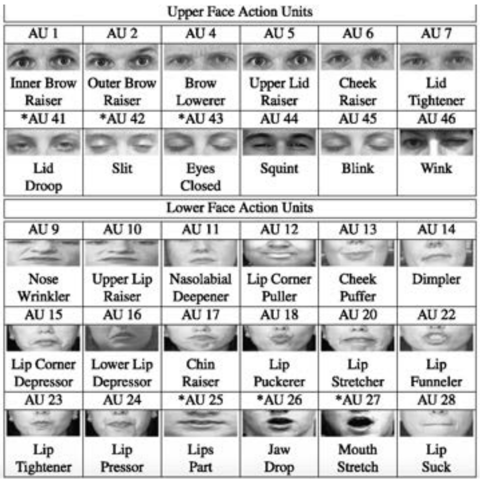
In contrast, message judgement approaches do not document all facial expressions and assume many to one correspondence, which directly contends with multiple studies from affective science [208]. Despite this large shortcoming, MHCI researchers have interestingly preferred the less-specific message judgement approach [131]. This is because a major impediment of sign judgement AFER is that it is far too exhaustive for most computer systems. Indeed, it takes several hundred hours of programming to become competent at FACS and sign judgement analysis and each minute of footage takes roughly one hour to score for all available AUs and ADs – making it utterly impractical for current automatic systems [131].

Due to difficulty, most MHCI researchers studying AFER have focused on detecting the 'basic' six universal emotions. However some MHCI AFER research has made tentative efforts to determine non-basic affective states, including fatigue [82], pain [120], agreeing, concentrating, interest, frustration [90], thinking and uncertainty [48]. Indeed, these studies represent a growing trend towards developing systems which offer automatic analysis of spontaneous facial expression data.

Several studies have focused on automatic recognition of AUs rather than emotions from spontaneous facial displays [10, 33]. With the expectation to improve and enhance computer vision processes before developing a fully viable AFER computer system or device. However, the conceptual framework followed by most AFER studies includes – facial registration, representations, dimensionality reduction and lastly recognition [131]. Overall, MHCI AFER performance has improved marked - recent studies can even provide the intensity of the displayed emotion

(a)

(b)



Upper Face Action Units					
AU 1	AU 2	AU 4	AU 5	AU 6	AU 7
Inner Brow Raiser	Outer Brow Raiser	Brow Lowerer	Upper Lid Raiser	Cheek Raiser	Lid Tightener
*AU 41	*AU 42	*AU 43	AU 44	AU 45	AU 46
Lid Droop	Slit	Eyes Closed	Squint	Blink	Wink
Lower Face Action Units					
AU 9	AU 10	AU 11	AU 12	AU 13	AU 14
Nose Wrinkler	Upper Lip Raiser	Nasolabial Deepener	Lip Corner Puller	Cheek Puffer	Dimpler
AU 15	AU 16	AU 17	AU 18	AU 20	AU 22
Lip Corner Depressor	Lower Lip Depressor	Chin Raiser	Lip Puckerer	Lip Stretcher	Lip Funneler
AU 23	AU 24	*AU 25	*AU 26	*AU 27	AU 28
Lip Tightener	Lip Pressor	Lips Part	Jaw Drop	Mouth Stretch	Lip Suck

FIGURE 2.4. (a) Upper and lower AU facial recognition of two expressions taken from Martinez et al. [131]. (b) Systematic table of FACS AU recognition system taken from Tian et al. [214].

and corresponding facial action [131, 189]. Several studies even better deal with spontaneous affect by recognising combinations of AUs rather than a singular AU in isolation [128]. Indeed, spontaneously displayed AUs rarely appear in isolation [189].

Most MHCI AFER techniques are reliant on machine learning techniques [159, 189]. As any machine learning application, the performance of an affect analyser is contingent on the quality and quantity of the training data coupled with the machine learning model [155]. For MHCI AFER systems, labelling data is a tremendously challenging process – indeed perceiving an emotion is quite subjective, therefore multiple annotators are regularly used [139]. However, this presents the challenge of combing multiple annotations by different annotators [139]. This has resulted in the emergence of another academic field focused on improving methodologies for AU annotation. For example, Zhang et al. have developed the most advanced interactive AU labelling system – focused on minimising collaborative human error [232].

Statistical modelling of annotated AU data is the next step. Most studies have used generic models such as support vector machine (SVM) modelling. However recent studies have aimed to tailor specific statistical models for affect recognition [189]. These specific models have focused on solving many issues faced during AFER - in particular, temporal variation of emotions, personalising affective displays, face configuration difficulties and correlated affective displays [189]. Indeed, the table below captures the recognition performance of some AFER systems.

Returning to the domain of this project, the Turrellian lamp - from the above overview it is quite clear to see that current AFER techniques like many computer vision problems suffer from being incredibly analytical, mathematical and computationally intensive. Indeed, each of the processes, outlined above, involves a multitude of complex and mathematical image-processing solutions and lastly a robust annotation process involving several experienced FACS programmers. Therefore, AFER approaches are certainly not currently suitable for the Turrellian lamp project.

Considering my original arguments, the high costs of entry include that an AFER system relies heavily on an expensive camera for footage, large pool of data for machine learning - which would be financially expensive to pay for public access from existing databases and suitable training time to become competent at labelling AU data for the Turrrellian lamp architecture. Equally, the small microcontrollers for the Turrellian lamp will not be able to process all the computer vision data locally.

Additionally, MHCI AFER researcher's insistence on utilising different statistical model's and divergent recognition rates – makes it very hard to determine if the AFER system is indeed usable and effective in real world scenarios. Naturalistic data or a homogenised feedback mechanism between AFER researchers – would be a far more practical means of determining the effectiveness of each AFER system for the Turrellian lamp.

Evaluation between AFER research is very difficult to achieve because most AFER systems have been developed utilising completely different posed data sets. Making cross comparison difficult - solutions suitable for posed and controlled laboratory settings are often impractical for everyday life [189]. Consequently, this is not suitable for the Turrellian lamp, which is designed to operate in everyday settings and environments.

Although more development is needed from MHCI researchers to ensure the Turrellian lamp utilises a realistic facial expression analyser which works within a normal and unrestricted interaction environment. As the above table shows, the recognition rates and performance of AFER has been high through MHCI researchers utilising a combination of deep and machine learning techniques - therefore in future the Turrellian lamp could certainly consider AFER approaches - once there are lower costs of entry and the methodologies becomes less sophisticated.

Input	*Performance*	*Reference*
Static	59.2% sparse representation classifier	[73]
	62% SVM with Gabor wavelet features	[233]
	61.2% sparse representation classifier with LBP from 3 orthogonal planes	[234]
	70.12% collaborative expression representation	[117]
Sequence	63.4% deep learning of deformable facial action parts	[123]
	70.2% joint fine-turning in deep neural networks	[87]
	69.9% AU-aware deep neural networks	[121]
	75.9% AU-inspired deep networks	[122]
	77.9% deeper CNN	[142]
	78.61% CNN and LSTM with spatio-temporal representation	[94]

Table 2.1: AFER system recognition performance adapted from research by Ko [100].

The next section of the literature review will turn to MHCI research conducted within auditory emotion recognition (AAER) and if the Turrellian lamp should consider a microphone within its system architecture.

2.4 Automatic auditory emotion recognition (AAER)

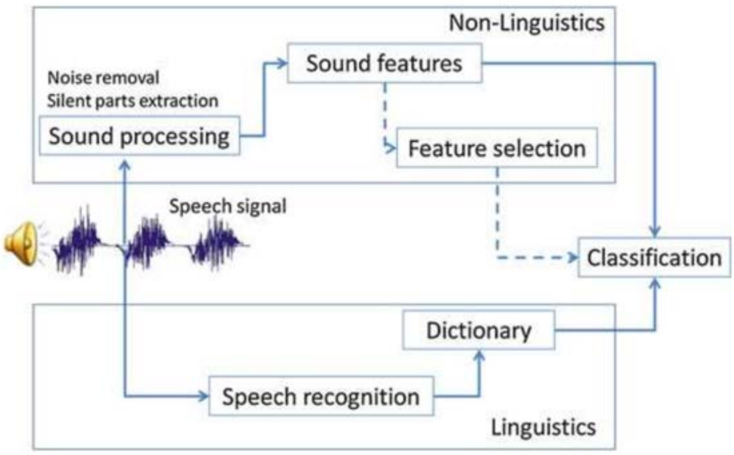
Since the 1950s much research has been conducted into speech recognition [48]. Consequently, there has been significant development in speech recognition i.e. successfully converting speech into a sequence of words – comprehensible for machine-based parsing [4]. The Turrellian lamp will not utilise a microphone within its system architecture because AAER is reliant on elaborate machine learning based methodologies and auditory databases are expensive to publicly access. Nonetheless, like AFER, it is still worthwhile for this thesis to critique AAER approaches because this project seeks to consider MHCI literature and future evolution's of the Turrellian lamp may utilise AAER approaches.

Speech is a key expressive modality in human-to-human communication [159]. Affective information is typically delivered in two forms – through explicit linguistic message and implicit message that reflects the tone of the message communicated. Notably, affective scientists have yet to reliably deduce an optimal set of vocal cues coherent with specific emotion states or Ekman's six universal emotional categories - these vary for each person, dialect and language [48].

In contrast human listeners are very adept at decoding emotional state from vocal expression and even non-linguistic vocalisations such as laughs, cries, sighs and yawns [88, 158, 183]. Accordingly, MHCI researcher Cowie et al. has tried to provide essential qualitative acoustic variations for certain emotions within the English language [36].

The linguistic content of speech carries emotional information. Some can be translated into specific emotional subsets utilising an appropriate dictionary or lexical parser [36]. However, a sizable part of the affective information lies in the language dependent cultural and situational

(a)



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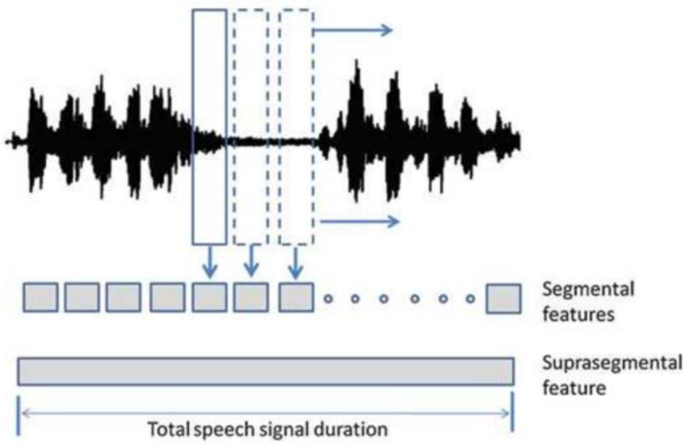


FIGURE 2.5. (a) Overall processing pipeline. (b) Segmental and suprasegmental extraction features. Both figures taken from Anagnostopoulos et al. [4].

context [4]. For example, British English culture is certainly steeped in higher amounts of sarcasm versus others [27].

Sensitivity to situational and cultural context is certainly very challenging to successfully achieve. Nonetheless, some researchers have had success detecting specific emotional states whilst utilising a vocal application. For example, Kwon et al. focused on detecting stress [110] and Ang et al. tried to effectively detect user's verbal annoyance and frustration [5]. MHCI researchers' efforts have even expanded to automatic recognition of non-verbal vocalisations such as laughter or cries. In terms of data collection, there are many naturalistic settings to collect good audio data for experimentation – call centres and dialogue systems have both been effectively used. Typically, AAER MHCI researchers and computer systems follow a basic processing pipeline divided into two categories: non-linguistic and linguistic analysis followed by eventual emotion classification [4].

Affective science has yet to categorise all non-linguistic vocalisations into discrete emotional states [36, 158]. Nonetheless, many human vocalisations are consistent with specific emotional categories [36]. For example, laughter elicits amusement or nervousness conversely a yawn elicits boredom or tiredness [158]. Consequently, AAER MHCI researchers have made solid strides towards automatically classifying non-linguistic expressions such as laughter [163], cries [157], emotional outbursts [195] and even coughs [133].

Linguistic information schemas that identify specific words or phrases which can be correlated to a specific emotional state [4]. Additionally, an effective and updated dictionary is crucial for the successful implementation of linguistics in emotion recognition [4]. Analysis from linguistics teaches the importance of prosodic features such as repetition and reformations in dialogue [11, 198]. For instance, repetition of the same phraseology may signify users intensifying anger or frustration [11, 199]. Furthermore, part-of-speech analysis finds that expressive nouns and adjectives are especially useful for decoding users affective state [4].

Based off these linguistic insights, AAER classification of emotional states has improved particularly in studies utilising salient emotion categories [4]. Rather than classification into specific emotions, AAER MHCI researchers have used non-specific categories such as: negative, neutral and non-negative. Under this renewed categorisation, recognition rates have improved markedly [115]. Semantic labels have been introduced to develop recognisable word sequences for affective speech [4]. In particular, Wu and Liang have used this as the basis for research with acoustic-prosodic information with some success for AAER affective recognition [225].

Some MHCI AAER researchers have established a hybrid of classification machine learning algorithms to deduce affective state [4]. This of course adds tremendous complexity and is highly computationally taxing. However, MHCI researchers have shown improvement in affective recognition, for instance Schuller et al. improved recognition by 8 percent utilising GMMs and SVMs [197]. Recently, there has been growth in the number of commercial emotional speech databases – based off the progress of MHCI datasets and systems research. Most of the developed emotional speech databases are not available for public use [4]. Consequently, there are little feedback systems or benchmarks for researchers to collaboratively improve. Additionally, due to legal and ethical issues, most of the databases use professional actors to test the effectiveness of the database [4].

Returning to the scope of the project, the Turrellian lamp system architecture will not utilise AAER methodologies - yet again AAER utilises many machine learning techniques to provide emotion recognition, which are too computationally intensive for the Turrellian lamp micro-controllers. Additionally, the high classification rates of AAER databases have been achieved through utilising actors and consequently not spontaneous speech. The classification range of 50 to above 90 percent for specific emotional subsets is obviously promising – however, for the most

Classifier	*Performance*	*Reference*
SVMs	87.5%-90% in Berlin EMO database	[196]
	88.15% for 6 emotions	[221]
	70.3% for 7 emotions	[196]
	78.16% for 4 emotions	[225]
GMMs	90% for 3 classes	[149]
	86% for Chinese LDC	[236]
	72.61% for 4 emotions with 2 speakers	[225]
	70.3% for 5 emotions	[161]
HMMs	89% in Berlin EMO database	[228]
	87% in 5 emotions	[230]
ANNs	83.2% in Berlin EMO database	[75]
	71.87% in 4 emotions	[225]
	65.37% in 6 emotions	[143]
C4.5	85.4% in emotional prosody transcripts	[101]
	61.5% in Berlin EMO database	[196]
RF	80.6% in 3 emotions	[180]
	77.2% in Berlin EMO database	[75]
k-NN	72.2% in 5 emotions	[161]
	61.83% in 6 emotions	[143]

Table 2.2: AAER system recognition performance adapted from research by Anagnostopoulos et al. [4].

part, the restrictions on publicly accessing the computer systems and underlying databases for constructing the Turrellian lamp system architecture is immensely frustrating.

Due to the differing experimental conditions – it is hard to achieve with certainty, which AAER system developed by researchers was independently most successful for natural environmental conditions and apply their methodology to the Turrellian lamp. Furthermore, this is detrimental to future MHCI research because it prevents the ability for effective academic feedback loops and benchmarks, which will improve overall AAER research. Consequently, it is too difficult to directly apply many AAER studies to developing a spontaneous multimodal affect-sensitive computer architecture such as the Turrellian lamp within the given time-frame of the project. However, the next section will discuss physiological (tactile) MHCI approaches, which were much easier to integrate into the Turrellian lamp system architecture than AFER and AAER.

2.5 Physiological tactile emotion recognition

Physiological signals refer to any data that is collected from the physical human body and its tactile systems [206]. The signal signifies the underlying response when a human body is subjected to stimuli – physiological metrics are collected from the central and autonomic nervous system (CNS and ANS) [206]. The Turrellian lamp will look to utilise physiological metrics because these signals occur unconsciously and thus offer an unbiased reflection of individuals affective state [158]. Additionally, physiological signals are both detectable and inevitable because sympathetic nerves of the ANS get activated when a person is positively or negatively stimulated [207]. For the Turrellian lamp, physiological signals have been crucial for placing participants on Russell's circumplex model [182].

Before explaining how the Turrellian lamp will utilise physiological metrics within its system architecture. Initially, it is important to discuss critique and evaluate the variety of physiological methodologies undertaken by MHCI researchers for emotion recognition. Numerous physiological systems have been researched for coherently determining affective state, including: the cardiovascular system, electrodermal activity, respiratory system, muscular system, physical movement and brain activity. Studies utilising all of these physiological systems have demonstrated recognition ability for both discrete emotions and for determining negative valence or arousal [207]. Yet in line with the embodied emotion tradition, Russell's circumplex model of valence and arousal has been largely preferred for most MHCI physiological studies [182, 207].

Physiological studies conducted by MHCI researchers typically involve a four-step process: (a) pre-processing the emotion elicitation stimuli, (b) feature extraction (c) feature reduction and lastly, (d) emotion classification.

Raw physiological data often suffers from contamination with external influences. Consequently low-pass filters are used to smooth the raw signals before processing. For example, Kim et al. segmented physiological signals into samples of 160s and filtered each signal for the part least prone to movement artefacts [96]. In contrast, Mandryk et al. developed a fuzzy normalisation process producing a percentile variable between 0 and 100 for each physiological variable [129].

Following pre-processing, statistical and featural information is extracted concerning the physiological signal. This statistical information can then be used for emotional content. Single physiological signals are rich in feature specific information and can thus provide many affect-relevant features. For example, 110 features were extracted by MHCI researchers utilising 4 physiological signals, namely, ECG, EMG, skin conductance and respiratory signal [96].

MHCI researchers have used multiple different mathematical models and methods for computing feature extraction. For example, Haag et al. computed the running mean and standard deviation of multiple physiological signals, namely ECG, BVP, EMG, SCG and respiration to help deduce tonic and phasic components regarding each analysed signal [62, 81]. Indeed, for the Turrellian lamp these mathematical computations such as running mean and standard deviation are much less computationally intensive to compute utilising micro-controllers.

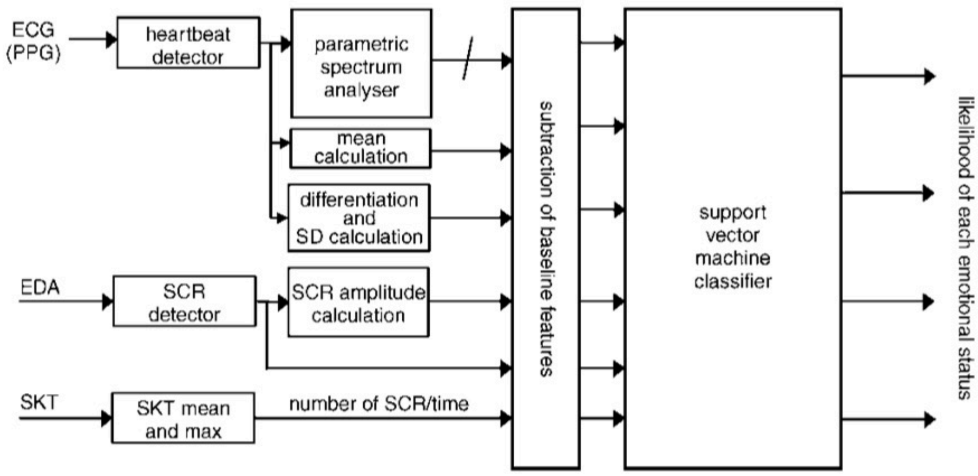


FIGURE 2.6. Developmental physiological MHCI architecture utilising skin temperature, electrodermal activity and skin conductance response taken from Kim et al. [96].

Some MHCI researchers have employed feature reduction to remove any physiological signals that are not ideally correlated with the emotion profile. Such uncorrelated features typically negatively impact the reliable performance of affective classifiers. After extraction – some MHCI researchers have trained machine learning classifiers to determine emotional states utilising the features presented. A wide variety of different algorithms have been successfully employed [81]. An overview of classification rates by different systems is noted in the table below. Successful classification rates range from 60 to 95 percent - with a sizable proportion over 90 percent.

Machine learning techniques are once again often utilised in the classification process for physiological affective MHCI techniques. However, in comparison to the earlier modalities of AAER and AFER for the Turrellian lamp physiological (tactile) affective signals perhaps offer the most straightforward opportunity for determining users affective state. Indeed, there are three clear correlations, which can be drawn from physiological-affective MHCI research, which are utilised for the basis of designing the affect-sensitive Turrellian lamp:

a. HRV increases with positive emotion and arousal

b. Heart rate increases with high arousal

c. Skin temperature increases with positive emotion

These correlations are incredibly useful for the Turrellian lamp determining participants current affective state within Russell's PAD model, which is discussed in chapter 3. Indeed the Turrellian lamp from physiological sensors can quickly determine participants arousal and valence levels.

Biosignals	*Performance*	*References*
Electrocardiogram, skin temperature, electrodermal, skin conductance and respiration	61.4-92% for up to 7 emotions with SVM	[96, 127] [239] [238]
Skin conductance, heart rate and electromyogram	83-66% for valence and arousal with HMM	[107]
Electromyogram, electrocardiogram, skin conductance and respiration	95-81% for up to 9 emotions with LDA	[70, 95] [127, 171]
Electrocardiogram, electromyogram, GSR electrodermal activity, respiration pulse, blood volume and heart rate	91-76% for up to 9 emotions with K nearest neighbour	[60, 176] [179] [147]
Electromyogram, electrocardiogram electrodermal activity and respiration	63% for 2 emotions with random forest	[179]
Electrocardiogram, electromyogram, GSR electrodermal activity, respiration pulse, blood volume and heart rate	91-63% for up to 6 emotions with neural network	[29] [62]

Table 2.3: Physiological signals machine learning classification performance adapted from research by Jerritta et al. [81].

Furthermore, unlike machine learning methodologies, these variables can be easily calculated by the microcontrollers within the Turrellian lamp system architecture. Although I broadly accept machine learning techniques may perhaps offer the Turrellian lamp a more robust determination of participants current affective state - given the time-frame of the project, microcontroller hardware and lack of accessible machine learning training data - calculating running physiological variables was preferable for the Turrellian lamp system architecture.

One potential criticism of the Turrellian lamp utilising physiological variables to calculate participants current affective state is that MHCI study participants have found the physiological sensors uncomfortable and even irritating [158]. However, potentially this criticism is unable to foresee the continued exponential growth of Moore's Law [126, 192] and advent of more non-intrusive, comfortable sensors and wearables for accurate physiological data. Indeed, the demand for smart, ergonomic and non-intrusive wearable body sensors has grown in prominence.

From mobile devices [28], watches [97], smart running trainers [74], glasses [83], to even jewellery [86] – often-AI driven "smart" physiological sensors designed to collect data on sleep, heart-rate, steps, respiration, bodily posture and plenty more. User requirements and competitive markets will help to ensure these devices get smarter, less obtrusive and collect better physiological data on their users, which can then subsequently be fed to affect-driven computer devices such as the proposed Turrellian lamp. Having discussed the benefits of a physiological focused affective architecture, notably its more preferable adaptation to the Turrellian lamp system architecture than AAER and AFER approaches. Now, I will turn to the conclusions of this chapter - notably the core criticisms of MHCI in order to satisfy one of this projects aims, which is to provide a critical taxonomy of MHCI systems and research.

2.6 Chapter conclusions – fusion of approaches?

As exposed by the taxonomy and thorough literature review, affect-sensitive MHCI still suffers from some shortcomings. Once these issues are considered – the development of empathetic devices should begin to pervade our everyday lives. Nonetheless, this chapter has situated the Turrellian lamp within MHCI research and expanded on the reasons why the lamp system architecture uses physiological tactile emotion recognition.

Unlike AFER and AAER, as discussed in the previous section, physiological or tactile approaches enable me to infer three basic and testable correlations – which can form the basis of designing an affect-sensitive system for the Turrellian lamp. Furthermore, these correlations do not require highly sophisticated machine learning methodologies, sizable amounts of training data, posed laboratory conditions and are not computationally taxing for the Turrellian lamp micro-controllers - therefore this approach was certainly most logical. Indeed for the pilot testing - the Turrellian lamp's emotion classification does not need to be discrete or as accurate as professional MHCI systems with longer time-frames for development and more researchers.

MHCI has experienced tremendous growth and improvements in recognition via the effective incorporation of computer vision techniques, machine and deep learning. However, this clear advantage is detrimental because very few researches are competent in sophisticated techniques such as machine learning technology and emotion recognition [63, 188]. Indeed, regularly PhD academics with these complex skills are hired commercially by large corporations as a part of a brain drain from academia [63, 188]. Therefore, developmental MHCI remains a niche subset of broader affective computing.

Another difficulty arising from utilising technical and diverse algorithmic techniques has resulted in a lack of appropriate feedback, constructive discussion and effective determination of clear benchmarks between researchers' findings. Thus far MHCI researchers have approached the research area with very different methodologies, laboratory settings, participant numbers and participant demographics – resulting in a lack of standardisation and preventing reliable and concrete conclusions from being inferred between different research. Consequently, this research seeks to use open source methodologies and physiological toolboxes favoured by other MHCI researchers to encourage standardisation and make the Turrellian lamp very accessible for future researchers.

This deliberate approach ensures the development of more accessible MHCI and affective computing. Equally this form of MHCI incorporates the increase in comfortable wearable sensors documenting our physiological modalities. Having covered much MHCI research and its relevance to the Turrellian lamp, in the ensuing chapter I will discuss insights from affective science most pertinent for developing the Turrellian lamp and future affect sensitive multimodal IoT devices. Notably, little academic literature has sought to deliberately synthesise affective science with developing multimodal IoT devices consequently MHCI researchers have often failed to accurately define what an emotion is, why and what their MHCI system is tracking. As explored in the next chapter the Turrellian lamp tracks physiological changes because these are the very emotion itself.

Chapter 3

Affective science

The core ideas and concepts of affective computing and MHCI can be traced back to insights from affective science, neuroscience, psychology and philosophy. As noted in the previous chapter, with the influential psychological-facial research from Ekman [43, 47] – insights from these disparate fields have enabled the development of all affect-sensitive computer systems and devices. Crucially there is currently no scientific consensus defining an emotion. Subsequently in recent years, in particular, the definition of emotions has become vigorously researched and intensely debated [191]. Yet to develop an affect-sensitive computer architecture we firstly need a clear theory and model of emotions - to effectively design a computer system sensitive to emotions [159].

In this chapter, I critically discuss insights from affective science most pertinent for developing the Turrellian lamp system architecture and future affect-sensitive multimodal IoT devices. Notably, little academic literature has sought to deliberately synthesise affective science with developing multimodal IoT devices [7, 114]. Many MHCI researchers have overlooked clearly classifying or defining emotions before designing their computer architecture and system. This oversight has consequently resulted in the design of overly complex systems for affective recognition and a failure to consider the significance or causes of participants modality changes.

In contrast, in this chapter, my research will firstly unify the fragmented discourse of affective science literature by providing a clear definition of emotions as bodily feelings (embodied) or physiological changes - this robust definition will help explain why the Turrellian lamp utilises physiological changes as the dominant channel to analyse the affect of its users [35, 79, 80, 173, 174, 190]. Afterwards, I will briefly outline Russell's circumplex model for emotion [182]. Following this, I will provide scientific evidence for embodied emotion theory and the three physiological variables synthesised within the Turrellian lamp affect sensitive system architecture. Lastly, I will introduce more recent research from affective science, most notably, scaffolded affective theory – which finds that emotions are situated and dependent on the environment - therefore the Turrellian lamp, which changes the environment with conducive coloured lighting should definitely positively influence users current mood [34, 35, 59, 105].

3.1 Emotion as bodily feelings

An important question to ask and attempt to answer is, *"what are emotions?"*. The Turrellian lamp design attempts to understand and influence emotions, so a good understanding of what specifically is an emotion will help explain why the Turrellian lamp utilises physiological changes as the dominant channel to analyse the affect of its users. Indeed, the most significant initial discovery within affective science came from William James – who announced that emotions occur when the perception of an exciting fact causes a bodily change, and "our feelings of the ... [bodily] changes as they occur *is* the emotion" (see figure 3.1a) [78–80]. The same idea occurred to Carl Lange around the same time [112, 113].

The James-Lange theory offered an inversion of common sense with autonomic bodily changes preceding our emotional experiences [173, 174]. Therefore, central to this bodily feeling theory is that the body acts as a sounding board and is fundamentally integral to experiencing the infinite subtleties of the bodily states and changes coherent with emotional changes [78, 175, 190].

A good example of this theory in action includes the common experience of feeling internally pangs and tingles [175]. For example, the common experience of, in pressurised situation (i.e. prior to an exam or rollercoaster), a common perception of a fluttery or churning feeling in the stomach. These sensations are symptomatic of the brain-gut connection and have become colloquially termed as *nervous butterflies* [134]. Furthermore, these feelings are fundamentally caused by the release of adrenaline and cortisol as part of a fight-flight autonomous response [134, 175]. Consequently, blood leaves the stomach to move to the muscles – the heart rate, breathing rate, blood pressure and alertness rises. Emotions are thus contingent on autonomous bodily changes; which individuals perceive as bodily feelings. Indeed, the feeling of the physiological change (ie. the sudden rise in body tension) is the very emotion [134].

In support of this theory, James convincingly asks readers to engage in a thought experiment: to abstract all physical bodily feelings from emotional experience, and once all the bodily feelings are gone, it is apparent there is simply nothing left but "feelingless cognition" [78]. Importantly, Lange's research, primarily focused on blood vessels and capillaries (the vasomotor system) whilst in contrast James' research is highly inclusive of all patterned bodily changes for emotion.

Therefore, MHCI system designers and the Turrellian lamp can measure a vast array of physiological bodily changes to coherently determine the emotion being exhibited by the user. For example, from James' theory bodily changes and feelings in the viscera, facial expressions and social (instrumental) actions can induce emotion [175]. Crucially both James and Lange affirmed that different emotions create different bodily patterns or changes – providing each emotion with unique distinctness [78].

In further support of James' theory - esteemed biologist Darwin observed multiple correlations between the body and emotional states. For example, Darwin's list of identified fear symptoms includes widely opened eyes and mouth, raised eyebrows, dilated nostrils, stiff posture, motionless, a racing heart, increased blood supply to the body, pallor of the skin and more [38]. Crucially, the influential work of Ekman fits very well with the somatic feeling theory as for Levenson, Ekman and Friesen's six universal emotions – each of these emotions correspond to a unique bodily pattern and physiological state [44]. Each emotional state is thus uniquely determinable from physiological sensors for MHCI affect-sensitive computer systems such as the Turrellian lamp.

This section has defined James-Lange emotion theory ie. emotions as bodily feelings and provided initial evidence for the theory. This Jamesian somatic bodily-feeling theory meshes well with the domain of the project, the Turrellian lamp and MHCI systems and devices. This is because the Turrellian lamp will utilise physiological changes as the dominant channel (or modality) to analyse the affect of its users - consequently Jamesian research strongly supports the Turrellian lamp's system design by defining emotions as physiological body changes. Therefore, the Turrellian lamp should track users current emotions accurately and improve their mood via lighting. In the next section, I will now explore the emotion model used by the Turrellian lamp to deduce participants current emotional state and their positive mood changes.

3.2 Russell's circumplex model

The Turrellian lamp utilises Russel's circumplex model (figure 3.1c) to classify experiment participants current emotional state and deduce their subsequent affective changes. Russell's circumplex model utilises two key variables namely, arousal and valence [154, 182]. This model suggests that emotions are distributed in a two-dimensional circular space, containing arousal and valence dimensions.

Unlike discrete and independent classification of emotion favoured by other researchers such as Ekman [44], the circumplex model helps to provide ranges of arousal and valence to determine users emotional state [154, 182]. The corresponding emotion is thus a unique vector represented by degrees of valence and arousal. Equally, each quadrant of the model classifies corresponding specific emotions relating to that quadrant [154].

For the Turrellian lamp, the four quadrant circumplex model (figure 3.1c) will be utilised to classify experiment participants and their subsequent affective changes. Indeed, Seo and colleagues have established the importance of the model for ease of emotion classification for intelligent affect sensitive IoT devices and systems [200]. In particular, affect-triggered physiological

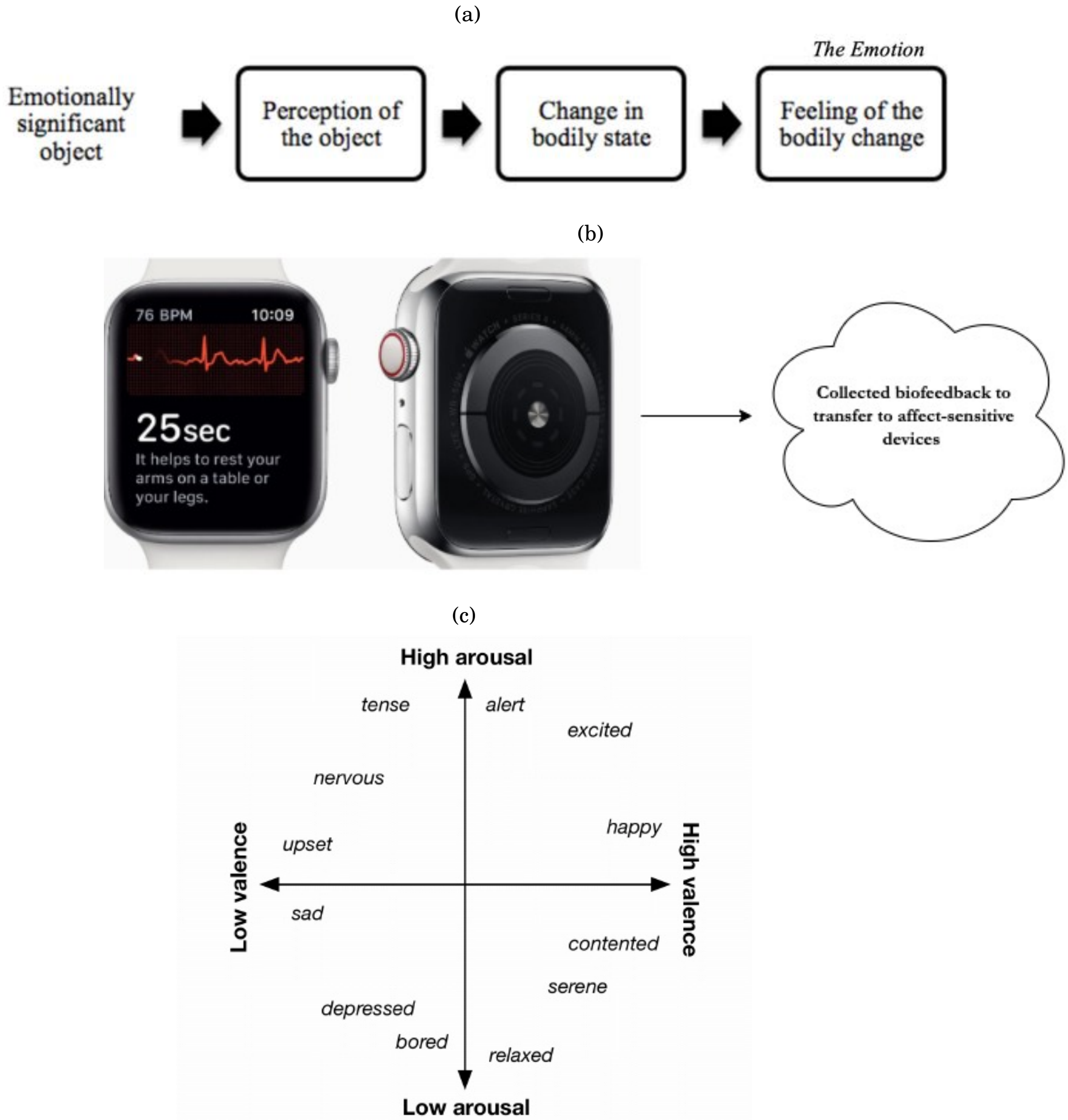


FIGURE 3.1. (a) James-Lange automic bodily feeling theory. (b) Biofeedback data can be provided from modern devices for compatible MHCI affect-sensitive systems. (c) The PAD circumplex model devised by Russell - emotions are distributed in 2-D with valence and arousal [182]

changes are classified incredibly accurately under the model's dimensionality classification [200]. Furthermore, Herbon et al. used the model to classify users experience completing computer tasks with peripheral physiological parameters – they strongly advocate the model for HCI design [65]. As discussed in chapter 4, the majority of affective-science, ambience and colour research, which has shaped and influenced the design of the Turrellian lamp has utilised either Russell's circumplex model or the very similar pleasure-arousal-dominance model (PAD) developed by Russell and Mehbrain [137, 184], which unlike the circumplex model includes a third dimension, namely dominance.

This section has presented the circumplex model, which will be used for the Turrellian lamp - this model holds two clear advantages. Firstly, maintaining consistency with other MHCI researchers who have favoured the circumplex model - enabling the Turrellian lamp to be compared with other MHCI researchers findings. Secondly, unlike discrete classification, the circumplex model easily classifies participants current affective state as a vector within a quadrant and is not too computationally taxing for IoT devices. The next section will now return to James' bodily feeling theory and provide more positive evidence to further support the design of the Turrellian lamp.

3.3 Positive evidence for bodily feeling theory

As noted in the preceding chapters, the Turrellian lamp utilises physiological changes as the dominant channel to analyse the affect of its users. In this chapter, I will discuss positive evidence for physiological changes being the very emotion (bodily feeling theory) and therefore why the Turrellian lamp and MHCI system designs should use bodily sensors within their system architectures to accurately track the emotional state of their users.

Research and evidence for the James-Lange bodily feeling theory has been increasingly successful over time. For example, many neuroimaging study of emotions have found excitation in areas of the brain associated with bodily response [173], meaning that there appears to be a direct mapping between the psychological experience of emotion and physical body morphology. In 2002, a research paper on the autonomic nervous system even concluded that the, “theory was hard to disprove” [53].

Neuroimaging studies concerning more advanced emotions have been antecedently associated with the registration and regulation of bodily response [37] - for instance, Shin et al. demonstrated cingulate and insula activity during guilt episodes [173, 205]. Jealousy is known to cause galvanic skin responses [20] and loneliness is associated with heightened cortisol levels [93, 173]. Aesthetic response (i.e. finding something beautiful rather than neutral) is correlated with activity in the anterior cingulate and orbitorfrontal cortex [91, 173]. Meanwhile moral judgements engage the posterior cingulate and medial frontal cortex [58, 173]. These help to show that bodily changes co-occur with emotional changes - thus the Turrellian lamp should be able to acutely track users current emotional state via tracking their physiological changes.

Studies in which participants were asked to pose with various facial expressions correspondingly led to changes in their respective emotional state [47]. Furthermore, recent findings from Nummenmaa has effectively topographically mapped bodily sensations for differing emotional states [152]. Although this evidence provides solid justification that bodily responses may co-occur with emotion – it does not conclusively prove that bodily responses are necessary for emotions [174]. However, recent insights from working with patients with spinal cord or vagus nerve injuries conclusively prove that introspective feelings of bodily change are necessary for experiencing emotion [31, 69].

Originally, Hohmann found that reducing feedback from the body from 25 individuals suffering with spinal cord injuries reported a significantly diminished emotional response [69]. The reductions in feeling and emotion even became more acute with higher injuries to the spinal cord. It is important to note that individuals with spinal cord injuries still have certain perceptive faculties including changes in throat, facial musculature, vagus nerve and blood stream [69, 173]. Therefore, spinal cord damage does not eliminate emotions because the vagus nerve has been determined as a crucial faculty for feeling the body [174]. Consequently, Bechara et al. found that individuals with pathologies impacting the vagus nerve had corresponding levels of emotional impairment [130].

From all this evidence, it is clear that physiological changes co-occur with emotional changes - thus the Turrellian lamp should be able to acutely track users current emotional state via tracking their physiological changes. Although the Turrellian lamp cannot track highly specific physiological changes outlined in the above research such as brain activity changes due to hardware limitations. However, for the Turrellian lamp I have chosen three common and effective physiological changes to help track the emotional experience of participants and orientate the Turrellian lamp:

1. Heart rate variability (HRV)

2. Heart rate (HR)

3. Skin temperature

In the ensuing sections, I will now define each physiological metric and its significance in relation to the circumplex model - enabling the Turrellian lamp to accurately recognise the current emotion of the user.

3.3.1 Heart rate variability

The first metric the Turrellian lamp will utilise to document the current affective state of its user is heart rate variability (HRV). HRV refers to fluctuations between consecutive heartbeat cycles. It is typically represented by the variation in RR intervals – the intervals composed of two adjacent R wave peaks of the cardiac cycle collected from the electrocardiogram (ECG) data [237]. R is a point corresponding to the peak of the QRS complex of the ECG wave and RR is the interval between successive Rs. Research on HRV has exponentially increased in the last 30 years since it initially attracted interest in the 1960s. Loss of HRV is a precursor of both heart damage and associated with negative emotional psychological conditions [92, 104, 229].

Anatomically the heart is innervated by the sympathetic and vagal nerves – the two branches of the autonomic nervous system (ANS) [84]. Physiological changes are controlled by ANS, which is further divided into sympathetic nervous system with excitatory effect and the parasympathetic nervous system with inhibitory function [237]. Depicted in figure 4.2b, these two systems maintain balance and a low degree of physiological arousal in normal state. When the individual is under physiological or psychological stress the activity of the sympathetic nervous system becomes dominant resulting in physiological arousal to accommodate the increase in pressure [237]. HRV measurements thus reflects this interplay between these two nervous systems and directly reflects the functioning of ANS and the emotional state of the participant [237].

For the Turrellian lamp levels of HRV is crucial to determine how a user is presently feeling and their mood. Indeed, having high HRV is associated with higher emotional well-being [201], lower levels of worry or rumination [156], lower anxiety [26] and being more regulated in emotional responding [6, 132]. Thus, individuals with higher HRV are better at regulating their emotions and have reported higher levels of well-being [132]. Therefore the Turrellian lamp from HRV metrics should be able to determine the mood of its user (see table 3.1 for classification metrics).

To promote the repeat-ability of HRV analysis researchers have disclosed a toolbox to effectively calculate HRV captured in the table below and promote standardised data [13, 219]. Consequently, the Turrellian lamp will use metrics from the toolbox to support standardisation and evaluate results versus the HRV indexes produced from a healthy individual captured in table 3.2.

Slight differences in HRV signal pre-processing and abnormal rhythm during HRV sequence construction will lead to distinct results [132]. Most successful emotion recognition HRV analysis has combined multiple forms of analysis. Indeed, Shi et al investigated that the average heart rate, SDNN, LFn and ratio of LF LF/HF in happiness and found those were higher than those in sadness, while HFn exhibited the opposite result [204]. In much the same way the Turrellian lamp will utilise multiple forms of analysis - including SDNN, RMSSD, SD1 and SD2 readings to calculate the HRV of participants experiencing the lamp (see table 3.1 and 3.2).

HRV in emotion recognition accuracy has improved through utilising non-linear methods, which is highly representative of the non-linear nature of physiological signals [237]. In particular research Guo et al. combined time domain, frequency domain, a Poincaré plot (see figure 3.2a and 3.3a) and a support vector machine (SVM) classifier to discriminate two (negative and positive) and five (sadness, anger, fear, happiness and relaxed) emotional states in 25 healthy participants without psychiatric history, obtaining accuracies of 71.4 and 56.9 percent respectively [61].

HRV Index	*Description*	*Significance*
LF	Low frequency power	Sympathetic activity
HF	High frequency power	Vagal activity
SDNN	Standard deviation of RR intervals	Signifies LF
RMSSD	Squared root mean squared differences in RR intervals	Signifies HF
LF / HF	Ratio of LF to HF power	Reflects balance
SD1	Standard deviation of distance y = -x + 2RR	Fast-beat variability
SD2	Standard deviation of distance y = x	Longer-term variability

Table 3.1: Snapshot of the HRV indexes. SDNN, RMSSD, SD1 and SD2 (figure 4.3a) will collected from participants within the Turrellian lamp pilot studies - definitions adapted from Zhu et al. [237].

Emotion	*SDNN*	*RMSSD*
Calm	64.56	35.43
Fear	86.44	60.96
Happiness	50.30	37.70
Anger	54.14	49.20
Sadness	40.04	40.74

Table 3.2: Data collected for SDNN and RMSSD readings from a healthy individual for emotion classification by Zhu et al. [237].

Following guidance from Guo's experimentation [61] – Goshvarpour et al. used a Poincaré plot to distinguish five emotional states and obtained the best classification rate of 97.45% [56]. Goshvarpour's analysis conclusively shows that typically Poincaré plots with more long ovular plots are coherent with a sinusoidal heart rhythm – resulting in greater HRV and positive emotional cognition (see figure 3.2a) [56]. Furthermore, they found that in a happy state for lagged Poincairé readings - SD1 variables decreased whilst SD2 variables increased (see figures 3.3a and 3.3b). This extremely high accuracy of 97.45% encouraged the use of Poincaré plots to determine the effectiveness of the Turrellian lamp and if users mood improved subject to lighting from the lamp.

Reciprocating these studies, the Turrellian lamp will collect SDNN, RMSSD, Poincare maps (SD1 and SD2) on subjects to conclusively document participants HRV state at the start of experimentation and subsequent HRV changes throughout the duration of experimentation - to determine if participants HRV readings and mood improves because of the Turrellian lamp. This data will not only coordinate the colour and light specifications of the lamp but provide feedback on the effectiveness of the Turrellian lamp at changing participants physiology positively and improving mood.

Discussed in the following section is the next physiological metric the Turrellian lamp system architecture will collect on subjects - heart rate. Although both are influenced by the ANS system (sympathetic and parasympathetic nerves i.e. figure 3.2b) heart rate variability unlike heart rate is the speed of the heartbeat measured by the number of contractions or beats of the heart per minute (bpm) - see figure 3.3c. Heart rate varies significantly depending on the body's physiological needs, particularly the need to respirate and increase oxygen in the bloodstream.

3.3.2 Heart rate

For the Turrellian lamp system architecture, heart rate is a very useful measure for subject's affective state and much like HRV, research concerning heart rate has increased significantly – particularly with the increase in wearable physiological ECG sensors [227]. The American Heart Association considers the normal resting heart rate to occur within 60 to 100 bpm. Bpm figures higher or lower usually signify underlying heart disease or a cardiovascular condition. Heart rate research almost conclusively finds that heart rate analysis serves as a reliable determinant of subject's physiological stimulation and arousal. For instance, for healthy participants, beats per minute (bpm) increases during exercise or intense physical activity - see figure 3.3c.

Heart rate data collected by the Turrellian lamp will be very insightful - bpm has been found to increase during periods of dehydration [186], stress [220], anger, ingestion of stimulant (i.e. caffeine or nicotine) [17], anxiety, panic, excitement and happiness. Therefore, heart rate serves its purpose as a reliable determinant of subject's arousal and stimulation.

Indeed, research by Wang et al. found a strongly positive correlation between subject's heart rate, galvanic skin response (GSR) and pupil size or dilation onset from deliberate stimulation or arousal [222]. Furthermore Yang et al. have utilised data collected from heart rate to reliably determine subjects present mental and cognitive arousal levels [227].

Lastly, a large ranging study by Shapiro and colleagues conclusively found that negative valence and high energy increased heart rate and blood pressure levels [202]. However, they broadly accepted that the association of bpm and mood or emotions varies case by case – due to individuals' habitual behavioural dispositions and coping mechanisms [202].

For the Turrellian lamp subject's bpm will be used to plot and particularly determine the arousal level of participants. Bpm will be a reliable determinant of participants cognitive arousal levels and the associated emotions with the upper quadrants of the circumplex model utilised by Russell et al. (see figure 3.2c) [182]. Now I will turn to the final physiological metric being collected from participants by the Turrellian lamp - skin temperature changes.

3.3.3 Skin temperature

Since the very early work of Darwin and Lange – skin temperature changes have been known to correspond with emotional experiences. Indeed, James noted the role of strong emotional fits such as excitement accompanying temperature rises in the human scalp [78]. Indeed, physiological thermographic regulation is certainly influenced by emotional experience - this data is therefore ideal for the Turrellian lamp to recognise changes in users mood.

Additionally, Darwin noticed the condition of skin changes in strong emotional changes in the form of piloerection (commonly referred to as goosebumps) in both humans and animals [45, 67]. Scientific evidence and self-diagnosis of piloerection has become attributed to intense emotions such as fear, euphoria, arousal and is typically experienced with sudden chills down the spine [224]. Scientists have concluded that it is symptomatic of a "fight or flight" response and the sudden onset of adrenaline [38, 45]. Fight or flight response refers to a discharge of the sympathetic nervous system resulting in a physiological reaction that occurs in response to a perceived threat preparing an animal for fleeing or fighting.

The role of the peripheral circulatory system strongly reflects cognitive emotional conditions, which will be effectively collected by the Turrellian lamp for insights into participants emotional changes. Initial research by Mittleman and Wolff found rapid variations in skin temperature readings during psychoanalytic interviews [141]. A reciprocated study by Newton et al. conclusively determined that negative emotion resulted in a mean fall in participants finger skin temperature [150]. Whilst positive emotions elicited the opposite outcome [150].

Extensive research by McFarland found that during two different musical selections – one evoking calm, positive emotions and the other evoking arousing, negative emotions participants skin temperature changed markedly [136]. Positive emotion and music selection terminated skin temperature decreases and perpetuated skin temperature increases [136]. In contrast, negative emotion and music selection terminated skin temperature increases and perpetuated skin temperature decreases [136].

Lastly advanced thermographic experimentation utilising thermographic cameras by Salzar-Lopez et al. conclusively found skin temperature as a somatic marker of emotion [185]. Skin temperature decreased during negative valence stimuli and increased with positive emotions and arousal - temperature changes were particularly sensitive on the outer extremities such as the nose and fingers [185].

Indeed, as depicted in figure 3.2c the Turrellian lamp will utilise participants skin readings to determine emotional state with lower readings signifying negative emotions and higher readings signifying positive emotional state and arousal. Additionally, data sampled will provide feedback as to the effectiveness of the device in shaping participants physiology and affective state. Having now discussed all physiological data to be collected by the Turrellian lamp, now I will turn to insights from scaffolded affective theory, which suggests that the Turrellian lamp will be very successful at changing participants mood.

3.4 Scaffolded affective theory

Recent insights from affective science holds tremendous promise for MHCI devices such as the Turrellian lamp. Guided by initial research from Sterelny – affective scientists find that human affectivity and cognition is environmentally influenced [34, 210]. Consequently, scaffolded affective theory supports that the Turrellian lamp - manipulating the environment with light and colour should certainly inspire positive improvements in participants mood.

According to this model, organisms carve out environmental niches and tools to which they adapt and increase their chance of survival [34, 210]. For example, computer devices extend our capacities to perform difficult tasks and computations – serving as informational tools. Another example involves the increasing prevalence of portable technologies for listening to music, which people rely on to feel more energetic, enthusiastic, romantic, unwind, relax, create a romantic atmosphere and rekindle past experiences [34].

Researchers have found that music does not only elicit emotion thanks to its temporal character, music helps vent or give voice to emotions, “articulating” them as the music unfolds [40]. In particular, researchers have found a phenomenon of widespread reliance (trust) on technologies for music reproduction for the purpose of emotion regulation [34]. Accordingly the Turrellian lamp will encourage both trust and personalisation amongst users through unfolding coloured lighting – to enhance the affect-sensitivity of the system.

Consider also the role that other everyday items of material culture play in our lives by acting on different aspects or “components” of our affective states [34, 194]. For example, many people wear brightly coloured clothes to contrast with the dullness of rainy days or choose soft items of clothing when they want to feel safe or cosy [34]. Furthermore, there is indeed evidence that colour affects mood [216], and the tactile qualities of furry sweaters contribute to releasing serotonin and dopamine, which lower stress levels [111].

In this sense, material items and computer technologies have tremendous capacity over individuals affective experience of the world through interaction, trust, individualisation, utility and entrenchment [34, 210], even if ordinarily this may be overlooked or taken for granted. In accordance, the Turrellian lamp through the connection of physiological sensing, the tactile projection of appropriate coloured lighting and response to personal sensing through an interface – should satisfy scaffolded theory and improve the mood of users [210].

3.5 Chapter conclusions

This chapter began with the definition of James-Lange emotion theory and its importance to understanding the physiological monitoring of the Turrellian lamp. Other MHCI researchers have detrimentally lacked clarity or conviction in their definition of what they consider an emotion to be and properly utilised insights from affective science resulting in complicated system architectures. Following this, I have highlighted the circumplex model of emotion and its appropriateness for designing affect sensitive MHCI devices and systems as well as its use within the Turrellian lamp system architecture. Then I offered clear evidence of the James-Lange bodily feeling emotion theory, which strongly supports the effectiveness of physiological monitoring of the Turrellian lamp. Additionally, I have covered the significance of insights from physiological markers, namely, HRV, HR (bpm) and skin temperature for driving and enhancing the Turrellian lamp's light sequences as well as providing insights concerning the effectiveness of the lamp - noted by figure 3.2c.

Lastly, I have turned to scaffolded affective theory – which holds crucial insight for the Turrellian lamp. Indeed, trust, individualisation, utility and tactile qualities – enable computer devices and systems to become materially significant to individuals affective experience. Ensuring that the Turrellian lamp and other MHCI devices have the capacity to become more useful and emotionally enhance users experience and cognition. The following chapter will now focus on light, colour and ambience research - particularly on how these environmental factors effect cognition and mood. Therefore, the Turrellian lamp by controlling light, colour and ambience will certainly impact users mood.

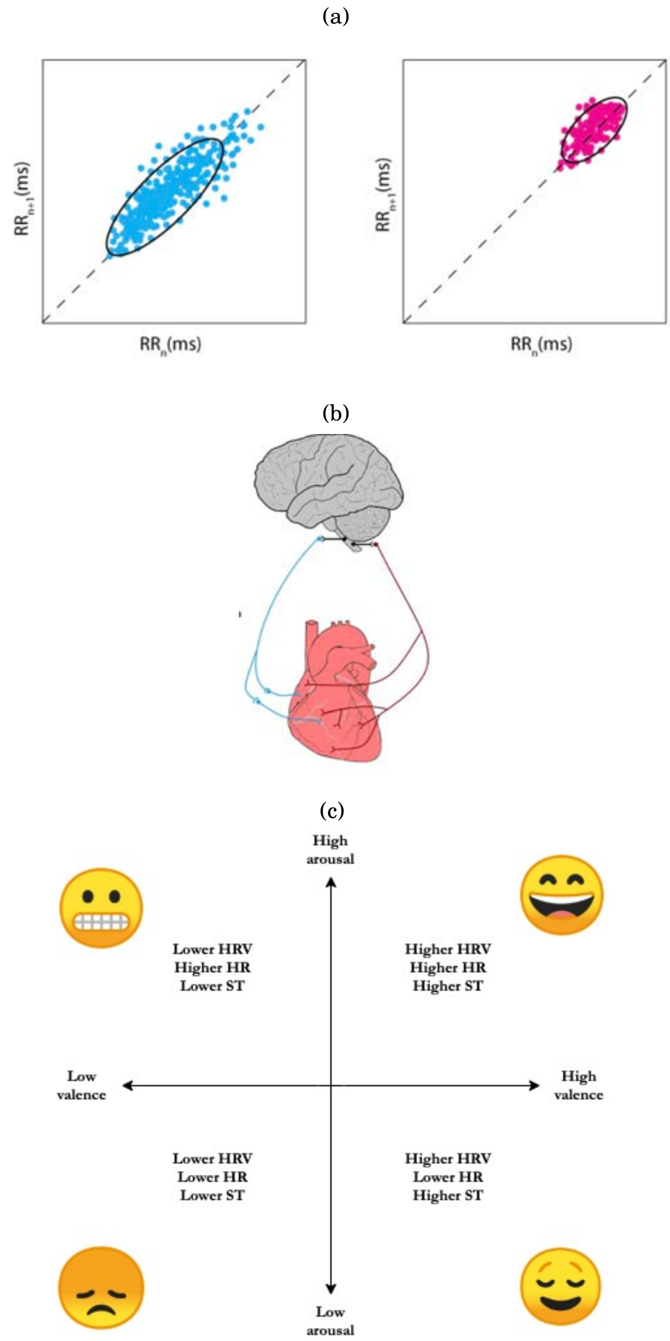
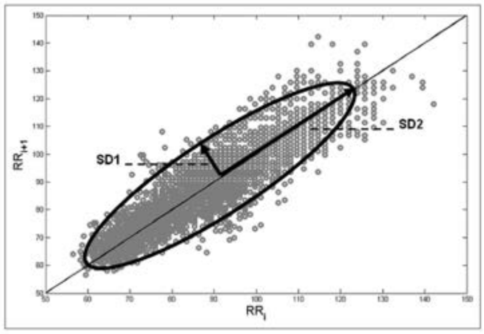


FIGURE 3.2. (a) Poincaré plot is a scatter plot diagram of RR intervals. The left map offers a greater spread of values - which would mean an increased HRV. In contrast, the right map demonstrates the plots closer bunched together and less HRV [50]. (b) Diagram of heart nervous systems - ANS in red and PNS in blue. (c) The PAD circumplex model adjusted for variables being tracked within the Turrellian lamp system architecture - users of the Turrellian lamp should have improved HRV, higher STs and a coherent HR.

(a)



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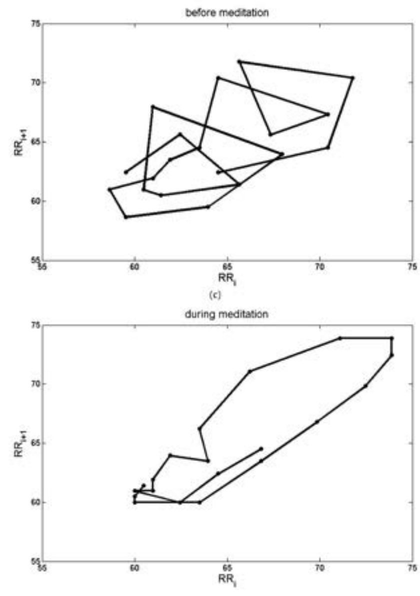

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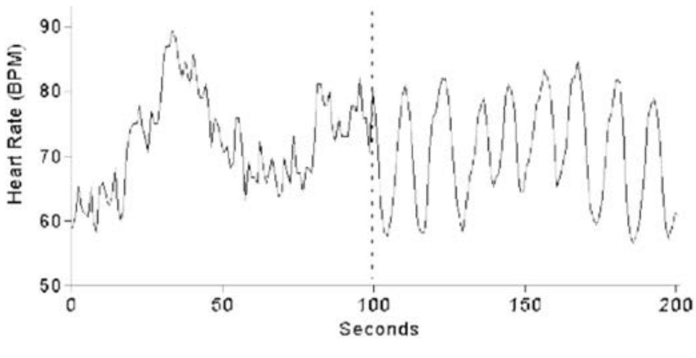


FIGURE 3.3. (a) SD1 and SD2 depicted diagrammatically adapted from Goshvarpour et al. [57]. (b) Goshvarpour's research which demonstrates a shift in HRV Poincaré readings during meditation [57]. (c) A highly stressed and aroused BPM during periods of anxiety shifting towards a more relaxed, less aroused and lower BPM taken from McCraty et al. [135]

Chapter 4

Role of light on mood

A fast growing range of artworks and research studies have utilised the mediums of light and colour to enhance users sensory experience, environmental ambience and subsequently the mood of users. As noted in the previous chapter, light in comparison to music has correspondingly had less consideration for its ability to positively enhance mood. Therefore this chapter seeks to rectify the balance by presenting research demonstrating the importance of good lighting for cognition.

In this chapter, I initially provide context for the Turrellian lamp with further discussion of the work of James Turrell. Secondly, I discuss significant ambience research involving light, colour and mood enhancement, in particular the research of Valdez et al. [216] which was used to inform the functionality of the Turrellian lamp.

4.1 James Turrell artwork

As discussed at the start of this thesis, the artist James Turrell has been an integral influence in the aesthetic design of the Turrellian lamp. Turrell's work is immersive and physical with visual coloured lighting prompting a strong emotional reaction. Indeed, research by Pelowski into Turrell's light art installations found they had a tremendous impact on individuals visiting through tracking eye movement and self-reported reflection [162]. Turrell's background in perceptual psychology has resulted in curated light exhibitions which as Freeland's research finds, challenges the metaphysical and epistemological assumptions of the world and ourselves [52].

Furthermore, Turrell's work is highly appropriate for the design of the Turrellian lamp because his installations are slow moving and hypnotic (see figure 4.1) [52]. In this sense, it takes time to enjoy a Turrell installation. For example, in Turrell's Guggenheim exhibition, the viewers were placed in an enclosed environment with seating in which the gradient and colours of the

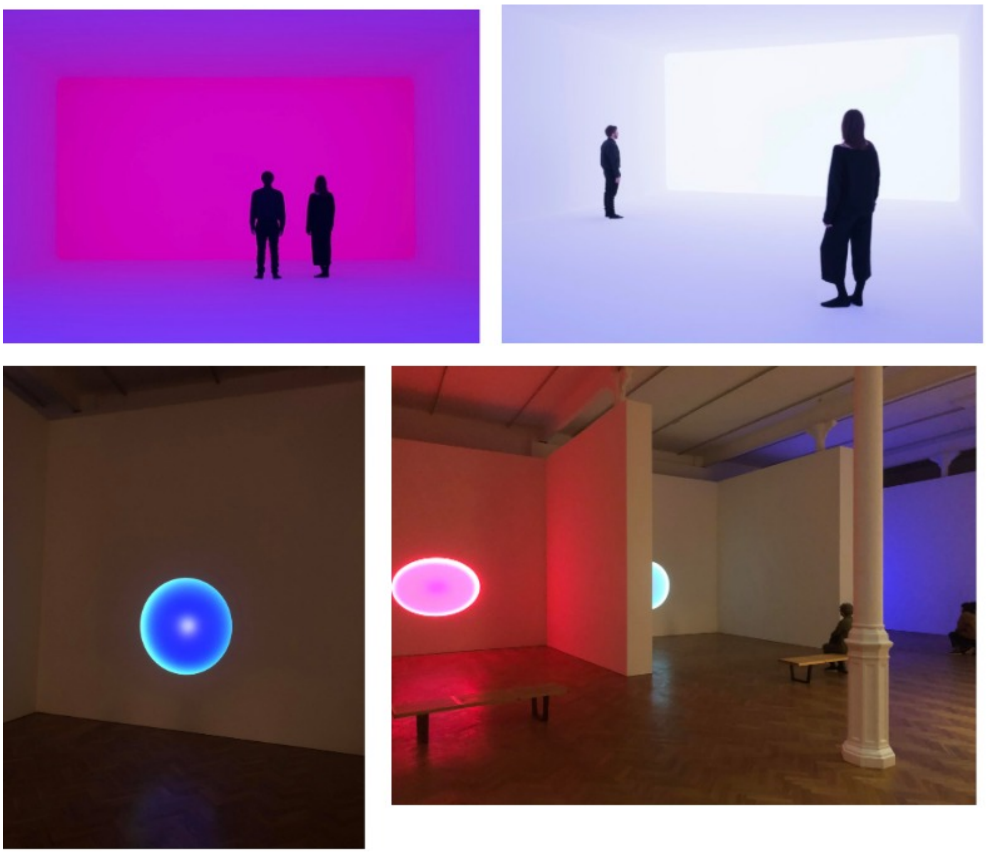


FIGURE 4.1. Top two are professional images taken of Turrell's ganzfeld effect. Bottom two are images taken at Turrell's London exhibition at the Pace Gallery 2020 exhibition demonstrating the viability of Turrell's LED lightscapes in a more domestic sphere and on a smaller scale.

lighting slowly changes and morphs. Within this interior space the colours modulate in complex and awe-inspiring forms linked to environmental factors such as the seasons and times of sunrise and sunset [52]. Consequently, this slow and subtle release of different spectrums colours of lighting inspires the performance of the Turrellian lamp.

Indeed, the Turrellian lamp intends to appropriately shift through colours to enhance users environmental ambience and cognitive mood. The shifts through colour spectrum's should be subtle and certainly not jarring equivalent to a strobe lighting effect. Furthermore, this means that the lamp would certainly not cause any discomfort or seizure amongst epileptic users. Therefore, the Turrellian lamp should provide an enhanced and comfortable environmental ambience rather than overwhelming environmental stimulant akin to nightclub lighting exposures. Now I will consider how Turrell's ganzfeld colour and lighting effect will enhance the Turrellian lamp.

4.1.1 Ganzfeld effect

Turrell's immersive coloured light installations have often utilised the ganzfeld effect (see figure 4.1). Derived from German, the ganzfeld effect refers to perceptual deprivation and is a phenomenon caused by a lack of visual stimulation [125]. Furthermore, Turrell's installations use the ganzfeld effect to immerse viewers in colour, hone the senses via the removing perceptive faculties thereby prompting relaxation and calmness [125]. For the Turrellian lamp design - I was keen to partially reciprocate this effect to help prompt relaxation via the total saturation of relaxing hues of colour. Indeed it is hopeful that users of the lamp will be able to reconnect with the joy of perception, colour and pure light.

4.1.2 Pace gallery London exhibition 2020

For the project I decided to visit Turrell's latest exhibition at Pace Gallery in London (see figure 4.1), to properly discern the qualities of his immersive lighting installations and learn more about his work. As a part of the Constellation series - visiting the works was tremendously useful for honing and improving the Turrellian lamp.

Turrell's series featured mesmerising glass ellipses and circles, which are animated by an array of technically advanced LEDs generated by computer programming. Visitors are invited to sit, be present and enjoy the subtle morphology of the light changes. The light changes are subtle and hypnotic running on a loop that is imperceptible to the viewer prompting a transcendental experience.

Unlike many of Turrell's installations the works were not too large and immersive. On the contrary, the ellipses could be mounted on the wall in a domestic environment. Therefore this exhibit proved a fantastic foundation for conceptually honing the Turrellian lamp. In particular, to build a multimodal lamp which slowly and automatically morphs across spectrums of colour, whilst users go about there routines. Thereby improving mood and adding environmental ambience, which is conducive to users present physiology, routine and mental state.

Having discussed the key influences from James Turrell's artwork on the design and engineering considerations of the lamp. This thesis will now discuss ambience research including light studies, coloured lighting and Valdez et al.'s findings and how this research has influenced the design of the Turrellian lamp.

4.2 Ambience research

4.2.1 Light studies

Light has a tremendous power over psyche - below I provide evidence supporting that lighting from the Turrellian lamp is conducive for users and encourages good moods. In ancient times, Greek physician Hippocrates documented the very absence of light in winter months can cause diseases [25, 212]. In the present day, light has been studied extensively as a crucial treatment for a variety of affective disorders - most notably seasonal affective disorder (SAD) [181, 212].

Consequently, light has been found to be a major impact on human circadian rhythms, particularly - hormone regulation, body temperature regulation, cognition and alertness [18, 22, 25, 124, 217]. The most extensive trials of bright light therapy (a mixture of white spectrums emulating daylight) have found that it effectively suppresses melatonin and improves mood [22, 212].

Affective disorders are increasingly prevalent and usually synonymous with disturbances in circadian rhythm [25, 212]. Indeed, recent studies find that light therapy has become the most common treatment for SAD and increasingly common for depression - remission rates under light therapy have been reported to be as high as 80 percent and crucially higher than pharmaceutical drug trials [212, 213].

Even for healthy individuals, light therapy (see figure 4.2a) has been found to improve health, mood, vitality and general well being - as shown by trials on nurses operating in poorly lit hospitals [23, 39, 55, 76]. Workplace lighting has also been found to have a major impact on improvements in workers productivity and general well being. So much so, the European Union (EU) has instated international guidelines providing an appropriate amount of lux or brightness for workers [25, 108, 109]. Based off this extensive research, the Turrellian lamp will utilise users physiology to produce optimum lighting, which will aid users cognition - supporting good moods and users routines. Now the ensuing section of the thesis will discuss the role of coloured lighting produced by the Turrellian lamp to ensure good moods for users.

4.2.2 Coloured lighting

The Turrellian lamp will utilise coloured lighting to improve users cognition and mood, initially this thesis will briefly introduce colour theory to understand the importance of coloured lighting for certain cognitive tasks and for fostering improvements in the lamp users mood. Colour has been researched and measured in multiple different ways - essential metrics for research into LED coloured lighting includes an understanding of colour wheels, RGB values and colour temperature. Wheels of colour were originally formulated under research conducted by Goethe and Newton (see figure 4.2b) [178]. By the early 19th century, colour theorists devised the RGB system which categorises colour as a formulation of the primary colours: red, green and blue (see figure 4.3a) [215].

Munsell significantly advanced colour theory with his coloured system - which added the variables hue, chroma and value (see figure 4.2b) [216]. Additionally, more recently, LED design and ambience researchers have calculated colour temperature to importantly deduce the intensity and exposure of white lighting - for producing the desired lighting effect [140]. The Turrellian lamp algorithm uses Munsell's colour system and appropriately calculated colour temperatures to hone the correct environmental setting and ambience. Having discussed the basics of colour

(a)

(b)

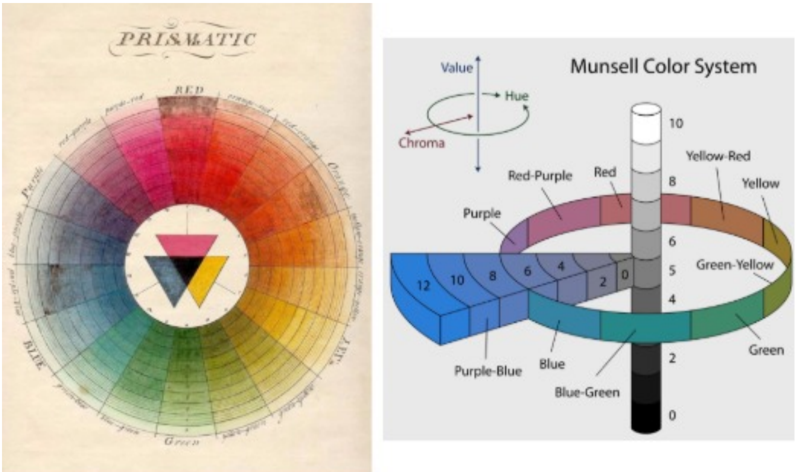


FIGURE 4.2. (a) Light therapy to improve SAD and other mental health disorders. (b) Left - early colour wheels drawn by Goethe. Right - the Munsell colour system which demonstrates the tri-dimensions of value, hue and chroma.

theory - now I will discuss lighting research, which has influenced the Turrellian lamp design, its ability to improve moods and routines.

Research into the effects of colours and coloured lighting on moods and task completion has increased markedly since Valdez et al.'s influential research. Red coloured lighting is associated with hazard, danger and high-levels of performance on detail orientated visual tasks [19, 49, 138]. In contrast, blue light colour increases creativity and innovation [138]. Whilst, green typically prompts calmness - abating stress and even treating headaches [218]. In particular, Vandewalle et al.'s research found that the spectral composition of ambient lighting influences amygdala and hypothalmus activation - thus impacting our ability to process emotional stimuli [218]. Meanwhile short wavelength blue light is most effective for activating human circadian rhythms. Meanwhile warmer colour temperatures are associated with increased sociability and cohesiveness amongst participants [140]. In contrast, cooler colour temperatures resulted in increased reading speeds from participants [140].

Dutch researchers, Kuijsters, Reidi et al. were able to affectively intensify daily experiences for elderly and vulnerable care home occupants using colour-enhanced lighting. Indeed, they manually provided cosy ambiences to reduce elderly participants anxiety and an activating ambience to stimulate arousal [106]. This study proves that a multimodal RGB LED lamp could serve its purpose by both enhancing users affective experience and improve on Kuijster et al.'s findings as the device will function both automatically and autonomously. Further underlining this, Kujisters et al. conclude, "we envision an adaptive ambience creation platform that can automatically adapt" – the Turrellian lamp and multimodal affect-sensitive computer software will help directly fill this void [106].

Having covered the basics of colour theory, coloured lighting and colour temperatures which focused on lighting ambiences supporting cognitive tasks and mood - all of which are considered in the Turrellian lamp design. Now I will cover the most influential lighting research for the Turrellian lamp design which is research conducted by Valdez and colleagues, which focuses on accurately measuring the coloured lighting which most improves mood, arousal and dominance utilising the circumplex model (PAD). From this research, Turrellian lamp colour sequences were devised to enable the lamp to emit lighting which appropriately encourages good mood for its users in different settings.

4.2.3 Valdez and colleagues research (1994)

This section will explore the role Valdez et al.'s research has had in developing the Turrellian lamp. Notably, Valdez et al.'s research utilises the circumplex (PAD) model and Munsell's colour system - to concretely establish colours which improved users mood, increase arousal and dominance [216]. Importantly, this research is very influential because of its specificity via utilising these two models. Valdez's research critically specifies the hue, saturation and chroma of the coloured lighting and its effect in relation to the circumplex (PAD) model enabling comprehensive analysis - resulting in strong and accurate conclusions [216].

Additional benefits of Valdez et al.'s research includes the use of over 250 subjects [216] - resulting in the largest sample size of participants for any experimentation into colour and affect. Furthermore, Valdez et al.'s research also collected GSR data making it ideal to extrapolate physiological data for forming the basis of the multimodal Turrellian lamp computer architecture. Consequently, Valdez's findings are crucial for designing the Turrellian LED lamp's colour sequencing and ensuring the lamp is effective at improving mood. Extrapolating from the research, crucial design insights for the Turrellian lamp can be neatly encapsulated as follows [216]:

- Brightness increases contributed to an increase in pleasure and reduced arousal

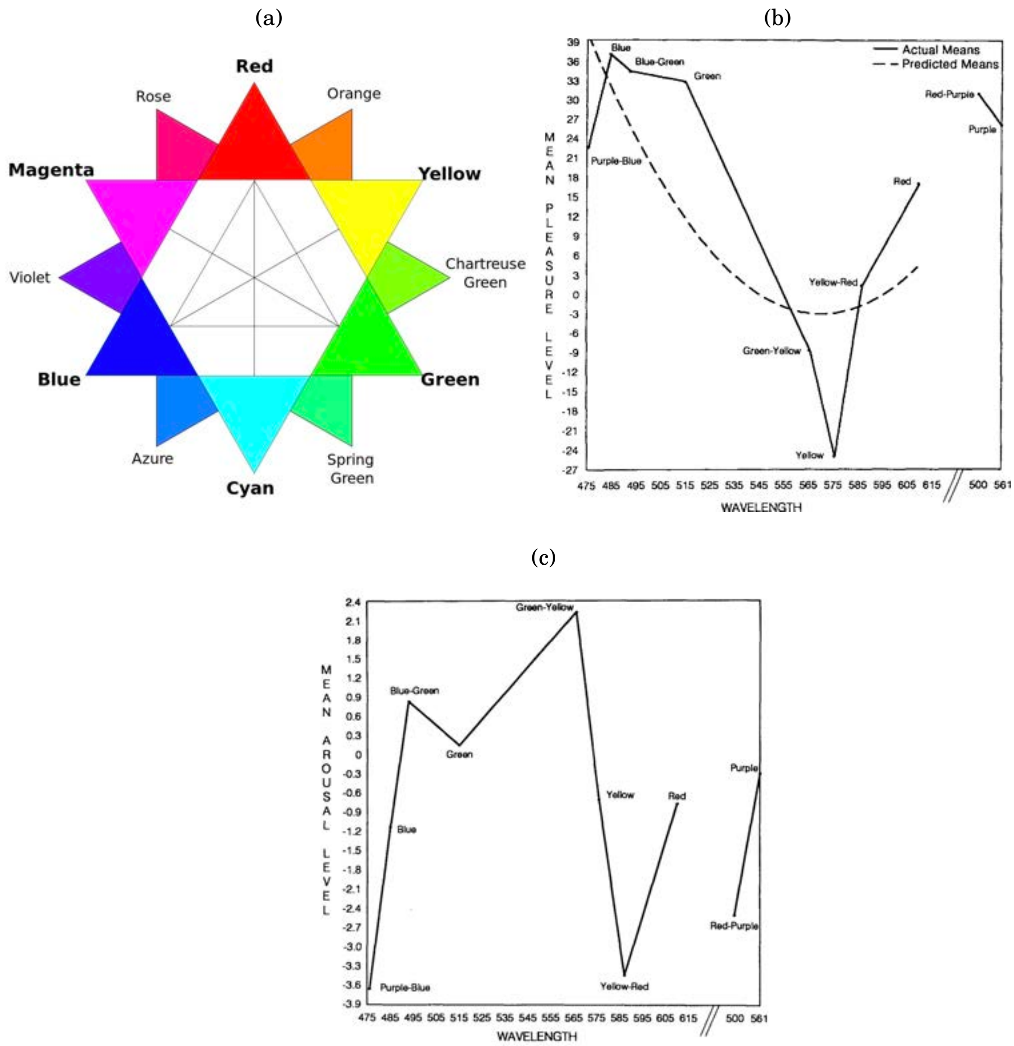


FIGURE 4.3. (a) An RGB colour wheel. (b) Valdez's findings concerning pleasure and wavelength of light dispersion. (c) Valdez's findings concerning arousal and wavelength of light dispersion.

- Purple-blue, blue, blue-green, green, yellow-red, red, red-purple and purple increased pleasure (see figure 4.3b)
- Higher saturated colours increased arousal (see figure 4.3c)
- Blue, blue-green and green increased arousal (see figure 4.3c)

Indeed, the relationships with brightness, saturation and darkness have notably been found to be curvilinear [216]. Additionally, Valdez et al.'s research comprehensively found that warmer colours induce greater arousal. Interestingly, the findings reciprocated pre-experiment predictions supporting the many intuitive groupings and interpretations of colours offered by practitioners and artists such as Turrell. From Valdez et al.'s findings - I was able to establish colour sequences for the Turrellian lamp to best improve mood (see appendix B and C). From this, I was then able to deduce, which colour sequences improved mood and increased or diminished arousal. Therefore I could develop colour sequences for the Turrellian lamp which would relax or excite users (see appendix B and C). Having established the success and importance of Valdez's findings for the project, now I will discuss the chapter conclusions.

4.3 Chapter conclusions - contribution to lamp design

Overall the insights from Turrell, light and colour research has contributed significantly to the design and conception of the Turrellian lamp. Initially, Turrell through his work made the very idea of light exciting, colourful and immersive particularly his exploration of the ganzfeld effect. Additionally, visiting his Constellation series helped assure the potential of exciting lighting devices on a small and more domestic scale. Light, ambience and colour research has emphasised the potential of the device for effectively and accurately improving mood. In particular, the accurate and comprehensive work of Valdez et al. enabled a structured and deliberate approach towards the Turrellian lamp producing coloured lighting sequences, which would best improve the mood of users.

The next section of this thesis will focus on competitor analysis and rival IoT light devices for the Turrellian lamp. This section will enable an assessment to be made on the strengths weaknesses of the Turrellian lamp as well as establishing the unique selling point (USP) of the Turrellian lamp.

Chapter 5

Rival IoT light devices

This chapter focuses specifically on competitor analysis. For the purpose of improving the Turrellian lamp pilot prototype. Indeed, it is crucial to identify and evaluate rival products and services - for the purpose of developing a profitable and competitive product. Equally, this analysis also provides critical background information, opportunities and helps deduced the Turrellian lamps' unique selling point (USP).

Firstly, my analysis centres on health intrinsic LED light devices, before secondly focusing on more common ambience-centred LED lighting IoT devices and platforms. After identification, strengths and weaknesses of the devices will be discussed before thirdly, emphasizing the role of the Turrellian lamp in mitigating these shortcomings and the advantages of the Turrellian lamp.

5.1 Health light devices

Used both privately and by health practitioners there has been marked growth in commercially available IoT health light devices and medical-grade lighting equipment for treatments [30]. These devices have typically been designed to treat three health conditions - depression [25, 212], skin conditions [3] and sleep disorders [24]. However, my competitor analysis will strictly focus on competitor devices for depression and sleep disorders because the Turrellian lamp is not designed to treat skin conditions.

For depression, particularly SAD disorders, two popular devices similar to the Turrellian lamp include the Phillips EnergyUp (figure 5.1a) [165] and Beurer TL100 (figure 5.1b). Unlike competitors, the Phillips EnergyUp offers 10,000 lux blue lighting - which as previous research has noted, offers the most brain activation for SAD treatment [165]. Additionally, the EnergyUp can be effectively used in 20-30 minute treatments [165].

The TL100 offers comparable lux to the EnergyUp but many more brightness settings and colour variations [14]. The TL100 is also controlled by an app - making it internet controlled unlike the Phillips EnergyUp [14]. Perhaps with its App and range of available colour spectrums the TL100 is a more effective lighting device than the EnergyUp yet comparably harder to properly use. Additionally both devices are quite small and designed to sit on bedside tables [14, 165].

For sleep disorders two best-selling devices include the Dodow sleep (figure 5.1c) and Phillips Somneo (figure 5.1d) [41, 166]. The Dodow is a small lighting device, which projects blue light onto the ceiling to guide deep breathing before sleep [41]. Additionally, the Somneo, also offers guided breathing functionality [166]. However, the Somneo also offers a greater range of lighting spectrums simulating, sunrise and sunset to promote energy and rest [166]. It is important to note that the Somneo is more expensive and larger than the Dodow, although both are designed for bedside tables - neither are controlled by applications [166]. Now I will evaluate these health light devices against the Turrellian lamp.

5.1.1 Assessment versus Turrellian lamp

Considering all health IoT light devices, I believe the most advanced health-specific lighting device is definitely the Beurer TL100 as it offers the widest range of coloured lighting and the greatest variation in brightness. Furthermore, the Beurer TL100 has an App for adept control unlike its rivals. In contrast, the Dodow is the most innovative device - as the first to offer light projections onto the ceiling to encourage relaxed breathing and help abate insomnia or sleeping difficulties [41].

The EnergyUp uses short-wavelength blue lighting which earlier research shows [218] is most adept for stimulation. Lastly, the Somneo is most aesthetically desirable and offers an all-round package - encompassing many of its competitors features. Critically, in terms of weaknesses, all the devices are quite small and designed for bedside tables - thus lack the immersive qualities of larger lighting devices. Furthermore, none of the devices offer 256 colour settings or an innovative GUI application for adept control. Indeed, only one of the devices is controlled by a web-based application.

The Turrellian lamp contrasts strongly with its fellow smart health IoT devices by being tethered and guided by users physiology based on insights from affect-sensitive MHCI. Also the Turrellian lamp is physically much larger, more immersive and offers a far greater spectrum of coloured lighting as well as higher lux levels. Comparably, the Turrellian lamp offers the same light functionality as the Somneo to simulate sunrises and sunsets - providing energy or rest for users.

None of the health devices claim to offer mood improvement for individuals not suffering from SAD - which obviously differs from the Turrellian lamp, which is directly trying to enhance users mood. Furthermore, the Turrellian lamp offers an advanced web based application and parser for controlling the lighting and ambience unlike the Dodow, Somneo and EnergyUp. Having

FIGURE 5.1. Pictures of health devices: (a) Phillips EnergyUp. (b) Beurer TL100. (c) Dodow Sleep. (d) Phillips Somneo.

considered the health light devices - I will now turn to competitor analysis on ambience IoT light devices.

5.2 Ambience IoT light devices

Ambience-centred IoT light devices have equally represented a growing trend commercially. Three of the most popular ambience-centred IoT light devices include the Dyson Lightcyle (figure 5.2a) [42], Phillips Hue (figure 5.2b) [164] and Nanoleaf light panels (figure 5.2c) [146]. Firstly, Dyson's LED Lightcycle auto-adjusts depending on age of user, tasks, senses motion and uses a 32-bit microprocessor to continually interpret daylight data to render the LED close to daylight colours [42].

Conversely, the most popular competitor device, the Phillips Hue is a line of colour changing 800 lumen LED lamps, strips and bulbs controlled wirelessly from Apps, vocally with Alexa or Google Assistant and configurable with iOS HomeKit [164]. Lastly, Nanoleaf Inc. are a diverse range of multicoloured LED light panels – usable with assistant software and touch sensitive [146].

These IoT devices differ enormously in terms of specifications, pricing, and market share. At the time of writing, the Phillips Hue is by far the most popular smart IoT LED light device with the range reporting yearly revenues at almost £600 million [209]. Similarly, much like its competitors the Hue adjusts brightness based on time of day, can provide visual cues for users notifications and can turn lights on with motion detection at predefined times – helping abate home burglaries [164].

Although not part of a broader range of lighting products and a newcomer within lighting markets, the Dyson Lightcycle offers eponymous elegant design. Intriguingly unlike competitors, the Lightcycle fails to offer a wide spectrum of colours and instead sticks to white hues. Furthermore, the price point of the Lightcycle is quite high at RRP over £500 [42].

Former Kickstarter start-up Nanoleaf offers an intriguing coloured range of LED light panels [146]. Nanoleaf differs from its commercial counterparts as an emerging start-up rather than large enterprise with a more niche subset of retail customers. In particular Nanoleaf is commonly used for back-lighting purposes for game consoles or televisions. Now I will evaluate these ambience light devices against the Turrellian lamp.

5.2.1 Assessment versus Turrellian lamp

The success of the Phillips Hue is potentially as a consequence of the breadth of its range and subsequent array of price points - thus catering to a wide spectrum of potential customers versus competitors. In contrast, the more expensive Lightcyle offers personalised design with appropriate lighting for different ages and tasks. Unlike the other devices, Nanoleaf light tiles can be built up into large displays offering canvassing potential and portability for large commercial installations.

For more expense, the Hue and Nanoleaf can be built up to make an immersive lighting platform throughout a users property [146, 164]. However, the Lightcycle is quite a small lamp - limiting its immersive qualities. Additionally, all the devices are on-command - in this sense they require users to directly notify settings and preferences - they do not operate automatically or offer an innovative GUI controller.

All devices fundamentally differ from the Turrellian lamp as none are tethered to users' affective state or offer mood enhancement. Rather the devices offer a more functional purpose –

FIGURE 5.2. Pictures of ambient light devices: (a) Dyson Lightcycle. (b) Phillips Hue smart-bulb. (c) Nanoleaf light panels.

providing ambient lighting on command. This design oversight is all the more surprising with the numerous research papers and art features exploring the role of light, colour, and affect-sensitive computing towards improving user's mood. The Phillips Hue and Nanoleaf light panels also differ from the Turrellian lamp because they offer the ability to use multiple products to create a synchronized ambient lighting platform within a given environment. Conversely, the Turrellian lamp is a stand alone product which is not part of a broader range of different ambient devices, which can be synchronised together. Perhaps the difficulty of affect-sensitive MHCI IoT devices deters designers from further exploring mood-enhanced LED light - particularly designing autonomous instead of on-command devices. However, as discussed earlier, physiological approaches should help settle many of the preconceived difficulties associated with affect-sensitive MHCI. Now I will discuss the chapter conclusions.

5.3 Chapter conclusions - Turrellian lamp USP

Having compared the Turrellian lamp with six fellow competitor devices. It is clear that the Turrellian lamp is unique because it is the only lighting device designed to improve mood for all users utilising physiological tracking and a GUI parser guided by the latest insights from affect-sensitive MHCI and affective science. Additionally, the Turrellian lamp is the only device to bridge the two defined categories of health and ambience IoT light devices. Furthermore, the Turrellian lamp offers a far greater range of colours and due to its larger size than the bedside-table counterparts, more lumens and light-immersion. However, unlike the Phillips Hue and Nanoleaf light-cycle the Turrellian lamp is not part of a broader range of lighting products which can be impressively interconnected into an immersive smart-home lighting environment.

Nonetheless, the Turrellian lamp offers automatic lighting and ambience for its users based on present mood and does not require users to orientate preferential lighting and colour. Equally, the lamp has inbuilt colour schemes to immerse users in the lighting most suitable for their present emotional state. Having finished the literature intensive section of this thesis, the next chapter will re-emphasise the hypotheses before discussing the implementation of the project - including design thoughts, prototyping and user stories.

Chapter 6

Prototyping and hypotheses

In this section I re-iterate the hypotheses, exhibit initial sketches and early prototyping of the Turrellian lamp. The focus of this project was on aesthetic outcomes, interaction, UX testing and early delivery of the lamp. Additionally, the lack of commercial devices utilising affect-sensitive platforms or LED coloured lighting to improve mood meant that a clear empirical and user-centric approach to research seemed most appropriate.

Throughout development of the Turrellian lamp for pilot studies – I decided to incorporate an agile development cycle resulting in fast development of multiple working versions and incorporation of user-feedback for continual improvement whenever possible. Only here due to the consequences of the Coronavirus pandemic and pioneering nature of the project – I proceeded informally and opportunistically, utilising friends, family, colleagues and even self-study whenever possible.

6.1 Hypotheses

Reiterating my hypotheses, I have formulated two central hypotheses for the project.The first hypothesis centres on quantitative data collection – precisely collecting data on users physiological and thus emotional data rendered in the presence of the Turrellian lamp. In contrast, my second hypothesis focuses on qualitative evaluation and user feedback from an Attrakdif survey versus a Philips Hue smart bulb control lamp:

1. Participants physiological readings will be notably altered by the Turrellian lamp's light changes and move closer to physiological readings coherent with a good mood. Participants will be able to recognise the affective change as a positive shift towards a better mood.

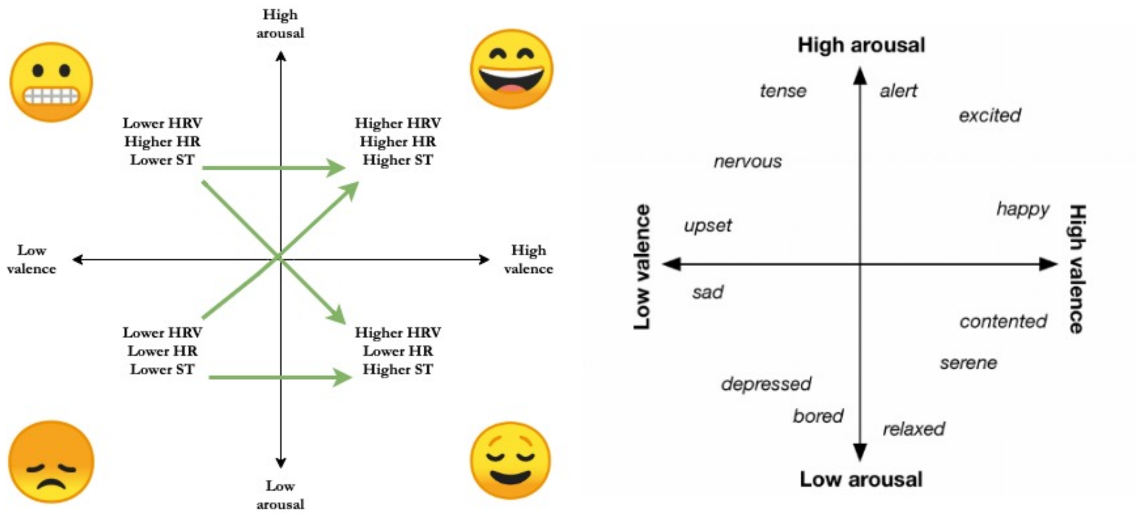


FIGURE 6.1. The left PAD model and green arrows denote that participants will be pushed by the Turrellian lamp lighting into the right two quadrants - associated with higher heart rate variability, adequate heart rate and higher skin temperatures. The right PAD model denotes the positive emotions within those quadrants [182].

2. The Turrellian lamp will score higher in all UX categories than the rival Phillips Hue smart bulb from feedback collected by the Attrakdif questionnaire.

To improve mood according to Russell's circumplex model - there are broadly two good mood quadrants, which users can cognitively enter. These are the far right two quadrants of the bipolar axes between valence and arousal. Consequently, to improve mood the lamp aims to push users into the two desirable quadrants via light patterns.

6.2 Initial design thoughts

The following section discusses the pros and cons of design thoughts taken during initial research for the Turrellian lamp. Indeed, some proved fruitful and were implemented in the final design. Since the Turrellian lamp is a novel implementation it felt appropriate to reflect on the prototyping of the design. Some methods used to replace initial ideas where because of contingency plans made at the onset of the project and inaccessibility of relevant sensors due to manufacturing disruptions.

However, due to the variety of skills and disciplines needed to complete this project, some ideas were realised from academic research and incorporating experts in various fields such as photography, lighting, micro-controllers and affective science. Thus advice for computer science students embarking on similar projects is to order relevant hardware early and build crucial relationships with academics relating to the project. Indeed, the initial core design idea was to build an immersive light installation responsive to affective data accrued from a user as well as controllable via a reflective mindful self-journal application.

6.2.1 Lamp sketches

After the Turrell exhibition and researching into programmable lighting technologies - I decided to incorporate LED strips into the design for the Turrellian lamp. Indeed, digital LED strips could be effectively immersive with up to 144 LEDs per metre and lux rates over 10,000. Additionally the nature of addressable Digital RGB Neopixel strips meant I could specifically program each singular LED pixel to glow a specific RGB colour.

Originally, I toyed with idea of utilising mirrors or even translucent glass panels to hold the Neopixel RGB LED light strips and project the light outwards as a part of the Turrellian lamp design. Additionally, I also considered the potential of different and exciting shapes to make the lamp - such as a retro tall cigar shape or even different variations of light boxes influenced by origami (see figure 6.2). This was before I settled on the vision of a tall (over 6 feet), self-standing and suitably immersive Neopixel RGB LED cuboid box which would provide the perfect vantage to project light onto the wall or directly onto the user as the core design of the lamp.

Additionally, unlike the other designs, the cuboid Turrellian lamp would be easier to aesthetically build and prototype from a design perspective with wood and perspex. Indeed, the worsening Coronavirus pandemic rendered 3D printers unavailable within London and prevented access to the University of Bristol laboratories to prototype more sophisticated and perhaps artistic designs. Not only, was this design most effective in projecting lighting appropriately, but the tall cuboid Turrellian lamp would fit well into domestic settings in either the corner of the room or next to furniture - taking up minimal floor space. Having discussed the physical structure of the lamp, now I will discuss design thoughts relating to the GUI.

6.2.2 GUI

For the Turrellian lamp GUI, I envisaged for it to be completely different from competitor devices. Rather than an on-command controller, I wanted the GUI to be similar to a personal journal - in which users could express their specific emotions and feelings during the day from which appropriate ambient lighting would be generated by the lamp via a web-based parser algorithm. Users from recognising their past experiences throughout the day would then specify which positive mood and emotion they desired to feel in the present.

Data from the web-based algorithm would be coupled with the physiological signals to improve and evaluate mood recognition accuracy. Furthermore, this is before even recognising that daily reflection, journal writing and expressive artwork has tremendous therapeutic benefits for mental health and mood. Additionally, the Turrellian lamp GUI would encourage users to presently feel gratitude because grateful cognition is scientifically known to cohesively alleviate negative emotions.

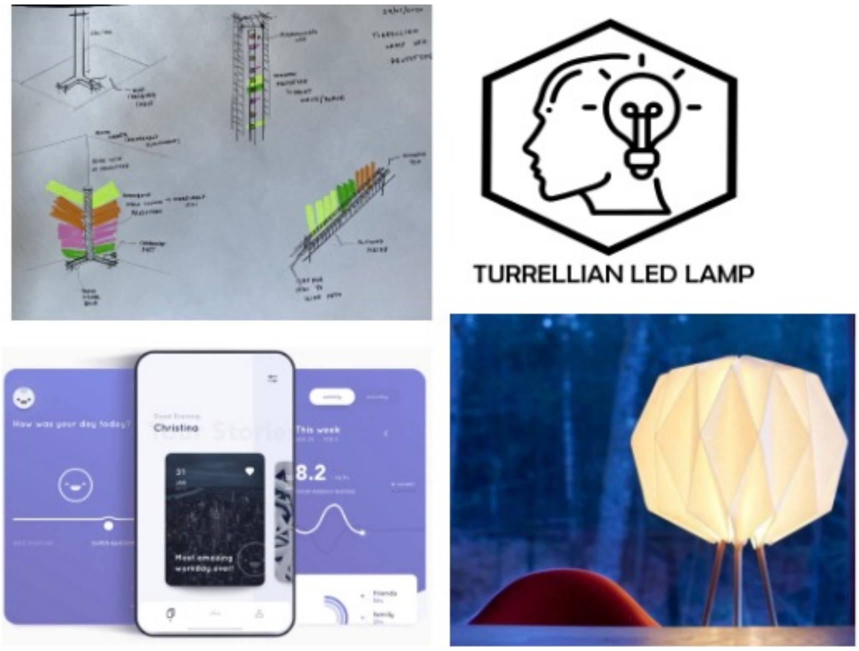


FIGURE 6.2. Upper left - initial sketches of the Turrellian lamp. Upper right - Turrellian lamp logo. Bottom left - Reflectly UI served as useful comparison. Bottom right - impressive origami inspired shapes considered for Turrellian lamp.

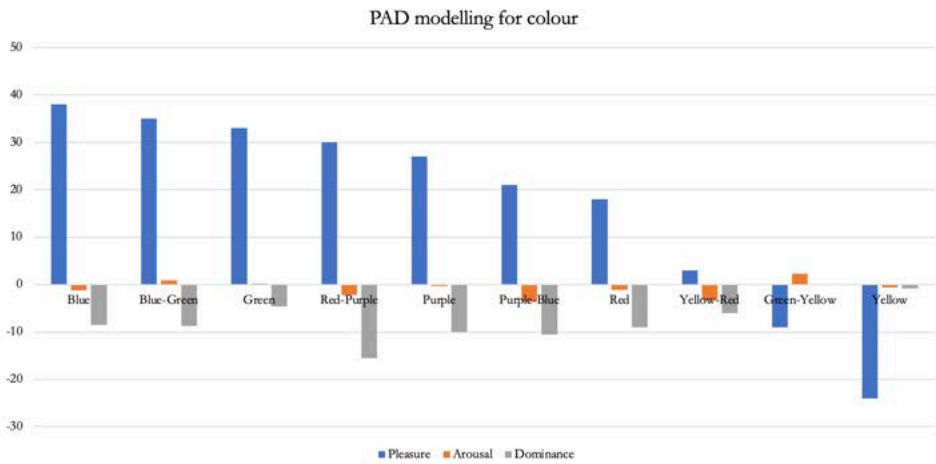
Initial sketches for the Turrellian lamp GUI are pictured below. As discussed in chapter 10, which focuses on software integration - multiple versions of the GUI were developed before final implementation and user feedback was incorporated throughout the design process. For critical comparison, I will now briefly discuss a similar journal application, namely Reflectly to the envisaged Turrellian lamp GUI.

6.2.3 Similar journal applications to the envisaged GUI

Several mindful applications offer similar user experiences to the Turrellian lamp GUI and self-journal parser. With respect to writing daily journal entries, the application Reflectly utilises artificial intelligence to help users' structure and reflect upon their daily thoughts and problems (see figure 6.2) [177]. Reflectly tracks users' moods, content progress and offers personalised motivational content [177].

Reflectly has an aesthetically desirable UI. Yet aside from collecting data Reflectly, unlike the proposed Turrellian lamp GUI, does not collect any physiological data or use that data to positively orientate user's hardware and environment. However, Reflectly proved a useful comparison and its growing popularity as an application helped ensure that the Turrellian lamp GUI would be effective. Having discussed initial design thoughts relating to the Turrellian lamp GUI - I will now discuss my initial calculations and thoughts relating to the light patterns produced by the Turrellian lamp.

(a)



(b)

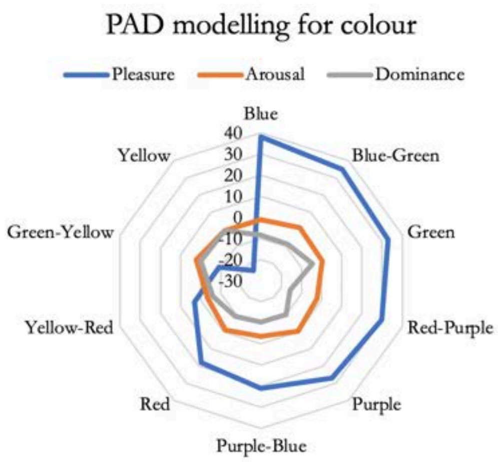


FIGURE 6.3. Two graphs presenting data collected by Valdez et al [216]. - 6.3a graphically and 6.3b in radar format.

6.3 Light patterns

For the Turrellian lamp's light patterns based off Valdez et al.'s research, I initially made colour palettes centred on there research and findings (see figures 6.3). I mapped the data into radar graphs to discern key colours relevant to Valdez et al.'s research for improving mood [216].

From this, I generated an algorithm to calculate the different colour values, colour temperatures, hue and chroma values and range of palettes in accordance with the Munsell colour system (see appendix B and C). This enabled me to effectively devise relevant colour gradient mappings and colour cycles, which would be programmable for the Turrellian lamp (see appendicex B and C). Initially I calculated RGB values, from this I calculated HEX values and then lastly RGB565 values.

Correlated colour temperature (CCT) was determined utilising equations appropriately as follows. Converting the RGB values to CIE trismulus values (XYZ):

$$X = (-0.14282)(R) + (1.54924)(G) + (-0.95641)(B) \tag{6.1}$$

$$Y = (-0.32466)(R) + (1.57837)(G) + (0.56332)(B) \tag{6.2}$$

$$Z = (-068202)(R) + (0.77037)(G) + (0.56332)(B) \tag{6.3}$$

Normalising chromacity values:

$$x = X/(X + Y + Z) \tag{6.4}$$

$$y = Y/(X + Y + Z) \tag{6.5}$$

Computing CCT values from:

$$CCT = 449n^3 + 3525n^2 + 6823.3n + 5520.33 \tag{6.6}$$

Having performed these calculations regarding envisaged light patterns for the Turrellian lamp - I then considered the system landscape of the Turrellian lamp and how the many different features of the lamp would work together coherently.

6.4 Prototypical system landscape

From conception, I decided to incorporate available physiological sensors and a web application to provide the Turrellian lamp with the necessary data for the underlying algorithm to discern the correct colour sequence for each users cognitive state. The premises for the affect-sensitive computer architecture was devised as follows in figure 6.4 and figure 6.5. Over MQTT protocol, JSON files would be used to transport data packets.

Hive MQTT was chosen as the optimum broker due to personal familiarity with using the free online system. JSON was a good choice as a format as it is open standard, human readable and lightweight, and was easy to integrate with all components in the system especially the IoT devices. Having considered the system landscape - I then focused on hypothetical user stories to best understand how a variety of different users would interact and effectively use the lamp.

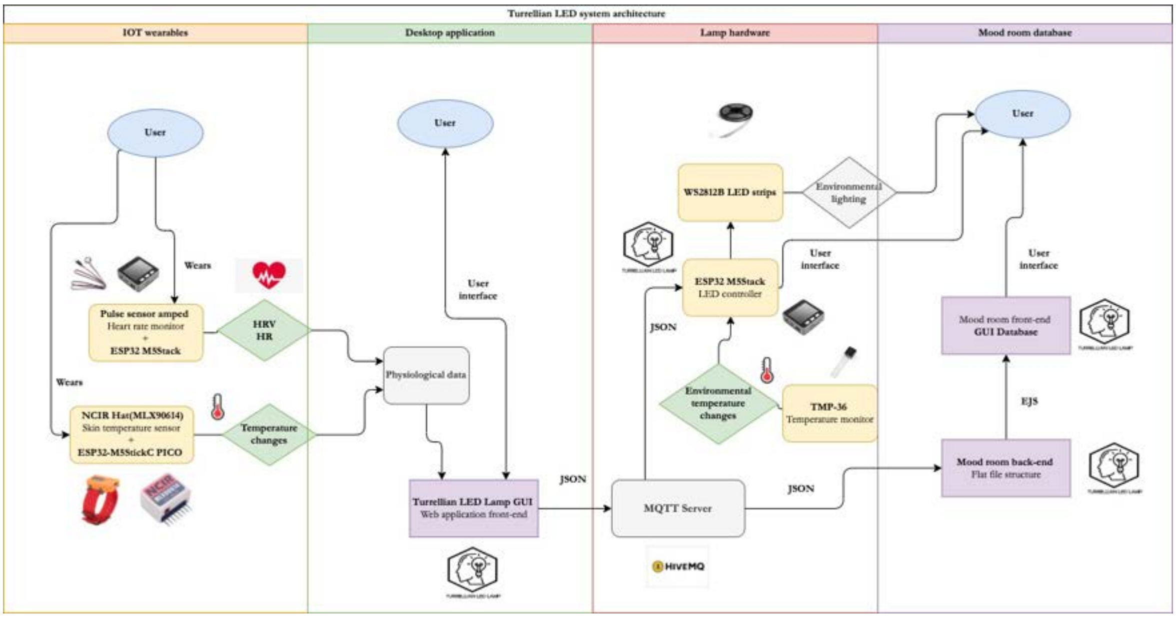


FIGURE 6.4. The devised system architecture for the Turrellian lamp.

6.5 User stories

To aid development I devised three user stories to detail the different interactions that a user may have with the Turrellian LED lamp. Devising user stories was an invaluable tool for understanding how customers would effectively utilise the lighting system and to demonstrate the purposes of the Turrellian lamp. Furthermore, user stories helped orient the device to succinctly determine which profile of users and target audience the device was best suited too.

6.5.1 User story 1

Mary is an elderly care home occupant - her care home environment, poor vision and lack of mobility can often be isolating, leaving her feeling stressed and confined. She has always enjoyed the ambience of music and would like to feel more comfortable in the evenings and more energy in the mornings - however she is largely constrained by her increasingly poor vision and inability to walk long distances.

6.5.2 User story 2

David is a successful employee at a large firm - he is starting to take on more responsibilities at the firm and eyeing a promotion. The pressures of his success have left him often feeling stressed and struggling to sleep in the evenings. He works and eats healthily but is increasingly dealing

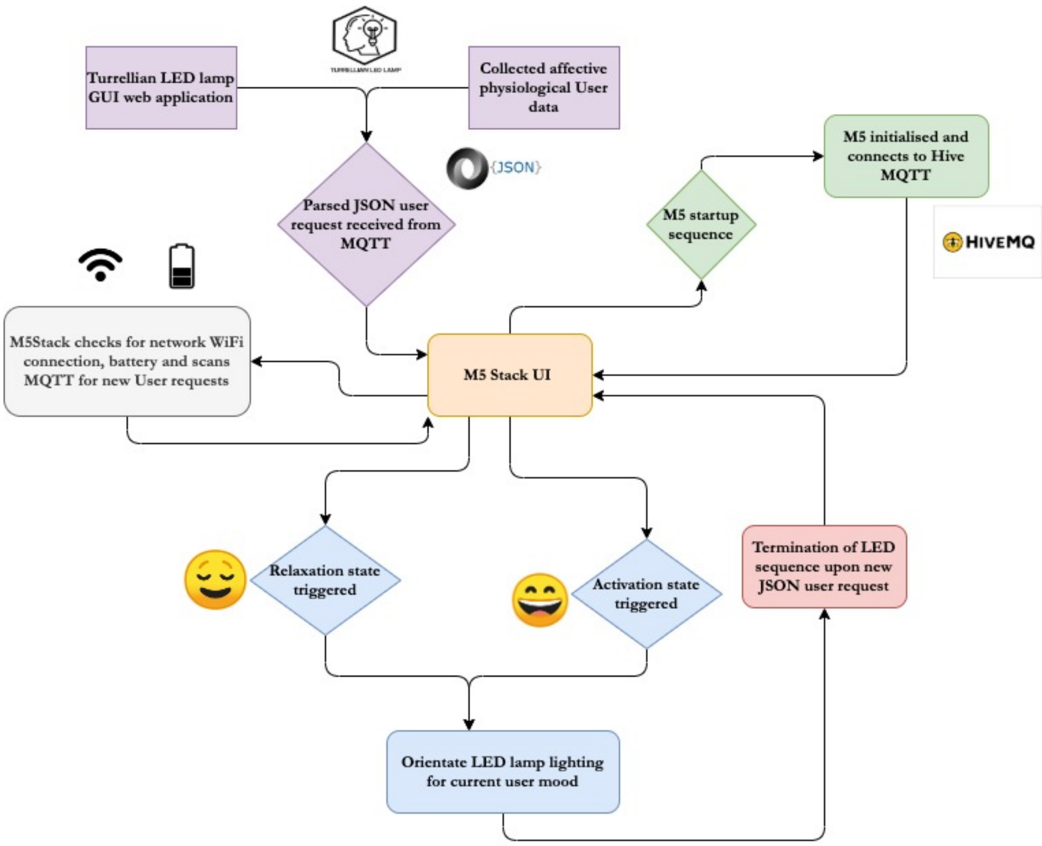


FIGURE 6.5. Envisaged state diagram for the M5Stack microcontroller - serve as core hardware functionality for Turrellian LED lamp.

with insomnia. David does not practice any forms of mindfulness and chooses not to communicate his emotions with others.

6.5.3 User story 3

Tom is a young child who struggles at school - he has been diagnosed with ADHD, which deeply affects his ability to sit at a desk, concentrate and focus. Furthermore, he struggles to properly wake up in the mornings and have a well structured daily routine. Tom's parents increasingly worry about his erratic behaviour and would like to support his emotional state.

6.5.4 Hierarchy of priorities

In light of these user stories, I used disciplined agile practices to prioritise the concerns and desires raised from the user stories as well as develop a clear profile of potential users of the Turrellian lamp. From the user stories, it is clear a wide age range of potential clients would appreciate features of the Turrellian lamp. In terms of hierarchy of priorities:

6.5.4.1 Emotion and mood support

All three user stories denote a need for more healthy cognition and daily moods. User stories 1 and 3 stressed a need for more energy and ability to focus. In contrast, user story 2 needs more relaxation. The Turrellian lamp would help by promoting the emotional benefits of daily journal entries and non-invasively construct environments most suitable to achieving moods and emotions the three users would need day-to-day.

6.5.4.2 Environmental enhancement

All three user stories find their environment is not conducive for their day to day emotional states, moods and general cognition. Consequently, the Turrellian lamp would benefit by providing optimum coloured lighting re-framing their setting visually - offering comfort, relaxation or focused lighting and ambience on command.

6.5.4.3 Improvements in daily routine

User stories 2 and 3 stressed the need for better routines to sleep or work. The Turrellian lamp can help by providing the appropriate lighting for these activities. Indeed, appropriate hues of environmental lighting ensure either arousal or relaxation.

6.6 Chapter conclusions

User stories 1 and 3 are both elderly and young users - consequently the Turrellian LED lamp GUI would have to be designed for both ends of the age spectrum to easily use daily. Indeed, the Turrellian lamp should not be too sophisticated to setup or configure. Ultimately, the Turrellian lamp prototype for pilot testing only required a socket for power, some physiological readings and a single journal entry to start working. I fully envisage for future Turrellian lamp prototypes to operate entirely automatically once provided with power and driven by physiological readings from connected wearable smart devices such as Apple watches.

At this early prototyping stage, I had successfully considered many features of the lamp including the Turrellian lamp hardware design, lighting patterns, system architecture, end users and future evolution's of the design. Having established much during prototyping, the next chapter of the thesis will focus on the tools used within the project to successfully execute the development of the Turrellian lamp.

Chapter 7

Tools

Due to the nature of the project – many hardware and software tools had to be used and integrated into a viable system architecture. Outlined below, are most of the essential software and hardware tools used within the Turrellian lamp architecture.

7.1 Platforms

I developed the Turrellian lamp on Windows 10 and Mac OS Catalina mainly because I was able to use a laptop with Windows 10 and a desktop with Mac OS. Furthermore, all of the major development frameworks I considered worked on either OS. In contrast, working on Linux in a virtual machine did not seem an option due to the likely performance demands of the project and the need to program multiple different microcontrollers.

7.2 Software

7.2.1 Arduino integrated development environment

The Arduino IDE is an open-source cross-platform development environment, which was used for programming all three of the Turrellian lamp's microcontrollers in both C and C++ - to orient the LED strips within the lamp and collect physiological data on users. Thereby enabling the successful development of a Turrellian lamp prototype.

The development environment is fantastic for dynamically programming all the microcontrollers. In particular, the program avrdude coupled with SPIFFS library enabled uploads of packets of code to either the microcontrollers firmware or flash memory – this particularly helped the development of the M5Stack's user interface. Equally, the Arduino environment has a strong community and rich documentation library to help solve many unforeseen bugs and errors. Lastly, the GCC compiler, build and upload sketch functionality made development very straightforward.

7.2.2 Visual Studio

The Turrellian lamp's web-page GUI was written in HTML, JavaScript and CSS within Visual Studio. JavaScript and JQuery functions ensured the successful delivery of data packets to Hive MQ. Meanwhile HTML included the GUI layout and lastly CSS offered appropriate styling. Tests for the correct functioning of the system were appropriately developed in Visual Studio and the inbuilt Live Server extension helped dynamically launch the web-page application for user testing over local-host and a computer port.

7.2.3 Processing

Processing is an incredibly flexible software sketchbook and Java-based integrated development environment for prototyping. Processing offered a highly resourceful GitHub and thriving community for fixing bugs and errors. Indeed, Processing enabled Turrellian lamp participants to successfully real-time convert heart-rate data into useful biometric readings to drive the lamp and discern the lamps effectiveness.

Furthermore, the Processing development environment helped live plot the coordinates of data onto appropriate graphs as well as provide optimum graphics for real-time visualisation of HRV data streams. In particular, Processing's serial communication, PDF and PNG export extensions helped immensely for collecting and documenting data.

7.2.4 Hive MQ

An efficient public IoT broker for sending parcels of JSON data across networks utilising the standard protocol MQTT. In particular, this platform helped function reliably across the Turrellian LED desktop UI and multiple IoT devices within the Turrellian lamp system architecture.

Additionally, Hive MQ had suitable low latency enabling fast and instant response from the IoT devices for sending and receiving data. Lastly, the HiveMQ system is free to run anywhere with easy integration enabling easy use with both Arduino products and on the Turrellian lamp web-applications.

7.2.5 Version control

I used Git for version control, hosting my repository with GitHub. This decision was based on my experience with the system, and the availability of free hosting.

7.2.6 Key libraries

7.2.6.1 SPIFFS

An excellent library and light-weight filesystem for writing to microcontrollers SPI flash chip. Indeed, this enabled successful reading and writing to SPI flash memory easily – which was crucial for developing the ESP32 M5Stack Turrellian lamp UI. Indeed, the ESP32 contains 4MB of flash memory, which proved optimal. Multiple libraries were used to appropriately configure the LED strips within the Turrellian LED lamp into appropriate colour sequences on command.

7.2.6.2 Adafruit neopixel

For initial prototyping the Adafruit Neopixel library was utilised – in particular the strand test and colour functionality. This library particularly helped deduce if Adafruit neopixel LED strips functioned appropriately with an UNO. As addressed in the bugs section of chapter 8 – most neopixel library functions did not function properly with the M5Stack microcontroller leading to the FastLED library being preferred.

7.2.6.3 FastLED

An important library for easily controlling and manipulating the beta prototype Turrellian LED lamp. Particularly, for effectively and efficiently controlled the LED strips from the ESP32 M5Stack microcontroller without errors. The FastLED library, enabled a quick start and high performance with key features such as brightness scaling and high performance 8-bit math for RGB manipulation – enabling easy creation of many different patterns.

This libarry helped provide numerous very useful examples and had compatibility with the cpt-city archive which contained an incredible variety of colour gradients. This collection includes themed colour palettes produced by renowned artists to even science-based colour schemes.

7.2.7 PulseSensor

A crucial open-source Kickstarter-led Arduino compatible heartbeat monitor and library. In particular, it produced highly optimal and accurate heart-specific data versus other tested heart monitors.

Additionally, the public library and toolbox contained both useful Arduino files to get started and Processing sketches to convert Arduino readings into more advanced heart rate variability time, frequency, biofeedback metrics and Poincare mappings. This library helped enormously by offering useful examples in both Arduino and Processing – helping lay the foundations for developing the Turrellian RGB LED system architecture.

7.3 Hardware

7.3.1 Arduino UNO

An Arduino UNO single-board microcontroller was used as the primary prototyping circuit board for the Turrellian lamp. The UNO proved to be the perfect development board due to its variety of pins enabling connection with input/output, analog inputs, power and ground.

A Raspberry-Pi for prototyping was initially considered. However, I had more experience programming within the Arduino development environment. Furthermore, the simplicity of the UNO microcontroller versus the single-board Raspberry Pi computer made it significantly easier for mitigating the hardware demands of the project. Indeed, the flexibility of the Arduino and its ability to work with multiple sensors, chips, devices, LED strips and learning resources made the Arduino the logical choice for designing a pilot prototype of the Turrellian lamp.

7.3.2 M5Stack ESP32

Two M5Stack ESP32 development boards were utilised, one to collect users physiological heart data and the second to orientate the LED strips contained within the Turrellian lamp. As an Arduino product, the M5Stack was easily configurable and scalable following initial UNO-led prototyping.

The M5Stack had all the relevant GPIO pins for connection to the heart rate monitor and LED strips. Furthermore, integrated WiFi modules enabled transfer of data within JSON packets to the Hive MQTT broker – to ensure coherent communication with the Turrellian lamp application. Furthermore, the M5Stack LCD display enabled data to be printed to screen during development and provided an appropriate eventual UI.

7.3.3 Neopixel RGB LED strips - WS2812B

Each WS2812B LED strips offered 144 individually-controllable LED pixels on PCB. The PCB provided extra flexibility and each LED could be controlled individually. Furthermore, the LED strips, digitally addressable functionality enabled the colour of each LED to be set red, green and blue component with 8-bit PWM precision (thus 24-bit color per pixel).

The LEDs are controlled by shift-registers that are chained up and down the strip enabling adjustments to the length of the strip. Furthermore, just 1 digital out pin is required to transmit data throughout the strip. Indeed, the PWM is built into each LED-chip - therefore the colour is maintained after appropriately setting the strips contained within Turrellian lamp. For the Turellian lamp system architecture - two strips were utilised. However, during prototyping phases over four LED strips were trialled and tested.

7.3.4 M5StickC ESP32-PICO

A single M5StickC ESP32-PICO board was utilised to track users skin temperature changes. Much like the M5Stack as an Arduino product, the M5StickC could neatly follow initial UNO led prototyping. Additionally, the M5StickC came with a comfortable wrist strap and a number of appropriate hats for documenting physiological data measurements.

7.4 Robbie's media

Robbie's media helped supply the wooden panels, wood varnish, PVC plastic and equipment to build a pilot prototype Turrellian lamp. During the pandemic this was especially generous – because I was able to use their on-site wood cutting and sanding equipment to help produce a desirable and aesthetic end product prototype.

CHAPTER 8

HARDWARE DEVELOPMENT

The following chapter firstly (1) describes initial sketches of the hardware design before secondly (2) the development of the hardware system for the Turrellian lamp. Lastly and thirdly (3), inevitable development bugs found and remedied for the Turrellian lamp. This chapter is particularly important as there is very limited public information reviewing hardware or sensor reliability for MHCI research, LED system designs and microcontroller performance. Furthermore, MHCI researchers and LED technicians often do not disclose there system architecture, circuitry and hardware used or if the hardware is even publicly available and affordable. Resulting in difficulty determining which publicly available, affordable sensors and LED hardware is reliable and making projects significantly more expensive due to development bugs.

8.1 Sketches and hardware design

As noted in the tools section, once I had initially decided to incorporate NeoPixel RGB LED strips into the hardware design with 144 LEDs per metre. Utilising the NeoPixel RGB LED strips was certainly a good decision – the number of NeoPixels helped provide immersive lighting, high lux levels and coverage of all colour palettes.

Consequently, I then had to focus on building a hardware container, which could offer functionality and aesthetic elegance. In terms of functionality the hardware container needed to hold the NeoPixel LED strips, two microcontrollers and cast immersive lighting within a room. Additionally, the design had to not be inefficient with space - without a large base surface area and thus take up little floor space in any given environment.

Initial design ideas focused on trying to build a unit which would immerse users in potent and high lux lighting. Therefore, the unit had to incorporate sufficient surface area to project lighting from the contained strips aptly. Consequently, the design had to be sufficiently tall and thin to incorporate the long and thin RGB NeoPixel LED strip without a large base - therefore I decided to build the Turrellian lamp as an LED tower.

My eventual design was further honed by the Coronavirus pandemic because the University closure meant that a 3D printer based in the University of Bristol's laboratories became largely inaccessible. Constructive discussions with my supervisor thus concluded that I should build in a practical and decisive manner using resources close to my home in London.

Following this, I drew appropriate sketches and then prototype useful 3D models of the Turrellian lamp tower shape out of cardboard. Branching out within my local community, Robbie's Media kindly offered their wood shop and a local wood worker Brian Sharlend helped provide invaluable assistance throughout the process. Therefore the next section details the methods of constructing the Turrellian lamp out of wood.

8.2 Method of construction

Construction of the Turrellian lamp focused on making both a box to hold the circuitry, electronics and the LED tower attached to the box. To create the tower two 1.8 metre x 6cm chamfered skirting boards were used to make the sides (see figure 8.1a). The cavity for the LED strip was made by joining two 2.5 x 1.75 cm moulding strips which when attached to the skirting boards creating cavity in the tower of 3cm square approx. All boards were cut to allow for the height of the box making a final height of 2 metres.

Measuring 1cm down from the edge of thinnest part of the chamfered skirting a 3mm deep channel was routed out the length of both boards. Perspex covered in a ground glass effect film, which was cut to appropriately fit across the gap. Perspex was trialled to appropriately diffuse the lighting within the environment aesthetically. The routed boards were aligned with the chamfer facing the front and the two joined moulding strips were fitted to the flat end of the skirting boards creating a cavity as described above. The tower sides were then secured with 40mm screws bracing each side against the other.

The box was built from one deal panel cut into panels. Each section was fitted with dowling rod for strength and each panel was glued to next creating an open ended cube. Holes were cut for wiring in the top panel which was then drilled to allow for the LED strips to be fitted. The top panel was also drilled to allow 60cm screws to secure the tower to the box. The weight of the tower was balanced to hold it upright by the size of the box.

Once fitted together the perspex (figure 8.1b) was simply slid into the channel and cap, secured with two 25mm screws, which was placed on top of the tower. After assembling the whole lamp was sanded with 80 grade to remove blemishes and scratches. Then professionally finished

(a) (b)

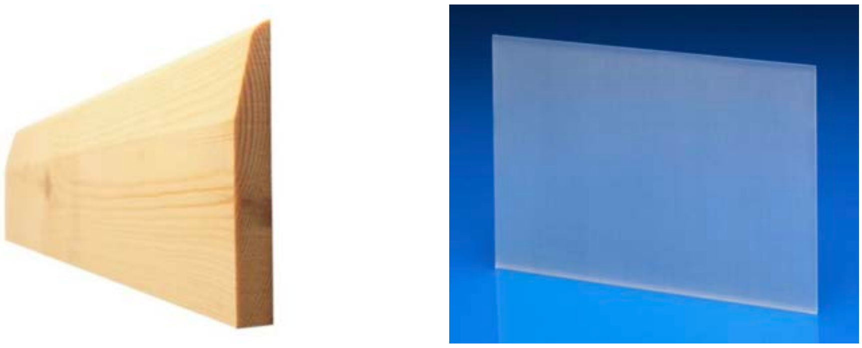


FIGURE 8.1. (a) Chamfered skirting board. (b) Perspex ground glass film.

with 400 grade. Finally, the last touch was to stain the whole assembly with walnut woodstain then polished with a soft cloth for a completed prototype Turrellian lamp made out of wood. Having discussed the construction process of the Turrellian lamp, next this thesis will consider the hardware testing and development involved in the Turrellian lamp architecture.

8.3 Hardware

Having constructed the wooden lamp tower encasing for the LED strips. The computer hardware for the Turrellian lamp architecture can be broken down into two faculties. Firstly, LED-specific hardware and secondly, hardware ensuring multimodal human computer interaction. Consequently, the hardware architecture for the Turrellian LED lamp is displayed as follows:

8.3.1 LED hardware testing

Initial LED prototyping for the Turrellian lamp focused driving simple LEDs with the Arduino UNO (see figure 8.2a). This stage even incorporated designing a 3 bulb lighting system, which fluctuated lit LEDs based on room temperature provided by a low voltage centigrade TMP36 sensor. The TMP36 sensor proved excellent at quickly determining room temperature to 6 decimal places - however was highly unsuccessful for determining skin temperature as a part of the Turrellian lamp multimodal human computer interactive design. Nonetheless the LED bulbs were easily powered and grounded appropriately by the Arduino UNO.

Having initially tested LED bulbs - I decided to continue testing with an Adafruit NeoPixel Ring - 12 x 5050 RGBW LEDs with integrated drivers (see figure 8.2b). These rings were perfect for prototyping potential colour sequences off the Arduino utilising 5V DC current - enabling easy transferal of Arduino code in C++ to effectively program the 5 meter long NeoPixel RGB LED strips within the Turrellian lamp.

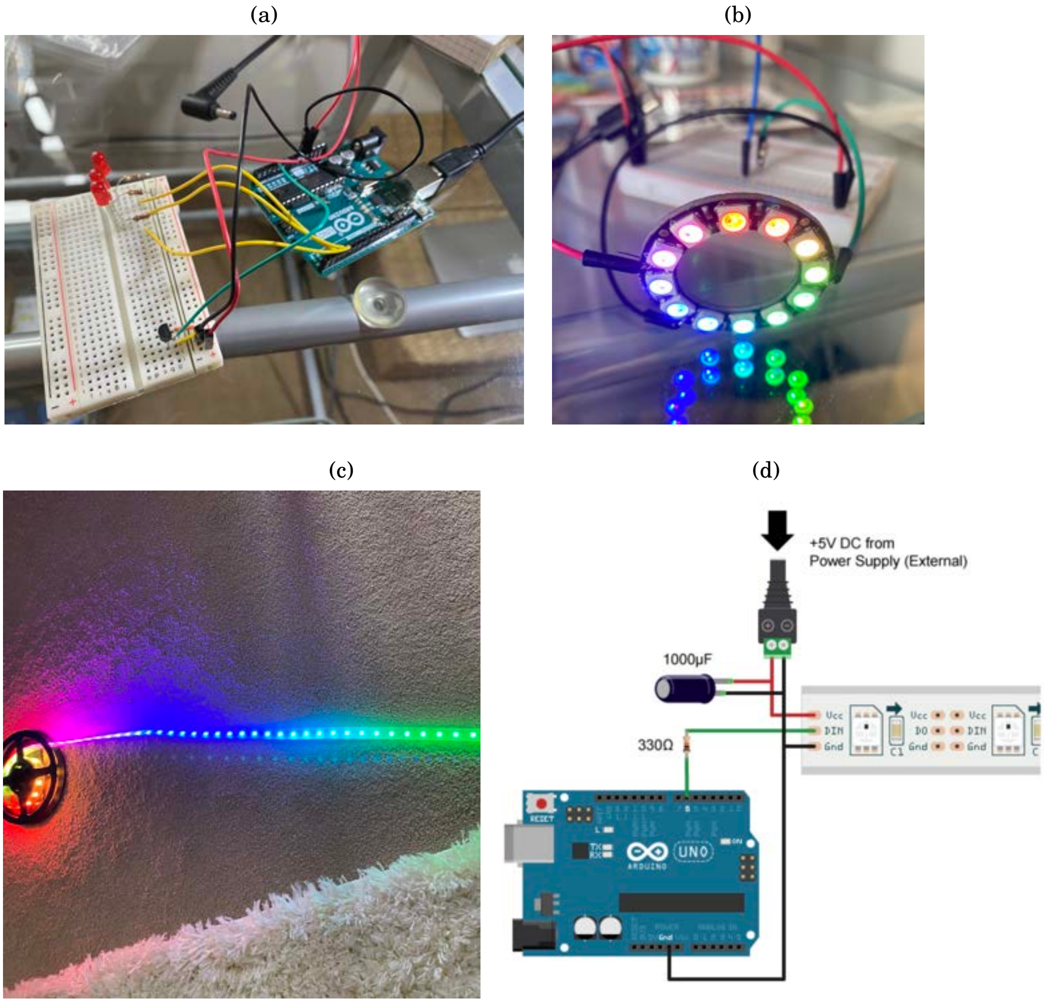


FIGURE 8.2. (a) Testing of the TMP36 LED hardware with LED bulbs. (b) Colour sequences devised utilising a neopixel ring. (c) Testing with the WS2812B Neopixel LED strip. (d) Correct circuit diagrams of testing with the WS2812B Neopixel LED strips.

Resulting in these programmed colour sequences devised in accordance with Valdez's research into light and mood. Multiple equations for dispersing colour effectively along the length of the strip were developed and tested (see figure 8.2c). In particular, colour wiping helped provide an aesthetic interchange between colours when cycling through the colour sequences and was subsequently chosen as best for participant testing.

8.3.1.1 Neopixel strips WS2812B

After intial LED testing, the NeoPixel RGB LED strips (W2812B) for the most part proved excellent for developing the Turrellian lamp pilot prototype for user testing. During prototyping phases several tests were run to determine the effective functioning of each LED strip - with the eventual Turrellian LED lamp architecture incorporating two strips.

Initial testing of the strips included testing the first four NeoPixel LEDs off the Arduino UNO 5V electricity. This start procedure was effective because it was an easy circuit to implement and did not damage the UNO microcontroller with too high current draw. Additionally, the second NeoPixel LED strip test implemented was Adafruit's strandtest - this inbuilt NeoPixel test was highly effective because it cycled through all potential colour sequences. Firstly, red, green, blue and multi-coloured sequences - therefore the strandtest was quick to identify any malfunctioning NeoPixels within each LED strip.

The strandtest also helped determine the need for the Turrellian Lamp to utilise a strip with 144 LEDs per metre - so as to therefore achieve the highest lux values, brightness levels and most immersive colour experience for participants. A lux light meter mobile phone application was utilised during testing to sample the lux values during the light cycles.

However, during prototyping three fundamental hardware issues had to be navigated when one of the NeoPixel LED strips started malfunctioning during the prototyping stage. This particular LED strip initially started blinking, glowing unaddressed LEDs, felt hot to touch and then completely broke. Upon reflection, I had originally been using the NeoPixel strips improperly and no further hardware issues were observed after making the following changes during development of the Turrellian lamp (see figure 8.3a for incorrect circuit and figure 8.2c and 8.3b for correct circuit).

Firstly, to safely power the LED strip a capacitor had to be put across the DC male to female power connector from the AC power adaptor. Indeed, a large capacitor (1000 µF, 6.3V or higher) across the + and – terminals prevented any onrush of current from damaging the pixels. Secondly, a correct AC power adaptor had to be sourced. Thirdly, three hardware issues had to be mitigated with the ESP32 M5Stack and data connection to the LED strips. Having discussed LED hardware for the Turrellian lamp, now I will review a variety of AC power adaptors tested within the Turrellian lamp circuitry.

8.3.1.2 AC power adaptors

Due to the NeoPixel LED strips sensitivity to voltage within the Turrellian lamp - three AC power adapters (aka wall warts) were tested - with one showing best performance for powering the entire Turrellian LED lamp circuit suitably. Firstly, an AmazonBasics Universal DC Power Supply - this power supply was solid, durable, offering multiple connectors and voltages. However, the male DC jack did not properly fit into standard female DC connectors - resulting in voltage being improperly and variably supplied to the strips.

Secondly, an EVER LE 12V 2A Power Supply for LED Strip Lights was tested for powering the Turrellian lamp circuit. This power adaptor did not suffer from connectivity issues - like the AmazonBasics - however, the current supplied was consistently too high for the circuit. Despite the Turrellian LED lamp circuit requiring 12V, the AC power adaptor would cause the LED strips to often flash white upon connection, suggesting voltage spikes above the rudimentary 12V and potentially irreversibly damaging the NeoPixels over time.

Thirdly and lastly, the SoulBay Universal 30W 3V to 12V AC/DC Adapter Switching Power Supply PSU was tested - this offered the best performance of all power supplies. Indeed, the SoulBay Universal came with a key to easily change the voltage for circuit requirements and did not suffer from DC jack connectivity issues with standard female DC connectors. Indeed, throughout all user testing - the SoulBay offered solidity and did not malfunction once. Therefore the SoulBay was considered optimum for the Turrellian lamp within the final design for pilot testing.

8.3.1.3 ESP32 M5Stack microcontroller - LED driver

Two LED drivers were used throughout development of the Turrellian lamp, firstly an ESP32 M5Stack and secondly an Arduino UNO. The ESP32 M5Stack came with numerous other useful inbuilt hardware capabilities - most notably including several ports to ground, drive LEDs, three buttons, WiFi modules and flash memory, whereas the Arduino UNO was comparably more reliable but had far less inbuilt functionality. Initially, prototyping with the M5Stack involved defining appropriate colour sequences through the LCD display.

Following this, I developed an M5Stack GUI and interface for the Turrellian lamp enabling it to be easily used properly throughout user testing. More on M5Stack GUI development is contained in the next chapter on software development, however the loops and UML state diagram of the M5Stack are for LEDs are pictured in figures 6.5 and 9.3.

As noted in the above section 8.3.1, colour sequences for the Turrellian lamp were initially programmed on the Arduino UNO and tested with the NeoPixel LED strips because discussion with my supervisor suggested to mainly use the reliable UNO throughout initial prototyping stages. In retrospect, this was excellent advice because when I transferred correctly functioning NeoPixel strip code, which worked properly on the UNO to the ESp32 M5Stack, I immediately encountered unforeseen hardware errors.

Firstly, in accordance with Adafruit documentation throughout initial UNO testing for the Turrellian lamp I had used a 300 Ohm resistor between the Arduino data output pin and the input to the first NeoPixel. Indeed, the resistor was appropriately placed at the end of the wire closest to the NeoPixel LED strip, not the microcontroller. However, the ESP32 M5Stack immediately malfunctioned and I started receiving a fatal error during uploads relating to a timed out packet header.

This was frustrating and a common hardware issue related to poor manufacturing of the ESP32 M5Stack. Indeed after carefully following several suggestions within the online M5Stack community for remedying the malfunctioning microcontroller. Eventually, I decided to utilise a backup ESP32 M5Stack so as not to sacrifice too much time. This was certainly the correct decision because I had time constraints and specific dates for my user testing.

Eventually, I deduced that the fault had originally arisen from programming the ESP32 M5Stack micro-controller whilst its ports were connected to the LED circuit and also a larger 500 Ohm resistor was required between the data outpin pin of the ESP32 M5Stack and the input to the first NeoPixel. Once this had been mitigated - the ESP32 M5Stack lit up the LED strip with the appropriate colours - however the LED strips would flicker inappropriately and unattractively during Turrellian lamp colour cycles.

Studying archived examples of code on the M5Stack GitHub page, I crucially deduced that unlike the Arduino UNO, the M5Stack could not properly utilise the Adafruit NeoPixel Library to transfer data to the NeoPixel LED strips. Consequently, I had to translate all C++ code written and instead utilise functions within the FastLED library.

Indeed, once I was utilising the correct library and a stronger resistor - the ESP32 M5Stack performed with the LED hardware well for the Turrellian lamp - without any further bugs or errors. Albeit the M5Stack could only maintain sufficient power to transfer data to the Turrellian lamp NeoPixel LED strips for about two hours at a time before it needed to be recharged. However, the ESP32 M5Stack's WiFi module performed well and reliably throughout all user testing - with no incoherent WiFi disconnection.

Notably, the FastLED library came with an advantageous archive of thousands of colour palettes developed by artists and scientists entitled cpt-city. Upon completion of the project - all Turrrellian lamp colour palettes will be submitted to the cpt-city archive for future research. Having discussed the power and drivers of the Turrellian lamp circuitry, now I will discuss the multimodal hardware within the lamp system architecture.

8.3.2 Multimodal human computer interaction hardware

Based on studies conducted by other MHCI researchers I decided to incorporate four physiological variables into the Turrellian lamp system architecture. Namely, galvanic skin response, skin temperature, heart rate and several heart rate variability metrics.

8.3.2.1 Galvanic skin response

During the prototyping phase - GSR was considered as a useful metric to collect for participants physiology. However, the unavailability of sourcing an effective and Arduino compatible GSR sensor during Coronavirus disruption, meant that I decided against pursuing GSR as a part of the Turrellian lamp system architecture. Nonetheless, future prototypes of the Turrellian lamp could look to utilise this metric because research into this variable has shown promise.

8.3.2.2 Skin temperature

Originally, a TMP36 low voltage temperature sensor was considered to take participants skin temperature readings (see figure 8.3c). However, during testing for the Turrellian lamp with a medical grade non-contact infrared thermometer - the TMP36 was found to give incorrect readings over three centigrade. Additionally the TMP36 meant skin contact for at least a minute to determine an appropriate temperature reading. Therefore the TMP36 was not considered as a part of the Turrellian lamp system architecture because of these discrepancies. The TMP36 was re-purposed as an environmental sensor to give room temperature readings during testing.

Instead, M5StickC NCIR Hat(MLX90614) was utilised, which provided two key benefits (see figure 8.4a). Firstly, readings from the NCIR hat were found to be highly accurate to 6 decimal places when tested with the medical-grade non-contact thermometer. Secondly, reliable readings were almost instantaneous (without lag time) and also as a part of the ESP32-PICO M5StickC setup the NCIR hat could be comfortably worn by participants like a wrist watch. Following skin temperature tests, the data could be collected and transferred into the Turrellian LED lamp GUI for both data storage purposes and to provide data for the lamp.

Other hats briefly tested during prototyping stages include the ENV Hat (DHT12, BMP280, BMM150) and PIR hat (AS312) - however these did not fit the purpose of the Turrellian lamp system architecture or offer useful physiological metrics. The ENV Hat disclosed irrelevant (albeit accurate) environmental data and the PIR hat only presented a value of 0 or 1 if a participant was close to the sensor, which was incredibly limiting.

8.3.2.3 Heart rate

Initially a relatively inexpensive ICQUANZX Heart Rate Pulse Module was acquired for testing with the Arduino UNO for the Turrellian lamp's collection of heart rate data on participants. However, testing with the UNO gave very unreliable heart rate readings. Excess noise on the data signal cable resulted in often irregular low or high bpm values for roughly 30 seconds - which greatly impacted mean and standard deviation calculations of heart rate for the Turrellian lamp.

ICQUANZX heart-rate data was calculated to be over 20 percent more discrepant from comparative bpm data acquired via a Fitbit Inspire HR in the same window. This unreliability prompted my acquisition of a Pulse Sensor Amped. Subsequent UNO testing with the Amped massively improved reading discrepancies with the Fitbit Inspire HR data to below 2 percent over a two minute sample window for the Turrellian lamp.

The reliability of the Amped coupled with the vinyl dot stickers, ear lobe and velcro finger attachment greatly improved the circuits heart-rate readings (see figures 8.4 for pictures of circuit and wearable). For experimentation, the velcro finger attachment was favoured because the ear lobe attachment was slightly uncomfortable for the duration of experimentation and difficult if a participant wore earrings. Additionally, testing over a two minute window found no clear data discrepancies in heart-rate readings between the finger and ear lobe to feed the Turrellian lamp with data.

During Turrellian lamp pilot studies, participants heart rate data was collected via an ESP32 M5Stack utilising a pulse sensor. These metrics were then exported over COMS port directly into an excel spreadsheet utilising data-streamer excel functionality. Before collected data was manually inputted through the Turrellian lamp GUI.

8.3.3 Heart rate variability

In accordance with heart-rate, a functioning Amped PulseSensor heart-rate module greatly improved heart rate variability readings for the Turrellian lamp. As discussed in the Software chapter - HRV readings were exported to a Processing file through COMS and live plotted on a graph. In terms of hardware, HRV data was taken by a pulse sensor from a pulse point using a finger velcro strap and connected to an ESP32 M5Stack or Arduino UNO.

During the Turrellian lamp prototyping stages and based on research conducted by other MHCI academics, I decided to incorporate SDNN, RMSSD, SD1 to SD2 ratio readings for determining affect-driven physiological changes. Consequently, this meant taking two HRV samples namely, a time domain or lagged HRV reading and a Poincare map of HRV data.

Ultimately, three of the HRV metrics SDNN, SD1 and SD2 performed very well at reliably determining physiological changes during my initial UNO testing and experimentation. However, RMSSD data readings were slightly more unclear during Turrellian lamp pilot studies and testing - this can be attributed to not enough HRV data taken within the 5 minute sampling window and because RMSSD is a considerably more marginal metric with small changes becoming significant for determining participant moods. Following data collection via the ESP32 M5Stack and Pulse Sensor, once again the data was inputted through the M5 Turrellian lamp GUI.

8.4 Chapter conclusions

The hardware eventually acquired for the Turrellian lamp performed very well. Much trial and error was required to circumvent bugs and I also had to purchase additional compatible sensors for better physiological readings. In particular, my findings concerning the unreliable packet header of the ESP32 M5Stack and bugs accrued with NeoPixel LED hardware are significant for future researchers.

Certainly testing for the Turrellian lamp revealed that the Arduino UNO is a much more reliable micro-controller compared to the ESP32 M5Stack. However, the ESP32 M5Stack did offer crucial inbuilt modules and functionality. Furthermore, the NeoPixel LED strips (WS2812B) offered excellent performance and high lux readings once they were properly used with correct circuitry.

Upon reflection, the hardware demands of the project were very high and my findings underline the importance of properly testing sensors to determine their accuracy and ultimately effectiveness within an MHCI system architecture such as the Turrellian lamp. Indeed, this hardware review should certainly help future MHCI researchers or NeoPixel LED technicians acquire the best manufactured publicly available hardware for their future architectures and designs. Now I will discuss the software used during the development of the Turrellian lamp.

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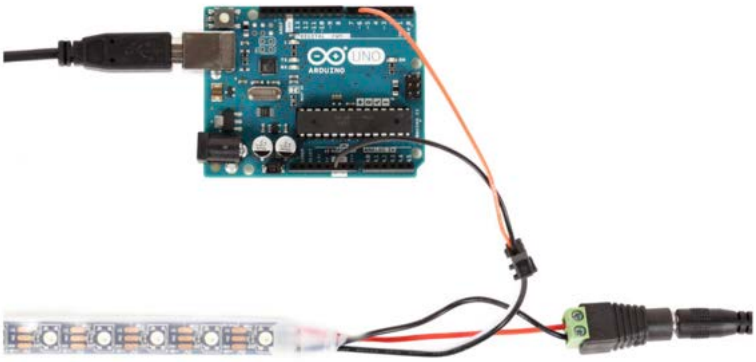

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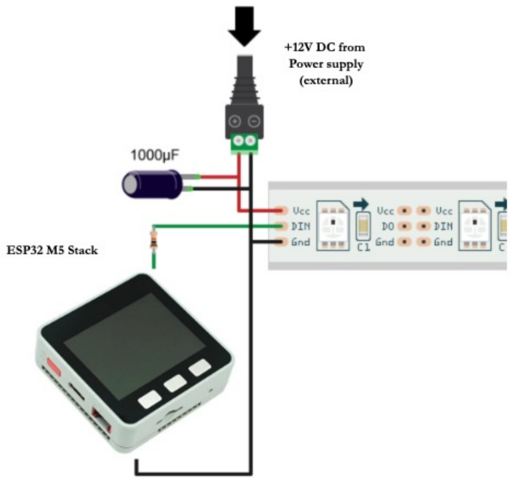


(c)

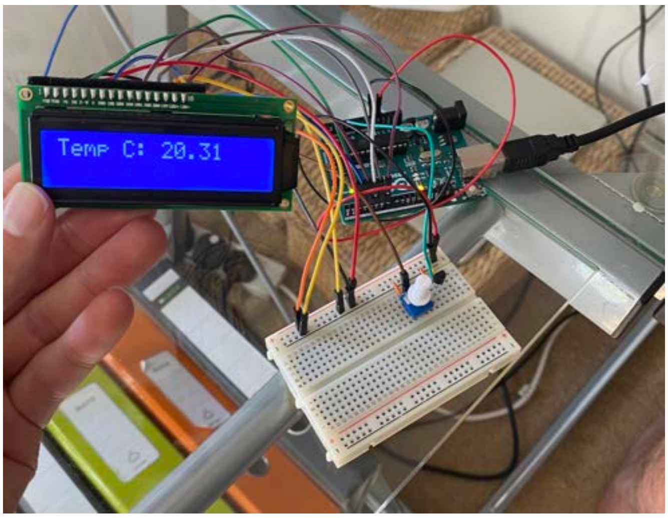
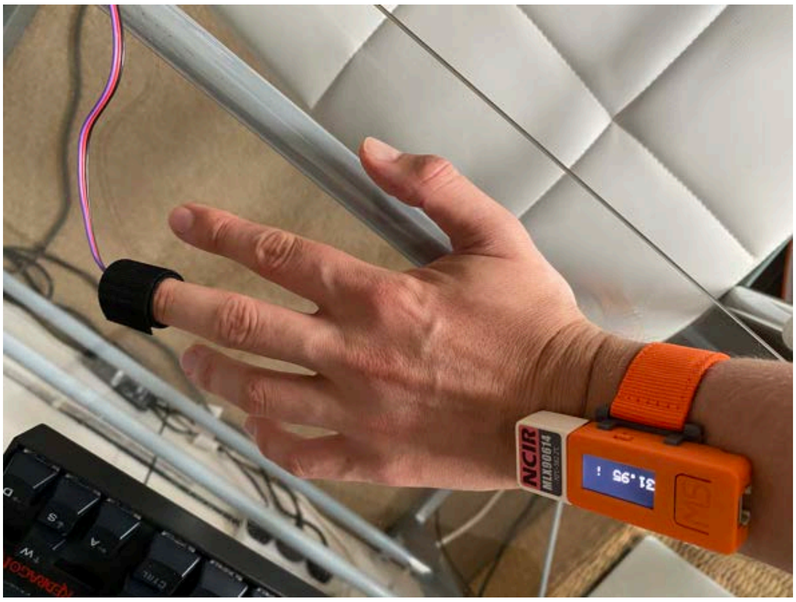


FIGURE 8.3. (a) Incorrect usage of LED strips resulting in strip breakage - no necessary capacitor or resistor. (b) ESP32-M5Stack connection to the LED strips correctly. (c) Testing of TMP36 tsensor for room temperature variables and skin temperature variables using LCD display.

(a)



(b)

FIGURE 8.4. (a) Participants wearing NCIR sensor on wrist to gauge temperature and PulseSensor finger strap on a pulse point to take all heart rate data. (b) The PulseSensor circuit diagram - with ground in black wire, 5V power red wire and pink-blue data wire.

CHAPTER 9

SOFTWARE DEVELOPMENT

This chapter focuses on the software development of the Turrellian LED lamp. The software development cycle can be categorised into three sections. Firstly, (1) the development of the lamps web application and database - written in JavaScript, HTML and CSS. Followed by secondly (2), the evolution of micro-controller code, ESP32 M5Stack GUI and integrated parser - written in C++. Lastly and thirdly (3), the development of a live HRV graph plotter in Processing - written in Java.

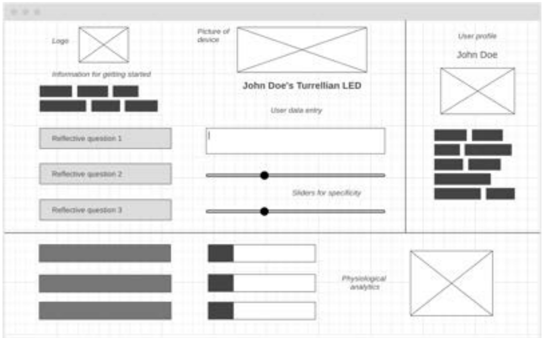
9.1 Turrellian lamp web application

Informal prototyping for the Turrellian lamp web application controller was carried out with friends and colleagues. This was opportunistic and structurally diverse, serving the ends of prototyping - confirming or altering design ideas. Informal testing varied from inviting people to simply play with paper prototypes of the web application and give free feedback, to presenting sketches of interface elements and paper prototypes, and asking people to interpret them.

From these initial sketches, I utilised wireframe.cc to create more functional sketches of the Turrellian lamp web application and help officially prototype a desirable GUI for test participants to eventually use (see figures 9.1). In terms of web application development utilising the Eclipse Paho JavaScript Client library was ideal for submitting the data in JSON format to the public MQTT broker Hive MQ.

Hive MQ is an easy to use public broker for fast prototyping of IoT devices and I had sufficient experience from my degree. The JSON file format was was ideal for transferring data packets of physiological data and participant requests because it was human readable, lightweight and

(a)



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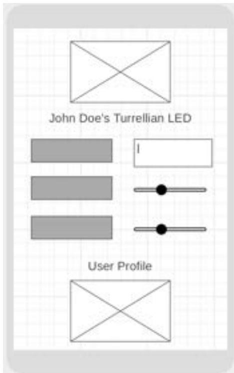


FIGURE 9.1. (a) Wireframe of desktop web application using wireframe.cc. (b) Wireframe devised for mobile phone device or tablet.

simple to parse.

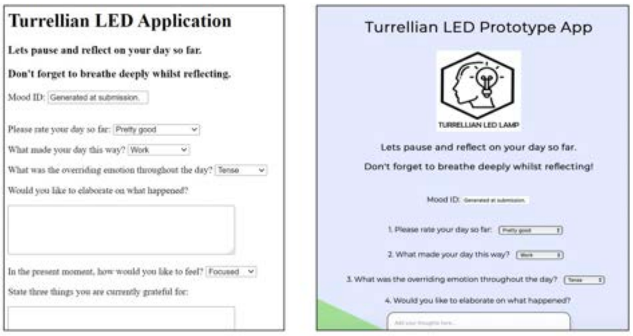
Before CSS styling I got a bare bones version of the system functioning pictured as follows, for conducting relevant transmission tests and trialling the effective functioning of the application (see figures 9.2). Afterwards, CSS styling was appropriately applied to create a more aesthetic end product for user experience (UX) testing.

Although not fundamental, I considered the aesthetics of the Turrellian lamp application important because I wanted the lamp to compare well with the Phillips Hue application during eventual user testing. Having discussed constructing the Turrellian lamp web application, next I will discuss the flat file database ie. the Turrellian lamp mood room.

9.1.1 Turrellian LED lamp mood room

With sufficient time on my hands, I decided to create a secondary web application entitled the Turrellian lamp mood room (see figure 9.2b), which would act as a flat file database. Consequently, this application would connect, subscribe and parse the Hive MQ MQTT topic, deserialise and

(a)



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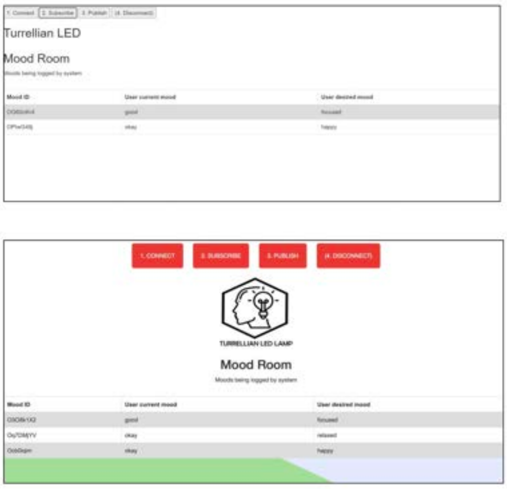


FIGURE 9.2. (a) Images of the web application before and after styling - initial functionality followed by aesthetics from CSS styling. (b) Mood room logging anonymized mood requests dynamically before and after styling.

effectively store requests and data submitted in JSON through the Turrellian lamp application. Much like the web application, the mood room was written in HTML, JavaScript and CSS. Equally, I developed in two tiers - firstly, with appropriate transmission testing and getting the application solely working. Before secondly, applying CSS styling to ensure a desirable end product.

This was certainly a very useful application for processing data inputted by participants through the Turrellian web application. Furthermore, I envisage for future prototypes of the Turrellian LED lamp - that this mood room application could eventually develop into a fully fledged database for users responses, enabling both data collection and serving as a resourceful database to provide users with insights concerning their day-to-day moods.

An essential part of the design focused on creating an HTML responsive table which would

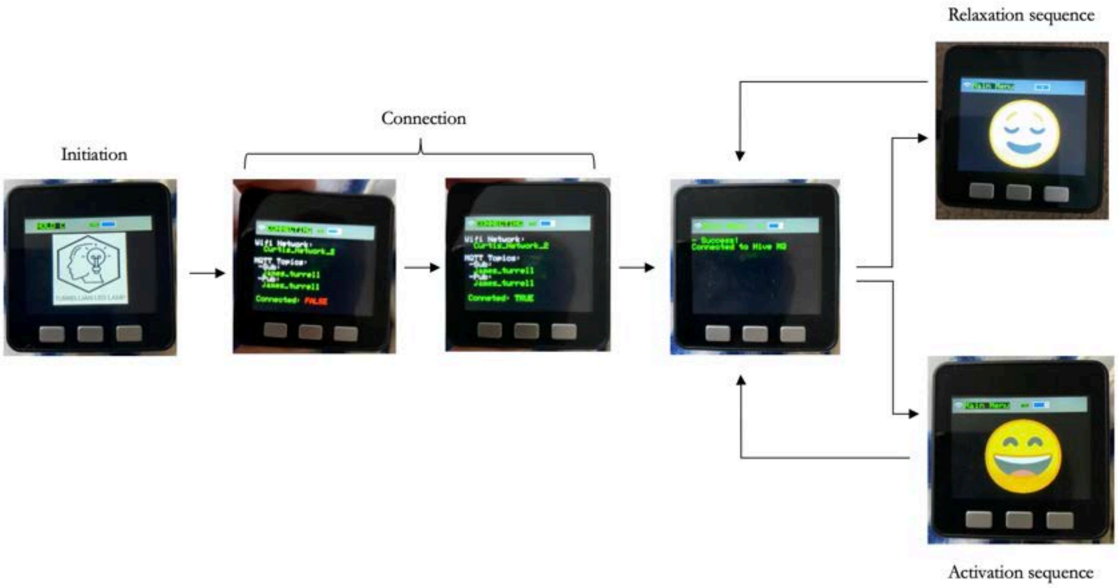


FIGURE 9.3. Figure representing sequences of ESP32 M5Stack GUI from initiation, WiFi connection, before controlling lamp based on physiological data and web application requests.

grow and shrink dependent on the amount of data inputted through the web-application. Furthermore, the Eclipse Paho JavaScript Client library was ideal for receiving and deserializing the received JSON data. The next section will discuss the development of the LED software in particular the M5Stack GUI, which controls the LED strips contained within the lamp.

9.2 LED software development

9.2.1 ESP32 M5Stack GUI

For the M5Stack GUI controlling the LED strips of the Turrellian lamp, I firstly prototyped by getting the M5Stack's LCD to sequence through the defined colour sequences. Having done this, development next focused on creating a simple GUI, which would make user testing easier. Upon suggestion from my supervisor, I focused on developing robust interfaces so as to ensure easy user testing with no sudden bugs or breakages. Indeed, stress testing regularly involved actively trying to break the application and deliberately cause it to malfunction. From this effective strategy - stress testing bugs encountered typically involved unreliable hardware.

For the ESP32 M5Stack GUI, I firstly developed a coherent start up page for connecting to WiFi (see figure 9.3). Indeed, this was integral so as to ensure proper WiFi connection prior to user testing of the Turrellian lamp. Following this, a main menu stage was encoded - which would update with the battery data of the micro-controller and check its WiFi connection. Both of these details were important as the micro-controller battery life was relatively short at typically two hours.

After this, I developed the relevant pages for each mood and encoded the light sequences. I decided to clearly use Google's own emojis to capture each relevant affective sequence for the Turrellian lamp. The ESP32 M5Stack would parse the MQTT pub sub topic for JSON data, deserialise the data using functionality from the ArduinoJson6 library, deduce the viable light sequence, output the appropriate affective lighting sequence and interface. After completing the sequence, the Turrellian lamp would subsequently return to Main Menu as entailed in the state diagram. Following discussing the GUI microcontroller for the Turrellian lamp, now I will discuss software development relating to the physiological code for wearables worn by users of the Turrellian lamp.

9.3 Physiology software development

9.3.1 Skin temperature

For the first Turrellian lamp wearable, I developed a very basic ESP32-PICO interface in C++, which would connect to WiFi and utilise the NCIR hat to submit participants skin temperature readings every few minutes to Hive MQ and for import into the Turrellian lamp GUI. After experimentation, I transferred all relevant skin temperature data to appropriate CSV files.

9.3.2 Heart data

For the next Turrellian lamp wearable to collect proper circulatory data I utilised an ESP32 M5Stack and Pulse Sensor Amped to firstly collect rudimentary heart rate data. For each participant a minimum of 200 readings were taken and submitted to Hive MQ. During experimentation, data streamer over COMS was utilised to immediately transfer the data into xhtml files succinctly. Similarly, HRV data collection involved the exact same hardware setup. Rather than xhtml, instead a Processing application written in Java would connect over COMS and live plot the HRV data for each participant onto appropriate graphs.

Development involved initially utilising open source Java examples provided by PulseSensor. To enable collection of both Poincare maps and time sensitive HRV data for each participant.

However, adjustments were made to the Processing Java code so as to improve the scale of the graphs ensuring accurate and optimum readings collected for each participant. A common hardware-software bug encountered during testing was that often the ESP32 micro-controller provided too much noise down data lines which interfered with reliable HRV readings. Consequently, this was mitigated by encoding the graph plotter to not plot outliers (ie. excessively high or low readings) and using longer data transmission cables.

However, when this was occasionally not effective - the ESP32 M5Stack had to be quickly restarted to make the noise less perpetual. Fortunately this problem did not occur during official user trials. Following reliable collection, HRV data was appropriately saved and stored in CSV files in the cloud. After focusing on wearable software development - now I will discuss conclusions for the chapter.

9.4 Chapter conclusions

Software development for the Turrellian lamp was multifaceted utilising many different languages and libraries. Furthermore development particularly focused on user interfaces and transmitting physiological data in JSON format reliably. Software performed very reliably - with limited bugs or errors - however often code had to be adjusted to account for hardware unreliability. For future researchers, I would definitely recommend researching as many demo examples as possible utilising the underlying hardware and stress test as much as possible. For each piece of Turrellian lamp hardware - there were plenty of useful code examples on Github and message boards concerning the best software practices for the underlying hardware and troubleshooting bugs. Furthermore, particularly for the M5Stack and ESP32-PICO - solutions to bugs such as excess noise on data lines were sometimes idiosyncratic (e.g. longer data cables).

Additionally, in terms of evaluation - my stress test development strategy, which focused on getting a robust and working bare system before applying aesthetic styling was certainly effective. Indeed, this strategy helped mitigate software bugs and ensured that eventual user testing was much more straightforward for the Turrellian lamp. The next chapter will now discuss calculations and prototype evaluation of the Turrellian lamp before considering the results of the project.

Chapter 10

Prototype assessment, calculations and test protocol

Due to the hardware demands of the project - this chapter firstly, evaluates and critiques the final hardware prototype of the Turrellian lamp (see figures 10.1). Following this, secondly, I discuss the testing protocol utilised for user testing of the Turrellian lamp. Lastly and thirdly, the chapter will discuss calculations for the statistical analysis employed to reach data results for the Turrellian lamp.

10.1 Final prototype

The final prototype of the Turrellian lamp is in essence a large LED strip tower that is controlled by a novel emotion journal web application, physiological biofeedback sensors and an integrated parser providing a mood database. The lamp can display any profile of colour sequences - however, light sequences have been designed utilising insights from Valdez et al. [216] so as to improve users mood. Now, I will evaluate the prototype by discussing weaknesses and strengths of the prototypes system, design and and hardware.

10.1.1 Weaknesses

Due to the fact that the Turrellian lamp is only a prototype there are obviously shortcomings, which would need to be solved in future prototypes of the lamp. Three key weaknesses of the prototype include that the system is not completely autonomous, the prototype is not fully integrated with existing commercial hardware and problems were encountered with programming the ESP32 M5Stack microcontroller hardware.

Although, the Turellian lamp is not quite fully autonomous - the groundwork is in place to immediately develop a completely autonomous version. Indeed, the existing Turrellian lamp does not employ sophisticated machine learning algorithms to collect sizable amounts of users data and recognise their desired lighting entirely automatically. Rather users must utilise an application and input physiological data to notify the existing Turrellian lamp of their desired emotion.

In contrast, future designs of the Turrellian lamp could look to collect and process extensive quantities of users emotional data throughout each day. Coupled with machine learning algorithms operating in the cloud - the Turrellian lamp could then learn to autonomously completely serve the lighting needs of the user without the need for any explicit commands. However, the existing application which mimics a journal entry is certainly novel and was very appreciated by participants. Therefore a fusion of both approaches utilising a journal application and machine learning would be very desirable.

The second key weakness is that the existing Turrellian lamp is not integrated with present hardware and common computer systems. For example, the lamp is not compatible with an Apple Watch, Fitbit or other common smart devices to collect the necessary physiological data. Indeed, the current Turrellian LED lamp system utilises an Arduino compatible heart rate, skin temperature sensor and the existing application is only controllable via computer. Instead future prototypes would have to be more polished - thus offer Turrellian lamp applications controllable from smart phones and existing smart devices.

Lastly, the ESP32 micro-controller's were fantastic for prototyping. However, a new specific and customised micro-controller would need to be designed for future Turrellian lamp system architectures. In particular, the battery life of the ESP32 micro-controller's meant only two hours of data collection, which is simply not long enough and multiple issues were found with noise affecting data collection. As highlighted by these three weaknesses, the final prototype of the Turrellian lamp for pilot studies is by no means the finished article and now I will consider the strengths of the lamp.

10.1.2 Strengths

The initial weaknesses of the Turrellian lamp can be largely attributed to the device being a prototype built and manufactured single handedly - resulting in not a completely polished product. Despite this, there are plenty of strengths concerning the present Turrellian lamp prototype - however for the purpose of evaluation, I would like to emphasise three core strengths. These strengths would be: its aesthetic yet large size, the revolutionary system architecture and the simplicity for users.

Firstly, the aesthetic yet large size of the Turrellian lamp is a huge bonus - it is a gigantic LED tower compared to commercial counterparts, standing at over six feet in height. However it has the elegance of a very slender base and thus taking up minimal floor space. Furthermore, the significant surface area of the design meant very high lux values and immersive lighting within any given room.

Secondly, with regards to the system architecture - like most MHCI designs it is incredibly novel to have a device which responds to how a user is presently feeling, their physiological changes and emotional signals. Indeed, the Turrellian lamp system architecture is certainly ahead of its time yet it still only utilises accessible open source micro-controller technology. Responses from individuals who have taken an interest in the project - have been of interest, awe and excitement at the potential of the system - both its artistic and technological contribution.

Thirdly and lastly, for the end user - the present Turrellian lamp system is in fact arguably more simple than competitor devices. Without a large setup and initialisation procedure through the App like the Phillips Hue. The Turrellian lamp requires a simple wall plug and utilisation of the App to immediately start working and providing ambient lighting. As noted earlier, with more automation of future Turrellian lamp architectures - the system has the potential to get even more simple for users to control. These core strengths coupled with the results detailed in the next chapter emphasise the burgeoning potential of the Turrellian lamp for both academia, MHCI and to improve users quality of life through immersive lighting and self-reflective journaling.

10.2 Testing protocol

Prior to all phases of testing all necessary cleaning and disinfection was undertaken for 10 minutes inline with Coronavirus guidelines. In accordance with University of Bristol guidelines testing was permitted over Skype phone calls. The lamp was delivered to my commercial partners' HQ and was easily accessible for all participants.

Testing for each participant was split into seven stages:

Initially a meet and greet over Skype began testing - a brief two to three minute session in which I readied the system, described general principles and answered questions.

First set of physiological readings - using the ESP32 PICO, ESP32 M5Stack and PulseSensor - participants physiological heart and skin temperature data was initially taken for 5 minutes.

Participants were then invited to utilise the Turrellian lamp GUI - it often took roughly 5-10 minutes for participants to use the GUI and enter all of their data.

Upon sending their data to the lamp, participants enjoyed the light sequence for five minutes whilst a second set of physiological readings were duly taken during light exposure.

Participants then filled in an AttrakDif questionnaire on the Turrellian lamp - documenting their experience for 5 minutes.

Following this, participants were invited to use the Phillips Hue GUI on a mobile device and control a smart bulb for roughly 5-10 minutes.

Then a secondary AttrakDif questionnaire on the Phillips Hue was taken for roughly 5 minutes.

Following testing any further questions were answered and some participants informally provided their thoughts before thorough cleaning and disinfection.

10.3 Statistical calculations

As noted in the previous section, physiological readings were sampled before and after the participants experienced the Turrellian lamp interface and lighting. The analysis conducted on the physiological data is as follows. Furthermore, for questionnaire data, I will briefly outline the AttrakDiff questionnaire system.

10.3.1 Heart rate and skin temperature

For participants heart rate (HR) and skin temperature data - the mean and range of both heart rate and skin temperature (ST) was calculated via equations 10.1-10.4:

$$Avg.HR = \frac{Sum\,of\,HR\,samples}{Number\,of HR\,readings} \tag{10.1}$$

$$Avg.ST = \frac{Sum\,of\,ST\,samples}{Number\,of ST\,readings} \tag{10.2}$$

$$HR\,range = HR\,max - HR\,min \tag{10.3}$$

$$ST\,range = ST\,max - ST\,min \tag{10.4}$$

From this, percentage change calculations were made utilising the formulae equation 10.5 as follows:

$$Percentage\,change = \frac{Value_2 - Value_1}{Value_1} \times 100 \tag{10.5}$$

Running statistical calculations for these variables was not computationally taxing - yet nonetheless can help provide an important snapshot of physiological changes for these variables.

10.3.2 Heart rate variability

In line with the toolbox utilised by fellow HRV researchers five metrics were calculated.

10.3.2.1 Time domain methods

The standard deviation of NN intervals (SDNN) was calculated - it is therefore a measure of changes in heart rate variability. Furthermore, SDNN reflects all the cyclic components responsible for variability in the period of recording, therefore it represents total variability (see equation 10.6 below). HRV research suggests that SDNN correlates with with low frequency (LF) power - reflecting the activities of sympathetic and vagal nerves, mainly sympathetic activity [237]. Secondly, RMSSD, the square root of the mean of the squares of the successive differences between adjacent NNs was calculated (see equation 10.7 below). Unlike SDNN, HRV research suggests that RMSSD correlates with with high frequency (HF) power - reflecting the vagal activity [237]. After calculating these variables for participants, they were compared to benchmark readings taken by Zhu et al. [237].

$$SDNN = \sqrt{\frac{1}{N-1}\sum_{j=1}^{n}(NN - \overline{NN})^2} \tag{10.6}$$

$$RMSSD = \sqrt{mean\,((NN_i - NN_{i+1})^2)} \tag{10.7}$$

10.3.2.2 Geometric methods

In line with both the toolbox of fellow HRV researchers and MHCI research utilising HRV metrics - Poincaré graphs were plotted. From these Poincaré scatter plots SD1, SD2 and the SD1 to SD2 ratio was calculated (see figures 3.3a and b). SD1 represents the standard deviation of the distances of the RR intervals to the lines y = -x + 2RR mean in a Poincaré plot - which quantifies the fast beat to beat variability of the HRV series [237]. In contrast, SD2 represents the standard deviation of the distances of the RR intervals to the lines y = x in a Poincaré plot, which quantifies the longer term variability of the HRV series [237].

Abstracting from Goshvarpour's research, circular and clustered Poincaré plots - typically are associated with negative valence and less HRV (see figure 3.2a). Additionally, the minimum changes in the lagged Poincaré measures were perceived during negative valence inducements. However, in positive valence stimuli represent a more cigar-shaped and well scattered Poincaré plot. Additionally, the greatest increment in SD1 and decrements in SD2 occurred during the happiness stimuli for lagged Poincaré plots - making the shape more ovular.

10.3.3 Questionnaire data

To get a very accurate reflection on user experience with the Turrellian lamp and the control light - the Phillips Hue smart bulb, I chose to use existing evaluation software called AttrakDiff. This software allows users to select how they feel using the interfaces by selecting an option on a scale between two word pairs. This approach removed bias, as founder of the AttrakDiff questionnaire method, Hassenzahl notes, “a poet may find beautiful words to describe her experience, this does not make it superior to what more mundane people experience.”

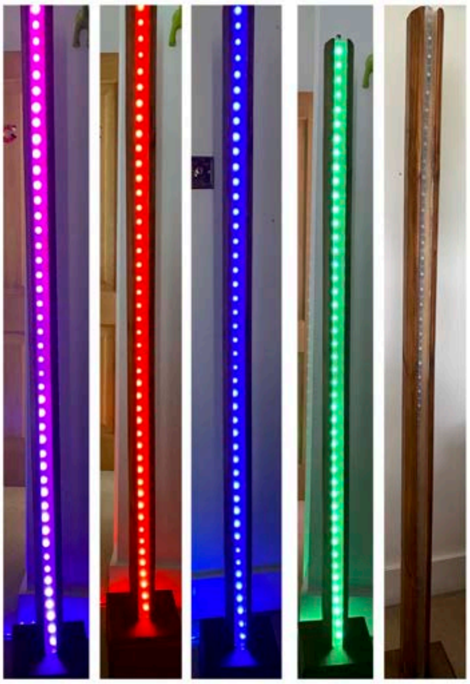
The responses collected were broken down and comparisons in user experience (UX) between the Turrellian lamp and Phillips Hue smart bulb were made to determine if the Turrellian LED lamp improves UX. Hassenzahl, identifies that a key concern of HCI in adapting technology to human nature. He find that UX has both pragmatic and hedonic qualities. Pragmatic quality refers to the product’s ability to complete potential tasks, whereas hedonic qualities allow the user to relate to the product and contributes directly to the user’s positive, or otherwise, experience.

Hassenzahl strongly criticises current models of UX evaluation is focused only on the pragmatic qualities, examining how well a product performs a particular task, rather than on how the user feels as that task is being carried out. The Attrakdif questionnaire software collects data concerning the pragmatic, hedonic and attractiveness of the product being evaluated. The hedonic aspect was an important component to the design of the Turrellian lamp, because it was important to determine if the Turrellian lamp resonated with users and left a lasting impression.

10.4 Chapter conclusions

This chapter has discussed the strengths and weaknesses of the Turrellian lamp pilot prototype. Before outlining the testing protocol, calculations made and Attrakdif questionnaire protocol. In terms of self-evaluation, I was ultimately very pleased with the final prototype considering the difficult Coronavirus circumstances. Admittedly proper testing procedures and a more polished version of the Turrellian lamp could certainly be achieved in more normal circumstances. The next chapter will now discuss results of the Turrellian lamp pilot testing.

(a)



(b)

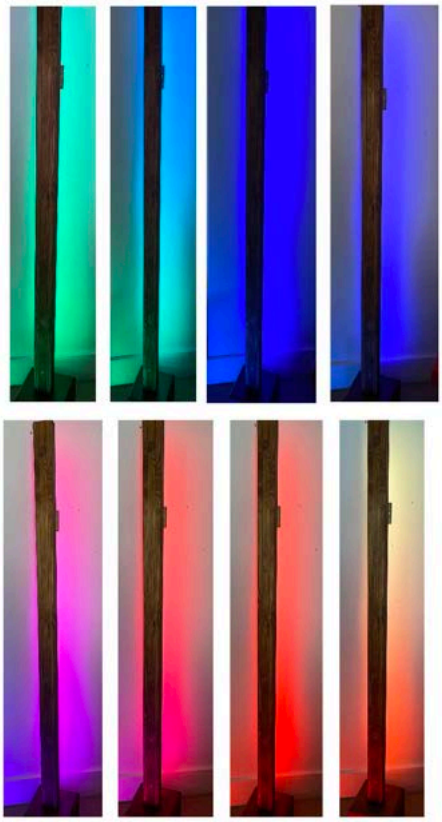


FIGURE 10.1. (a) Turrellian lamp front view with different colours and switched off. (b) Projection of Turrellian lamp coloured lighting against a white wall.

CHAPTER 11

RESULTS

This chapter will firstly cover all physiological data and whether participants mood did improve and trend towards the emotion requested - thanks to the Turrellian lamp application and lighting changes. Following this, I will discuss the questionnaire data and the Turrellian lamp performance versus the control - the Phillips Hue smart bulb. Lastly, I will evaluate some of the minor limitations of this pilot testing during the Coronavirus pandemic.

11.1 Physiological results

Each participant made personalised requests through the Turrellian lamp GUI application - I will briefly discuss the physiological data collected for each participant and provide tables showing changes. Before evaluating overall conclusions on the data collected. During live testing at the beginning of August - 6 participants were tested with a commercial partner based in London. The company wanted to determine if ambient lighting would improve their day-to-day services.

For reminder, HR denotes heart rate and ST denotes skin temperature. Whilst, for HRV metrics RMSSD denotes the square root of the mean of the squares of the successive differences between adjacent NNs and SDNN denotes standard deviation of NN intervals - all explained calculations are in the previous chapter 10.

11.1.1 Participant 1

State	*Avg. HR*	*Range HR*	*Avg. ST*	*Range ST*	*RMSSD*	*SDNN*
Pre-lighting (nervous)	88.1	23	32	0.5	39.9	40.7
Post-lighting (relaxed)	87.1	42	31.5	1.1	38.8	48.1
% change	-1.1	+82.6	-1.6	+120	-2.76	+18.2

Emotion change (fig 11.2)	*S1*	*S2*
Nervous to relaxed	↑	↑

Participant 1 initiated through the Turrellian lamp GUI, a preference to move from a nervous to relaxed state. They self-reported that the Turrellian lamp helped them significantly feel more relaxed. Initial readings suggest the participant is feeling nervous and sad with a high avg HR, wide HR range suggesting nervousness and both SDNN and RMSSD readings are close to 40 correlating with sadness.

Subsequently, almost all of the physiological data correlates with the participant feeling more relaxed thanks to the Turrellian lamp lighting observed changes post-lighting include - a fall in average HR, fall in RMSSD towards a more calm emotion reading of 35 and rise in SDNN towards a more happy emotion reading of 50. However the rise in HR reading range does suggest the participant still feels slightly nervous.

Yet, the small skin temperature fall and widening of range inclines a decrease in overall mental arousal and is thus also coherent with a more relaxed state. Additionally, the rise in both S1 and S2 correlates with an increase in HRV - denoting a better overall mood and increase in pleasure.

11.1.2 Participant 2

State	*Avg. HR*	*Range HR*	*Avg. ST*	*Range ST*	*RMSSD*	*SDNN*
Pre-lighting (tense)	89.4	73	33.4	0.4	65.5	55.9
Post-lighting (excited)	90.6	23	33.2	0.6	108	87.9
% change	+1.3	-68.5	-0.67	+50	+64.9	+57.2

Emotion change (fig 11.2)	*S1*	*S2*
Tense to excited	↑	↑

Participant 2 requested a preference for the Turrellian lamp lighting to help them move from a tense to excited mental state. The participant self-reported that lighting from the Turrellian lamp did help them feel reasonably more excited. The pre-lighting readings certainly suggest the participant is feeling tense with a high HR reading, SDNN reading of 55 inclining anger and RMSSD reading of 65 suggesting fear.

Equally, post-lighting readings suggested a reasonable degree of increase in participants excitement with an increase in HR, consistently high skin temperature reading and increase in the SDNN, which is coherent with an excited mental state. Additionally, the rise in both S1 and S2 correlates with an increase in HRV - denoting a better overall mood and cognition. However, as will be evaluated the final RMSSD reading of 108 is inconclusive.

11.1.3 Participant 3

State	*Avg. HR*	*Range HR*	*Avg. ST*	*Range ST*	*RMSSD*	*SDNN*
Pre-lighting (bored)	90.7	25	32.9	0.6	87.3	68.9
Post-lighting (contented)	79.9	15	33.3	0.1	46.7	36.5
% change	-11.9	-40	+1.2	-83.3	-46.5	-47

Emotion change (fig 11.2)	*S1*	*S2*
Bored to contented	↓	↑

Participant 3 indicated that the lighting from the Turrellian lamp should help them move from a bored to contented cognitive state. The participant self-reported that the Turrellian lamp did help them feel better and more contented. The pre-lighting readings in particular the high avg HR reading suggest the participant was feeling perhaps slightly stressed. However the initial SDNN reading is coherent with low arousal and boredom.

The post-lighting readings strongly suggest the Turrellian lamp helped the participant shift towards a more contented mental state. In particular, the significant decline in avg. HR, rise in skin temperature, additionally the SDNN reading suggests low arousal and RMSSD reading is incredibly close to a happiness reading of 37. Furthermore, as research by Goshvarpour has demonstrated - the fall in S2 and rise in S1 is most coherent with happiness [56]. Additionally, the overall increase in HRV - denotes better mood and cognition.

11.1.4 Participant 4

State	*Avg. HR*	*Range HR*	*Avg. ST*	*Range ST*	*RMSSD*	*SDNN*
Pre-lighting (depressed)	90.1	10	32.2	0.8	44.1	32
Post-lighting (happy)	91.2	46	34	1.1	53.7	51.4
% change	+1.2	+360	+5.6	+37.5	+21.8	+60.6

Emotion change (fig 11.3)	*S1*	*S2*
Depressed to happy	↑	↑

Participant 4 requested a shift from a depressed to a more happy mental state. Initial readings highlight a sad mental state with a low avg skin temperature reading, both RMSSD and SDNN readings correlate with a sadness reading of 40. The participant self-reported that the Turrellian lamp helped them feel more happy.

Furthermore, bar the RMSSD reading, the physiological data is certainly very coherent with a happier mental state - the rise in avg. HR, rise in avg. skin temperature and SDNN reading of close to 50 are all coherent with a happier mental state thanks to the Turrellian lamp lighting. Furthermore, the rise in both S1 and S2 correlates with an increase in HRV - denoting better overall mood and cognition.

11.1.5 Participant 5

State	*Avg. HR*	*Range HR*	*Avg. ST*	*Range ST*	*RMSSD*	*SDNN*
Pre-lighting (happy)	88.3	15	32.5	1	76.3	54.9
Post-lighting (excited)	101.1	60	33.5	1.1	56.3	56.9
% change	+14.5	+300	+3.1	+10	-26.2	+3.6

Emotion change (fig 11.3)	*S1*	*S2*
Happy to excited	↑	↑

Participant 5 initiated a move from a happy mental state to more excited. The initial SDNN is slightly incoherent but relatively close to a happiness reading of 50, the consistently high skin temperature and normal HR certainly suggests a positive mental state. However, the RMSSD reading is incoherent. The participant reported that the Turrellian lamp did not do much for their emotions as they already felt good.

Despite this self-reflection, the sharp rise in avg. HR above 100, sizable fall in RMSSD and persistent SDNN reading suggest that the participant physiologically certainly started exhibiting more arousal and excitement as a consequence of the Turrellian lamp light exposure. In equal measure, the rise in both S1 and S2 correlates with an increase in HRV - denoting better overall mood and cognition.

11.1.6 Participant 6

State	*Avg. HR*	*Range HR*	*Avg. ST*	*Range ST*	*RMSSD*	*SDNN*
Pre-lighting (excited)	93.6	17	33.5	0.8	50.4	51.8
Post-lighting (focused)	93	84	33.3	0.2	53.9	42.6
% change	-0.6	+394	-0.6	-75	+6.9	-17.8

Emotion change (fig 11.3)	*S1*	*S2*
Excited to focused	↓	↑

Participant 6 indicated a movement from an excited to focused mental state. The initial readings - high avg. HR, high avg. skin temperature, SDNN reading suggest that they felt positive with high arousal. They self-reported that they still felt very similar however they liked the lighting and would like to study or work with such ambience.

Indeed, the physiological readings correlate with this self-reflection - although the range of HR increased, the avg. HR, avg. skin temperature, RMSSD reading remained almost unchanged. However, the SDNN fall suggests a shift towards slightly more arousal. Much like participant 3, the fall in S2 and rise in S1 is most coherent with a happy mental state [56]. Equally, the overall increase in HRV - denotes better mood and cognition.

11.1.7 Evaluation and physiological reading conclusions

For each participant the Turrellian lamp lighting caused physiological changes and four out of six participants - 67% self-reported direct improvements in mood, which they directly attributed to the Turrellian lamp. Notably, the physiological readings and the biometric data collected suggested that five out of the 6 participants or 83% physiologically improved towards their desired positive mental and emotional state from the Turrellian lamp lighting.

The physiological readings coupled with participant self-reflection through the web application offered an accurate and sensitive methodology for classifying participant's present mental state within the Turrellian lamp system architecture. Consequently, I certainly expect that future versions of the Turrellian lamp could certainly acheive above 75% automatic emotion classification accuracy with enough participant data, the PAD model and utilising machine learning techniques.

Physiological readings for skin temperature, HR and SDNN were highly reliable as demonstrated in Table 11.1 - with the capacity to show sudden spikes or shifts in arousal and emotion caused by the lighting. However, both skin temperature and HR metric changes could not classify participants current emotion as effectively as HRV. Across the participants, the HRV readings - particularly SDNN helped provide highly sensitive classification of specific emotion, therefore it is unsurprising these metrics have been typically favoured for machine learning MHCI affective classification algorithms. Additionally, the readings for S1 and S2 helped effectively denote changes in participants HRV and were helpful to determine if participants were trending towards improved cognition and overall mood.

Collectively, the physiological readings for participants demonstrated accurate metrics for determining positive improvements in participants cognition caused by the Turrellian LED lamp lighting. However, as noted in Table 11.1, the RMSSD readings on some occasions produced inconclusive and erroneous readings - as demonstrated in participants 2, 3 and 4 - this can be attributed to spikes from excess noise along data lines for the PulseSensor and certainly insufficient HRV data collection.

Participants heart data was only collected for 5 minutes at a time which for long-term metrics such as RMSSD is perhaps too short - indeed I would certainly expect improvements in physiological readings via classification over a much longer period and through utilising machine learning techniques.

Overall, the data collected provides two positive conclusions. Firstly, the physiological data collected within the MHCI Turrellian system architecture could reliably classify improvements in

Participant and state	*HR*	*ST*	*RMSSD*	*SDNN*	*S1*	*S2*
P1 (nervous)	✓	✓	✓	✓	✓	✓
P1 (relaxed)	✓	✓	✓	✓	✓	✓
P2 (tense)	✓	✓	✓	✓	✓	✓
P2 (excited)	✓	✓	×	✓	✓	✓
P3 (bored)	✓	✓	×	✓	✓	✓
P3 (contented)	✓	✓	×	✓	✓	✓
P4 (depressed)	✓	✓	✓	✓	✓	✓
P4 (happy)	✓	✓	×	✓	✓	✓
P5 (happy)	✓	✓	✓	✓	✓	✓
P5 (excited)	✓	✓	✓	✓	✓	✓
P6 (excited)	✓	✓	×	✓	✓	✓
P6 (focused)	✓	✓	✓	✓	✓	✓

Table 11.1: ✓- the metric was successful for achieving emotion recognition compared to benchmark readings. × denotes an inconclusive potentially erroneous physiological biofeedback reading. Consequently, SDNN, HR, S1, S2 and ST provided highly reliable physiological metrics - SDNN, S1 and S2 in particular enabled specific emotion classification according to Zhu and Goshvarpour's benchmark readings [56, 237]. In contrast, RMSSD provided mixed results for classification due to briefness of readings for the more long-term variable.

the emotional state of users and mood. Secondly, it shows that ambient lighting and the Turrellian lamp lighting hold much promise for enabling users to reach desirable positive cognition and improving their overall mood based on physiological and verbal feedback. In the next discussion I will discuss the questionnaire results from participants.

11.2 Attrakdiff questionnaire results

Participants used both the Turrellian LED lamp and Phillips Hue separately and were given sufficient time to answer Attrakdiff questionnaires.

For reminder, Pragmatic qualities (PQ) referred to the usability of the interface. Hedonic qualities (HQ) are divded into stimulation (HQ-S), which refers to how novel and interesting is the interface experience, and identity (HQ-I), which refers to the extent, which a user can identify with the interface. Finally Attractiveness (ATT) describes a global value of attractiveness based on the interface's quality.

Pragmatic qualities (PQ) - Both the Phillips Hue and Turrellian lamp must look to get higher overall PQ values. The Phillips Hue setup procedure frustrated participants for being overly technical - admittedly the bulb was without a Phillips Hue Bridge to make it straightforward. In contrast, participants found the Turrellian lamp unpredictable and confusing - particularly with all the wiring of two bodily sensors.

Hedonic qualities interaction (HQI) - Both the Phillips Hue and Turrellian lamp scored highly for interaction - participants seemed to greatly enjoy the ambience of coloured lighting. The Phillips Hue scored consistently and particularly highly for a professional interface. However, participants generally rated the Turrellian lamp higher particularly for integration and style - despite some considering it a less professional product than the Hue.

Hedonic qualities stimulation (HQS) - Many of the participants had used a Phillips Hue lighting system before consequently it scored quite low for overall stimulation. In contrast, the Turrellian lamp scored very highly - with many praising its inventiveness, creativity, boldness, innovation and novelty.

Attractiveness (ATT) - Both lighting systems scored highly for attractiveness. The Phillips Hue scored consistently across all word categories. In contrast, the Turrellian lamp scored very highly with many praising its attractiveness and motivational qualities.

Ultimately the Turrellian lamp scored better than the Phillips Hue smart bulb - this shows the promise of the system and an MHCI architecture integrated with lighting. In particular the Turrellian lamp really stimulated participants with an attractive overall design, albeit a slightly unprofessional product compared to the commercial Hue.

11.3 Overview and evaluation of results

The results are positive for MHCI and affect sensitive lighting design. The lighting produced by the Turrellian lamp supported users desired positive mental state and the physiological data collected was accurate for recognising physiological changes. Furthermore, the MHCI Turrellian affect-sensitive lamp design compared highly favourably during Attrakdiff UX testing against a commercial counterpart. These results meant that both hypotheses reiterated in chapter 6 relating to the lamp inducing positive participants physiological changes and better UX design of the Turrellian lamp versus the Phillips Hue were ratified by the project results.

Reaffirming the data conclusions, four out of six participants - 67% self-reported direct improvements in mood, which they directly attributed to the Turrellian lamp. Notably, the physiological readings and the biometric data collected suggested that five out of the 6 participants or 83% physiologically certainly improved towards their desired positive mental and emotional state from the Turrellian lamp lighting.

However, there are some clear limitations of the study. Firstly, participants were offered a £10 amazon gift voucher for participation during the pandemic which would have implications for bias. Secondly, the sample was not random with all study participants coming from the same corporate business partner and not taking place in a laboratory. Thirdly, the Phillips Hue bulb versus an impressive Turrellian lamp tower is ultimately not a fair reflection of the Phillips'

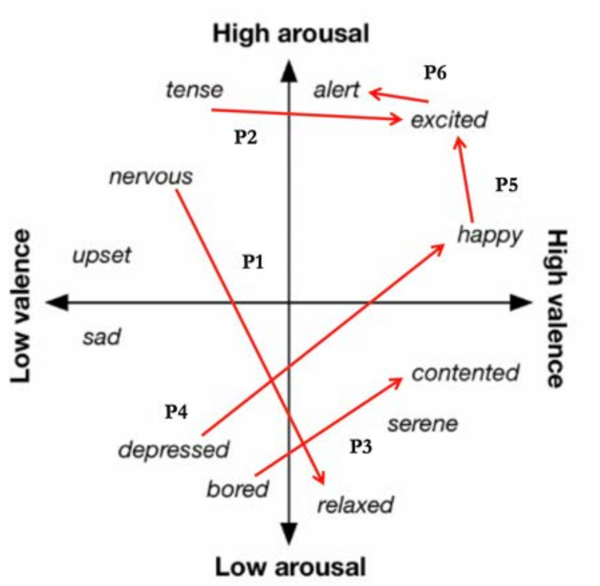


FIGURE 11.1. Figure represents the overall emotional changes requested from all participants through the Turrellian lamp GUI during the pilot study.

range products - a better counterpart would have been Phillips' own LED tower - the Signe LED floor light.

In response to these limitations, my project budget could ultimately not afford an appropriately expensive Phillips lamp. Furthermore, the pandemic made any in-person user testing challenging and pushed the testing environment outside of laboratories - therefore it was excellent to collect any participant data in such difficult circumstances.

11.4 Chapter conclusions

To conclude, the Turrellian lamp performed very well during pilot study although limitations are acknowledged especially during the pandemic circumstances. All participants physiological data changed when exposed to the lighting with physiological improvements occurring 83% and verbal improvements 67% of the time. The Attrakdiff data equally produced exciting results for the Turrellian lamp against a commercial counterpart - namely a Phillips Hue smart bulb. The following and final chapter discusses overall conclusions from the Turrellian lamp project and suggestions for future work.

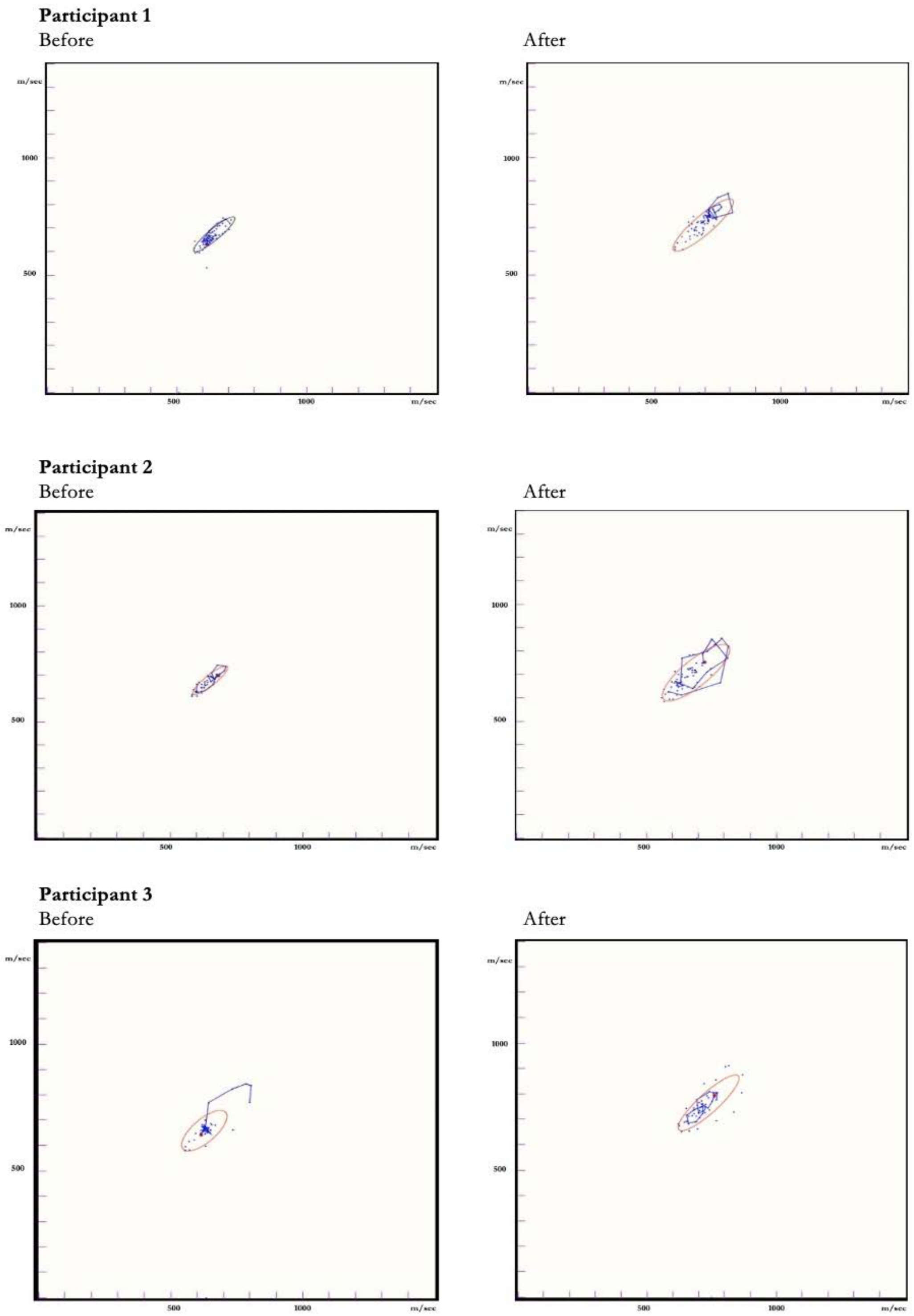


FIGURE 11.2. Blue line denotes final 20 HRV readings and red oval is a line of best fit. Participants 1-2 Poincaré map data demonstrate increases in S1 and S2. Whilst participant 3 shows a decrease in S1 but increase in S2. Results from all participants correlate with HRV and valence increases.

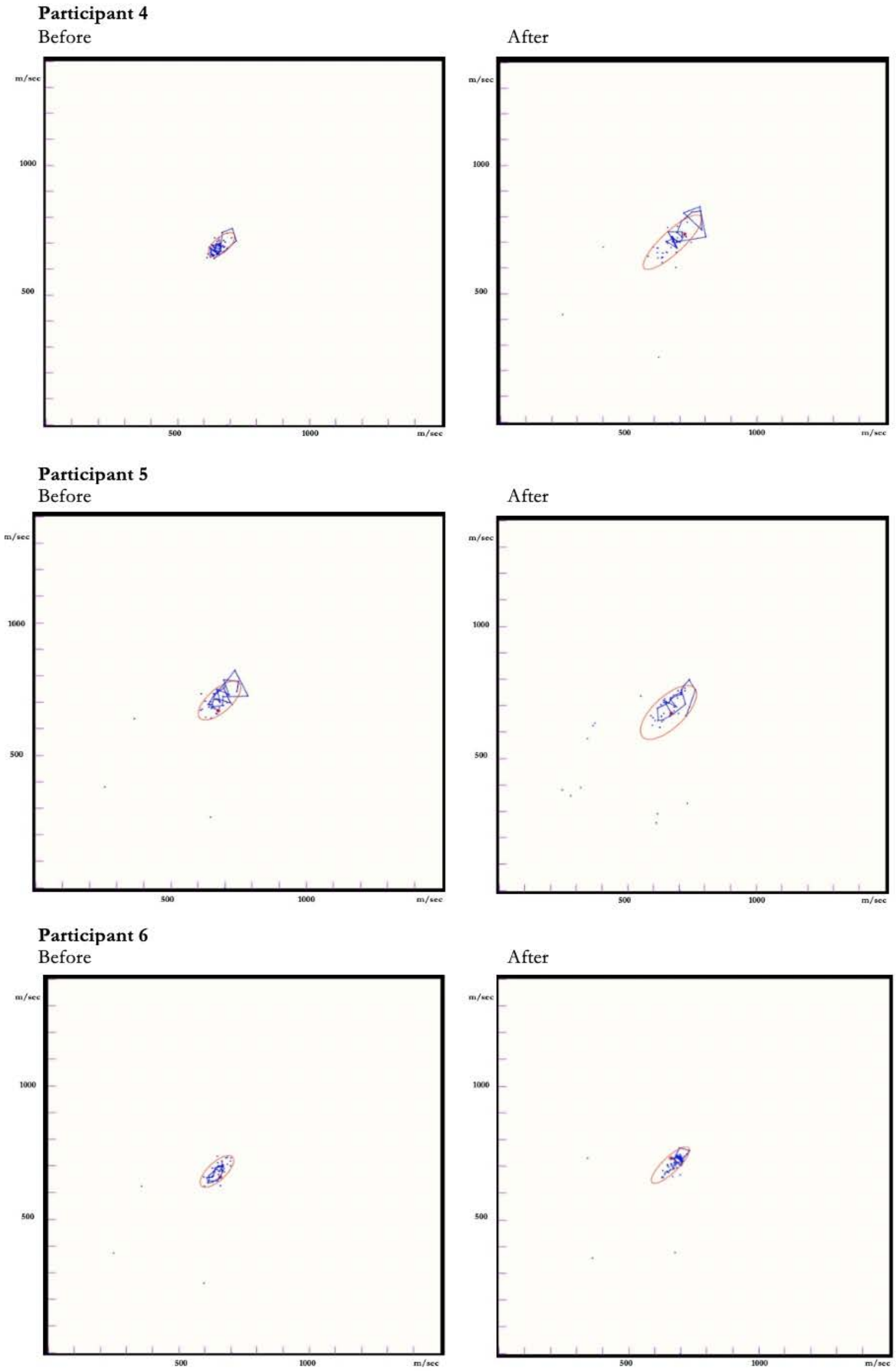
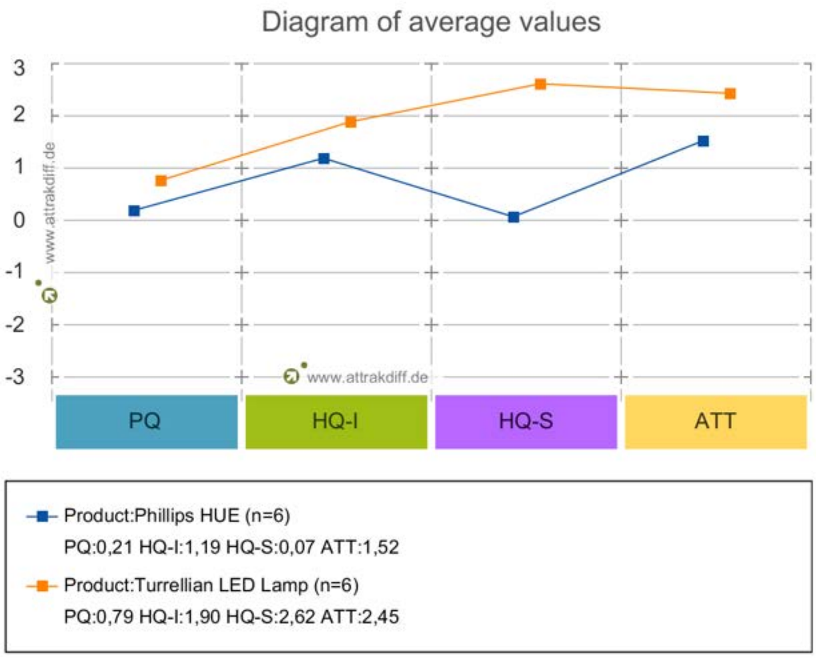


FIGURE 11.3. Participants 4-5 Poincaré map data demonstrate increases in S1 and S2. Whilst participant 6 shows a decrease in S1 but increase in S2. In particular, participants 4-5 results correlate with HRV and valence increases.

(a)



(b)

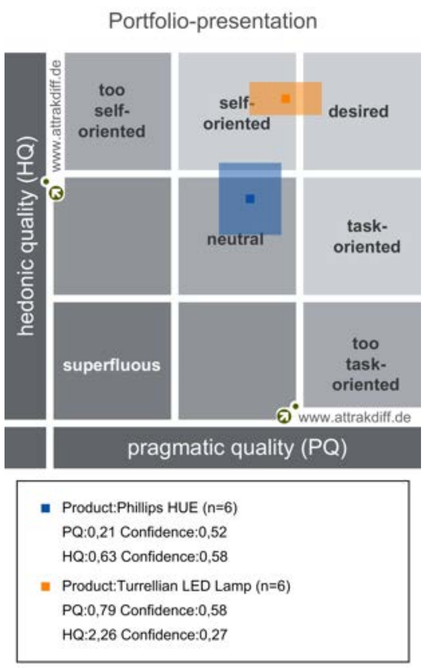


FIGURE 11.4. In figure 11.4a from the UX Attrakdiff survey results the Turrellian lamp outperformed the Phillips Hue in all categories - marginally in PQ, HQI and ATT. Yet, significantly higher in HQ-S. In figure 11.4b, the Turrellian lamp is found to be more self-oriented and desirable.

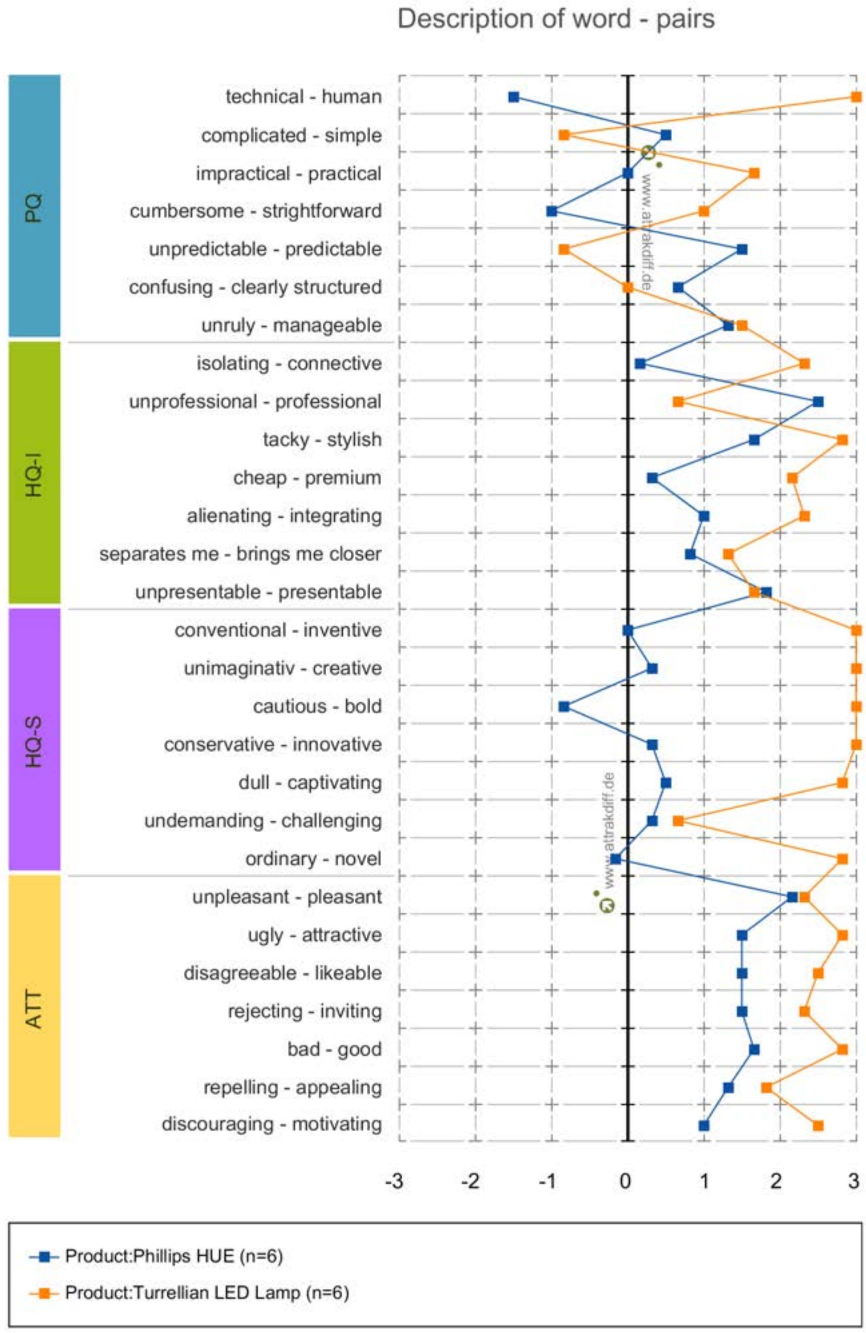


FIGURE 11.5. From word pair results the Turrellian lamp is found to be less professional, confusing and unpredictable. However, the Turrellian lamp is more inventive, creative, bold and innovative.

Chapter 12

Conclusions and future work

12.1 Conclusion

12.1.1 Findings

With respect to the project aims and objectives outlined at the start of the thesis, this Turrellian lamp project has critically taxonomised current affect-sensitive MHCI literature (chapter 3), provided insights from affective science (chapter 4) and evaluated existing market available LED lighting devices (chapter 5). From this literature review, this study has designed a USP for a new ambient emotion-centred lighting device called the Turrellian lamp.

The Turrellian lamp is a novel low-cost open-source lamp which adapts to users mood based on physiological insights and a GUI journal application. Thereby providing conducive mood enhanced lighting primarily motivated by scientific and artistic insights from Turrell and Valdez et al. [216]. Furthermore, this study has outlined the Turrellian lamps design and construction period, including evaluation of the hardware and eventual prototype (chapters 6 - 10).

Initial findings from a pilot study suggest that the Turrellian lamp can indeed improve mood based on 6 users conscious self-reflection and subconscious physiological readings whilst experiencing conducive light changes from the lamp (chapter 11). Additionally, the Turrellian lamp in Attrakdiff pilot studies performed comparably very well versus a market leading competitor device - namely, the Phillips Hue smart bulb. Notably, the Turrellian lamp excelled in hedonic qualities and user stimulation. Lastly, for the project aims to be fully completed I will now suggest pathways for future research.

12.1.2 Suggestions for future work

After the Coronavirus pandemic has subsided, initial additional user testing in controlled laboratory conditions can be implemented to collect further data from users experiencing the MHCI Turrellian lamp. Following this, there are several further opportunities to develop the Turrellian lamp further:

Machine and deep learning - As noted throughout the thesis, machine and deep learning techniques occurring within the cloud should be robustly employed for the next Turrellian lamp prototype. This was beyond the time constraints of the project, however such techniques would enable an automated lamp to work off pure physiological data streams from the user or users - which would be interesting. There have been numerous existing emotion algorithms employed within MHCI research - but none to live orient a lamp for conducive affect-driven lighting.

More modalities - The present Turrellian lamp architecture touches the surface of potential modalities to provide data to orient the lamp. For example, with respect to physiological modalities, GSM was considered during prototyping but a sensor unable to be successfully acquired. Aside from physiological modalities, there are a number of unexplored MHCI modalities to recognise emotions from users such as using a camera to conduct AFER or using a microphone to conduct AAER on the lamp users.

Synchronisation with existing computer devices - The present Turrellian lamp architecture uses open source Arduino compatible sensor technology. However, it would be an important next step to hone the lamp with smartphone health technology, smart watches, fitness devices and any other smart body sensors. Furthermore, the design of an iOS or Android App would also be ideal. These developments would enable the Turrellian lamp to be even easier to use and as polished as current rival counterparts.

Wider research pool - The pilot testing of the Turrellian lamp has certainly faced limitations onset by the Coronavirus pandemic. Therefore, further testing with even specific societal groups and businesses would be fascinating. For example, replicating a study by Kuller et al. [108] - it would be novel to test the Turrellian lamp within an elderly care home. Or even, to test the lamp at the opposite end of the age scale, within a education environment such as a school. Indeed, these environments need conducive lighting to improve occupants mental state and quality of life.

Different hardware designs - Currently the tall cuboid 6.5 feet LED tower of the Turrellian lamp is highly functional, provides desirable lux ratings, takes up a small floor surface area and met all functional requirements for initial pilot testing taken in a workplace environment. However, it would be exciting to explore different hardware designs, shapes, perhaps even lamps designed to mount on the wall and ceiling. Certainly, these more novel designs utilising origami and a 3D printer could be potentially very exciting for emitting coloured LED lighting within different environments.

12.1.3 Concluding remarks

At the time of writing, Phillips have expanded their smart Hue LED coloured lighting range for retail in 2020-1. However, MHCI computer architectures still remain a largely forthcoming market and retail innovation within lighting and many other sector technologies. However, as demonstrated by the Turrellian lamp - environmental lighting ambience certainly plays a crucial role in users current mood and accurate MHCI architectures classifying off physiological biofeedback can be developed at a low cost utilising open source available hardware. Additionally, a small group of participant questionnaire results suggested that they largely preferred the self-orientated mood enhanced Turrellian lamp compared to a commercial Phillips Hue smart bulb.

Indeed, future researchers should remember this going forward, which will hopefully result in MHCI adaptive computer architectures and mood-sensitive lighting systems becoming commercially available sooner such as the Turrellian lamp. Increased perforation of MHCI and emotion sensitive lighting architectures certainly have the capacity to significantly raise users overall moods and day-to-day livelihoods.

APPENDIX

A

FACULTY ETHICAL APPROVAL FOR STUDY

University of BRISTOL

Faculty of Engineering Research Ethics Committee (FREC)
Queens Building
University Walk
Bristol BS8 1TR
Telephone: (0117) 331 5830

18th August 2020

Mr Humphrey Curtis
Dr Paul O'Dowd
Department of Computer Science
Merchant Venturers Building
Woodland Road
Bristol
BS8 1UB

Dear Mr Curtis and Dr O'Dowd,

Ref: 109702
Title: Developing an affect enhanced "Turrellian" RGB LED lamp designed to improve mood: towards multimodal affect-sensitive computing and devices.

Thank you for responding to the issues raised by the Faculty of Engineering Research Ethics Committee (FREC) as stated in our letter dated 27.07.20. Your response to the issues raised by the FREC has been reviewed and the above-named study has received a favourable ethical opinion.

Please note that the FREC expects to be notified of any changes or deviations in the study.

Good luck with your research.

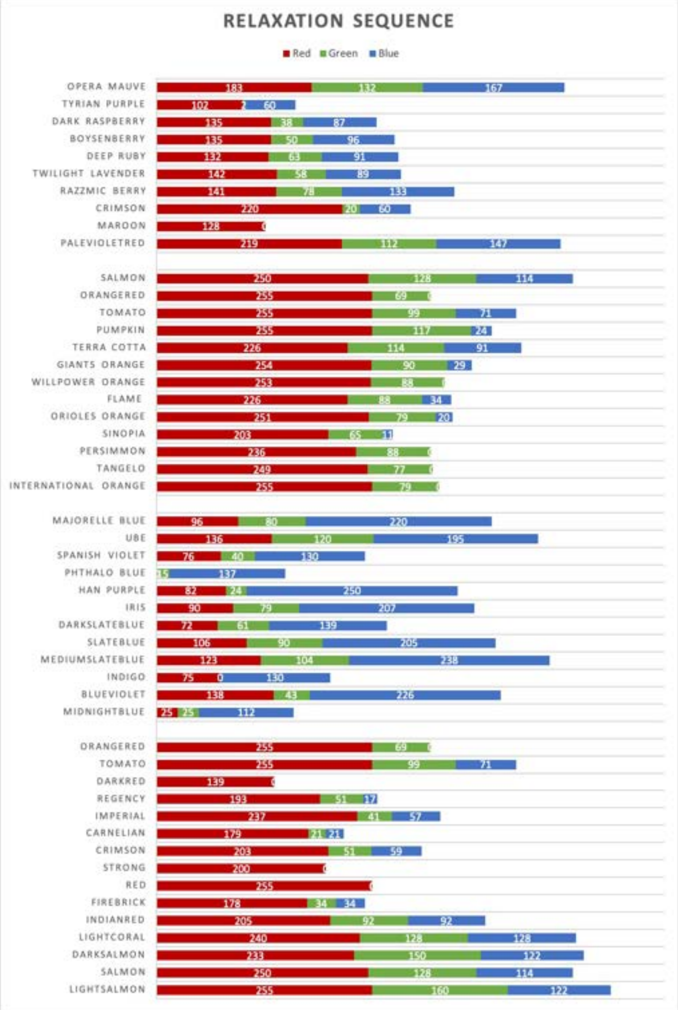
Yours sincerely
Chris Bennett
Research Ethics Assistant

pp
Dr Conor Houghton,
Engineering Faculty Research Ethics Officer (FREO)

APPENDIX

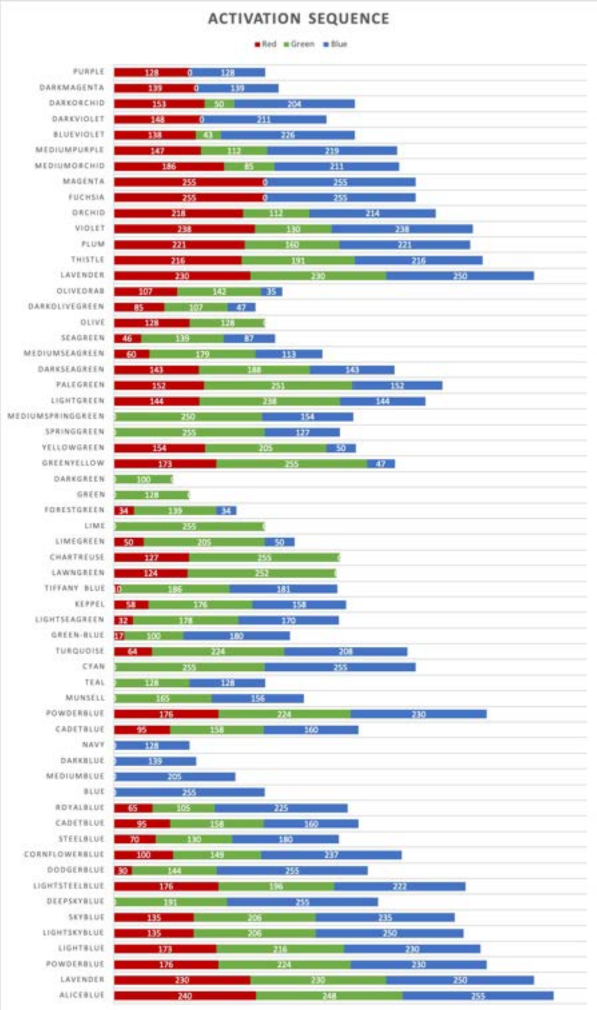
B

TURRELLIAN LAMP RELAXATION LED COLOUR SEQUENCE



Appendix C

Turrellian lamp activation LED colour sequence



Appendix D

Turrellian lamp resources

To find more information, concerning the lamp code base and further photos please see my online repository at https://github.com/HumphreyCurtis/Turrellian-LED-lamp or contact me via email to dr19500@bristol.ac.uk

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