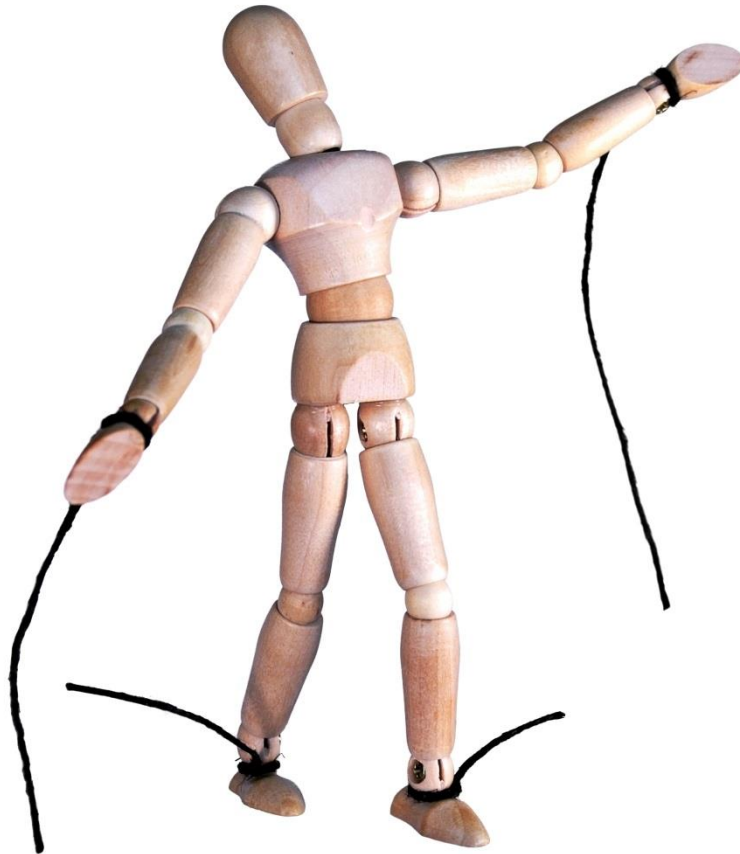




CHALMERS
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No Strings Attached

User Experience Design Guidelines for Wireless Charging Applications

Master's Thesis in Interaction Design and Technologies

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Department of Applied Information Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

Master's Thesis 2017:04

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Abstract

In this thesis, we present general user experience guidelines for wireless charging applications. The research was conducted iteratively in four stages, A-D. Stage A involved interviews and participatory design sessions. Stage B involved creating wireless charging prototypes, and C – conducting an online survey for determining what animations and LED behaviours the prototypes should display. The final stage, D, involved user testing the final prototypes. The outcomes of each stage all contributed to the resulting 12 design guidelines regarding function, feedback and applications of wireless charging devices.

Sammanfattning

I den här rapporten presenterar vi riktlinjer för att skapa goda användarupplevelser för trådlösa laddningsprodukter. Arbetet utfördes i fyra stadier, A-D. I det första stadiet, A, utfördes intervjuer och deltagande design. I stadie B skapades trådlösa laddningsprototyper, och i C skapades en enkät för att fastställa vilka animationer och LED-beteenden prototyperna bör visa. I sista stadiet, D, utfördes användartester av de slutgiltiga prototyperna. Resultatet utav varje stadie bidrog till sammanlagt 12 riktlinjer angående funktionalitet, respons och tillämpning av trådlösa laddningsprodukter.

Glossary

A – Ampere, unit for electric current.

C – Capacitance, measured in farad, is the ability to store electric charge.

DC – Direct Current.

LED – Light Emitting Diode.

PCB – Printed Circuit Board.

RGB – Red, Green Blue: an additive colour model widely used in electronic devices.

UI – User Interface.

USB – Universal Serial Bus.

V – Volt, unit for electric potential.

UI – User interface.

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1. INTRODUCTION

From a user experience perspective, wireless inductive charging and wireless power transfer is a promising emerging technology. In this thesis, we will explore how such technologies can benefit the design and implementation of novel, innovative user interfaces. The research includes development of various hardware and software prototypes, primarily transmitters but also receivers, and involves empirical evaluation of such prototypes in order to estimate the expected benefits in terms of novel UI design spaces, scenarios of use, and user experience.

1.1. BACKGROUND

Wireless power transfer has already been adopted into consumer electronics including induction cooktops, electric toothbrushes and, more recently, smartphones. Currently, wireless charging is often limited to a small area a few millimetres above the transmitter coil. However, recent advancements in technology have enabled greater distances using resonant charging [1] [2] [3] allowing for greater spatial freedom and improving the user experience. We hypothesize that these advancements may also enlarge the UI design space and related scenarios of use.

Some recent efforts have been made towards resonant charging for phones. MagMIMO [4] uses resonance and magnetic beamforming to allow charging up to 40 cm away from the transmitter. However, this system is lacking in feedback beyond the contingent notification of the phone in use.

Currently, the feedback of wireless chargers rarely extend beyond a single LED – indicating whether power is being transmitted. While this might be inherent to the small sizes of the transmitters, here, we aim to leverage larger areas, thereby allowing for more advanced and expressive feedback. Although a single LED can provide more than two states, as described by Harrison et al. [5], we plan to experiment with animations as well as colours spanning an array of LEDs expanding on research by Matviienko et al. [6].

The large horizontal areas targeted here make our project somewhat related to interactive tabletops, such as the ReacTable [7]. Such tabletops typically have a strong emphasis on user experience through feedback provided by projectors or LCD displays; they serve as inspiration and reference for our project.

1.2. AIM

The aim of the thesis is to explore the possibilities of inductive charging and wireless power transfer from a user experience perspective. Through iterative prototyping, we aim to investigate and address the shortcomings of current UI design in wireless charging applications and provide guidelines for this design space. The focus of the thesis will be the transmitters with receivers providing use cases and context.

1.3. PROBLEM STATEMENT

In such a novel and complex area as wireless charging, there are many questions to be answered regarding user experience. We aim to explore the design space and provide actionable guidelines. Thus, the research question for this thesis is:

*What user experience guidelines should be considered
when designing wireless charging applications?*

Furthermore, the research has been divided into three areas that have been identified and thought to have great impact on the user experience.

- *Functionality:* What technical and functional requirements must be fulfilled in order to meet user expectations?
- *Feedback:* What type of feedback do users expect and appreciate that indicates the behaviour of wireless charging devices?
- *Applications:* What type of devices do users want to wirelessly power, how and when?

Users inherently have expectations of how a product or system operates – their mental model. Faulty or not, this mental model will affect how the user perceives a product. A user's mental model will influence the actions they think are required and the outcome of said actions. A mental model is often intuitive or the result of previous experiences but can also be influenced by design. Therefore, this thesis will explore how to communicate the concept of wireless charging, how it works, and what actions are required of the user, through design.

Cords and connectors provide tactile, tangible, feedback. The satisfying click of the connector when set in place communicates to the user that their action has been recognised and carried out successfully. How can we, without such interactions, provide users with similarly satisfying and immediate feedback in our wireless charging applications?

In this thesis, we want to investigate users' needs regarding wireless charging and find what pre-conceptions and concerns they have regarding the technology. Potential health and safety concerns might limit where users want to use wireless charging technology and what type of devices they find suitable for wireless use. If unfounded, how can we address such concerns through our design?

Additionally, all prototypes developed should adhere to one or more current wireless charging standards and specifications such as Qi [1] or Air Fuel [3]. Some modern phones come equipped with wireless charging receivers and it is therefore advantageous to allow users to charge these

phones without modifications or add-ons. This will not only improve the user experience but also decrease costs and the amount of e-waste generated throughout the product’s lifespan.

A major challenge will be to incorporate all areas described above into a desirable product. We aim to, by eliciting user requirements, strike a balance between form and function and maximise the user experience.

1.4. SCOPE

This thesis will be limited to design, prototyping and evaluation with focus on visual feedback. We do not strive for technical advancement or development of wireless charging technology. However, we will cover the application, and use, of such components. The physics of induction is not covered; however, we will provide the information necessary for understanding the design.

1.5. METHODOLOGY

The execution of the work is presented in four stages, A-D, in which the outcome of one stage dictated how the subsequent stage was performed. For a general flowchart, see Figure 1.1. Stage A involves interviews and participatory design sessions. The following two stages, B and C, were executed in parallel. Stage B involves creating wireless charging prototypes, and C – conducting an online survey for determining what animations and LED behaviours the prototypes should display. The final stage, D, involves user testing the final prototypes. The outcomes of each stage are all contributing to the resulting design guidelines. After presenting the guidelines, the methodology and outcome of each stage are discussed. See Table 1.1 for a summary.

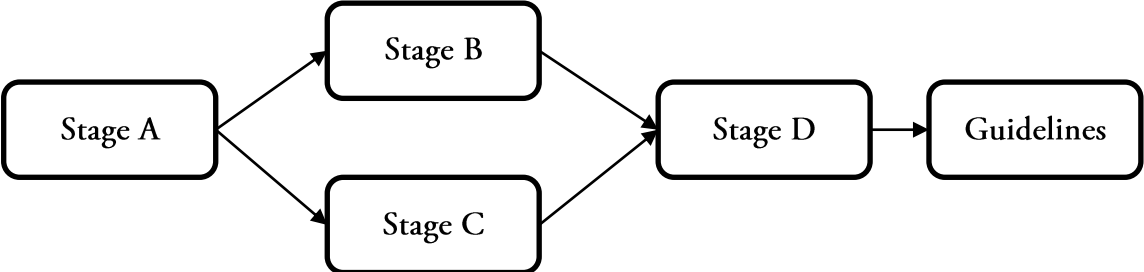


Figure 1.1: Execution flowchart showing how the stages relate to each other and the resulting guidelines.

| | Purpose | Outcome | Issues and Concerns |
|---------|---|---|---|
| Stage A | Elicit requirements for wireless charging design. | Requirements for creating prototypes that appeals to users. | Population and sample size. |
| Stage B | Create prototypes of high enough fidelity to provide useful data. | High fidelity charging module- and- receiver prototypes. | Time and material constraints. |
| Stage C | Find the most suitable animations for the wireless charger. | The highest rated animations for the charger behaviours. | Concerns regarding sample size and colour variations. |
| Stage D | Evaluate prototypes. | Design guidelines. | Sample size. |

Table 1.1: Summary of the four stages of execution.

2. STAGE A: INTERVIEWS AND PARTICIPATORY DESIGN

The aim of the interviews was to determine the understanding of wireless charging among users and to involve them in participatory design. The participatory design sessions involved brainstorming regarding use cases, requirements and module shapes.

The interviews, carried out on the campus of Singapore University of Technology and Design, were semi-structured where participants were asked about their experiences and expectations of wireless charging technology. The interviews started with the participants describing previous experiences with wireless charging. They were then invited to elaborate on how, when and where they would like to interact with this technology – how the chargers would look like, what devices they would like to charge wirelessly and where they would use them. Participants were also asked if they preferred the chargers to be visible or hidden from sight. Lastly, they were asked to assume that wireless charging technology can be added to furniture such as desks and tables and if they would like to buy new or modify existing furniture to support wireless charging.

After answering the questions, the participants were asked to assume that the charging device was a surface comprised of modules. In the pilot study (three participants, one female, mean age 28), the participants were tasked with rating four shapes, square, triangle, rhombus and hexagon, on how well they communicated ‘charging’, ‘wirelessly’ and ‘cool’ using a seven point Likert scale (see Figure 2.1). This approach was inspired by Raptis et al. [8].

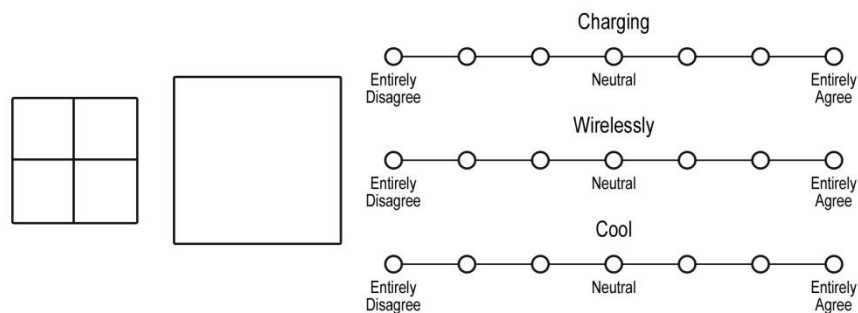


Figure 2.1: The ratings used in the pilot study for the square shape – inspired by Raptis et al. [8].

After the pilot study, the shape rating section was changed due to feedback from participants. In order to provide more context and understanding, paper cut-outs were presented – four of each shape. The participants were encouraged to try out and arrange the shapes in different configurations before rating them. The order in which the shapes were presented was randomized so that no two participants saw all shapes in the same order. Only the ‘cool’ statement remained and nine other statements, with corresponding Likert scales, were added for each shape. The new statements regarded ‘desirability’ and ‘rebelliousness’ as defined in [8]. See Figure 2.2 for all statements.

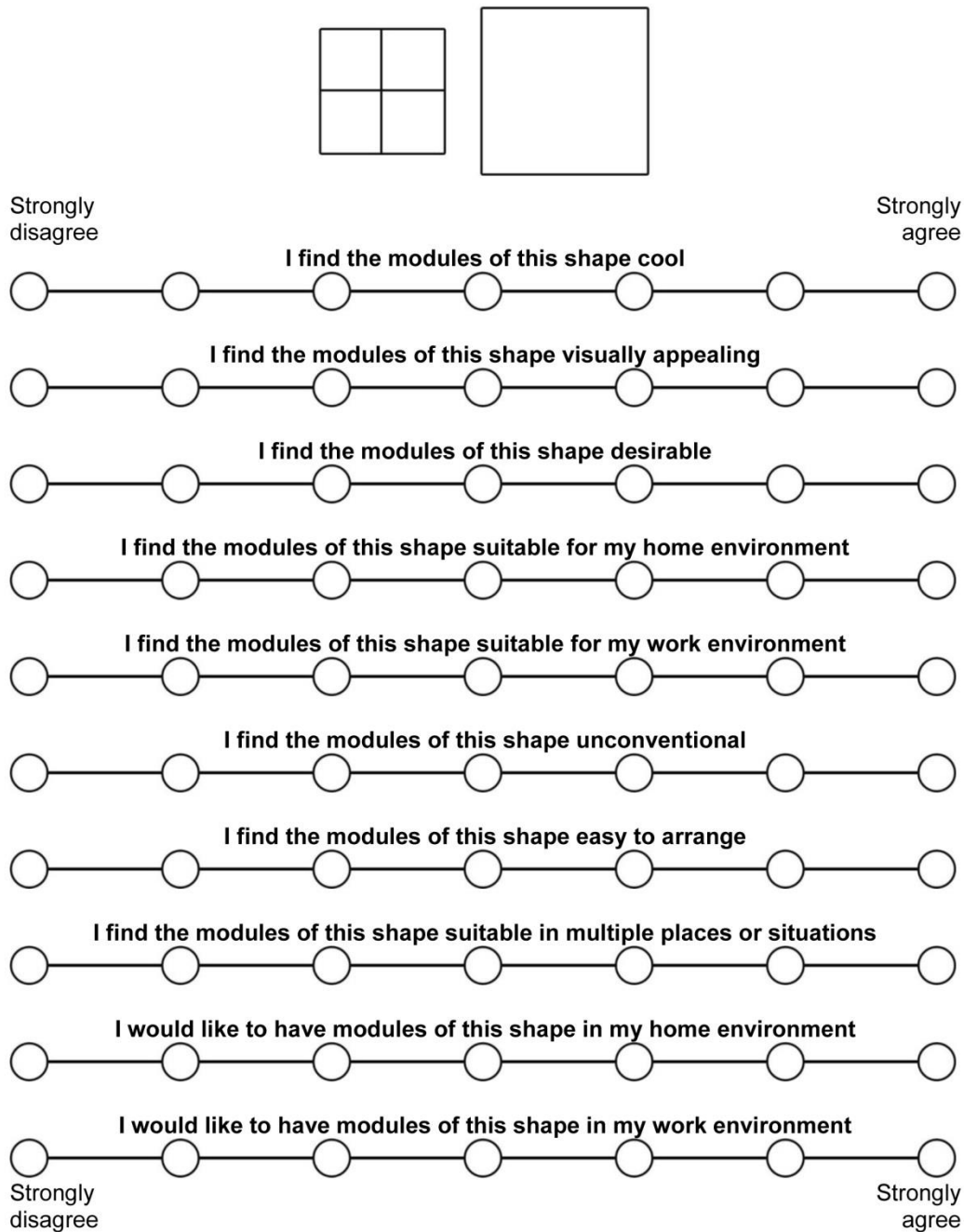


Figure 2.2: Statements and scales for the square shape used in participatory design sessions – inspired by Raptis et al. [8].

2.1. OUTCOME

Excluding the pilot study, ten interviews were conducted. All participants were students at undergraduate and graduate level between ages 21 to 25 (median 23) attending Singapore University of Technology and Design. Three were female. Four of the participants had previous experience with wireless charging but only one had ever owned a wireless charger. One participant had never heard of wireless charging technology. The awareness of this sample is slightly higher than average, which is 76% as of 2015. However, the usage of wireless charging is much lower than the 20% average, again as of 2015 [9].

When asked to elaborate on how they would like the technology to behave and look like, all participants gravitated towards having wireless charging at specific areas – tables in particular. The participants wanted these areas to be large enough to be able to put down their phone or other devices haphazardly on it and have their charged, alternatively get a notification that wireless charging is available and start the charging process manually. Some suggested that chargers could be mounted under, or integrated inside, tables or if placed on top – the chargers should not be bulky but aesthetically pleasing and easy to clean. Two participants also stressed the importance of having this technology built into their devices, without having to use extra adapters or cables.

Regarding the question if the chargers should be visible or hidden, the participants were less decisive. Half of the participants wanted the charger to be visible, four hidden and one stated that it wholly depended on the aesthetics of the device. Upon further questioning, it became clear that some sort of indication as to where the charging area is located is important – especially for public places. However, the visibility of the charger itself was less important but some concerns were raised about finding the device and making adjustments if needed. One participant added that it felt foreign and unpleasant having the charger hidden.

Whereas to modifying or buying new furniture to support wireless charging, once again, the participants gave mixed results. Six participants said that they would like to modify the furniture they already own – citing waste and environmental reasons as well as concerns for aesthetics and design of new furniture that they might disagree with. Three participants wanted to buy new rather than modifying since they found it easy and convenient. One participant preferred modifying if it is easy and not too time consuming [10-15 minutes]. Four participants suggested a modular system for flexibility.

The average results from the Likert scales (Figure 2.2) can be seen in Table 2.1 with corresponding bar chart see Figure 2.3. The scores were consistent with the square or hexagon in the top, followed by the triangle and rhombus shape, except for “unconventional” where the rhombus scored highest and square lowest. Overall, the hexagon shape scored highest (Figure 2.4).

| | Square | Triangle | Rhombus | Hexagon |
|-----------------------|--------|----------|---------|---------|
| Cool | 2,2 | 3,3 | 3,5 | 5,1 |
| Visually Appealing | 2,7 | 2,9 | 3,2 | 5,2 |
| Desirable | 3,6 | 3,1 | 2,9 | 4,2 |
| Suitable for Home | 4,3 | 2,8 | 2,4 | 3,8 |
| Suitable for Work | 4,2 | 3 | 2 | 3,6 |
| Unconventional | 1,2 | 2,3 | 4,1 | 3,6 |
| Easy to arrange | 5,1 | 4,2 | 3,8 | 4,6 |
| Suitable for multiple | 4,8 | 3,3 | 2,8 | 4 |
| Like to have at Home | 3,5 | 2,9 | 2,6 | 4,4 |
| Like to have at Work | 3,8 | 2,9 | 2,4 | 4,2 |
| | 35,4 | 30,7 | 29,7 | 42,7 |

Table 2.1: Module shape average scores. Values below ‘neutral’ (3) are shown in red.

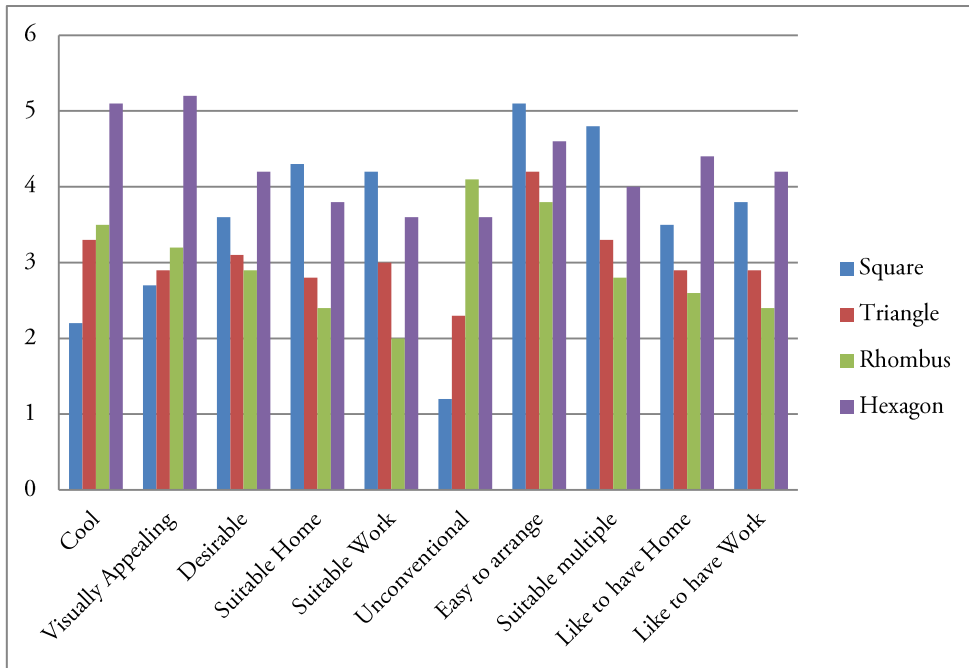


Figure 2.3: Module shape average scores – bar chart.

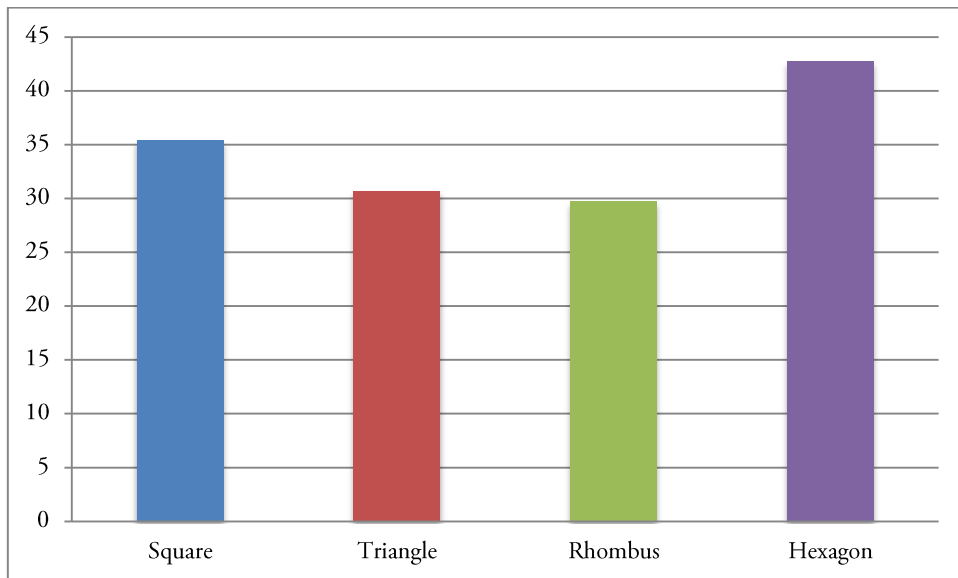


Figure 2.4: Sums of average shape scores

To what shape they finally preferred, seven participants cited the hexagon and three the square. This is reflected in the data where the hexagon ranks highest in regards to both ‘like to have’ statements. Interestingly, the square was deemed more suitable for home and work. This might speak to the ‘rebelliousness’ [8] of the hexagon shape.

3. STAGE B: PROTOTYPING

In this section, we will detail the process of creating transmitter- and receiver prototypes. The core methodology was an iterative, from low to high fidelity, data driven process starting in simple sketches and resulting in physical products.

3.1. TRANSMITTER MODULES

The reason for developing a modular system was twofold. Firstly, since we were aiming for larger charging areas, a modular system allows for multiple configurations and is therefore adaptable to different surfaces and situations. Secondly, modules can be placed on, in or under existing desks, nightstands etc. where users wish to enable wireless charging.

One of our primary goals was that a user should be able to place a receiver anywhere on the transmitter modules and have it charge. It was also important that the modules should communicate their status effectively. From these requirements, a general composition of components could be established, as seen in Figure 3.1. As indicated, visual feedback using LEDs was chosen as the only feedback channel. The implications of this design decision are discussed in section 7.

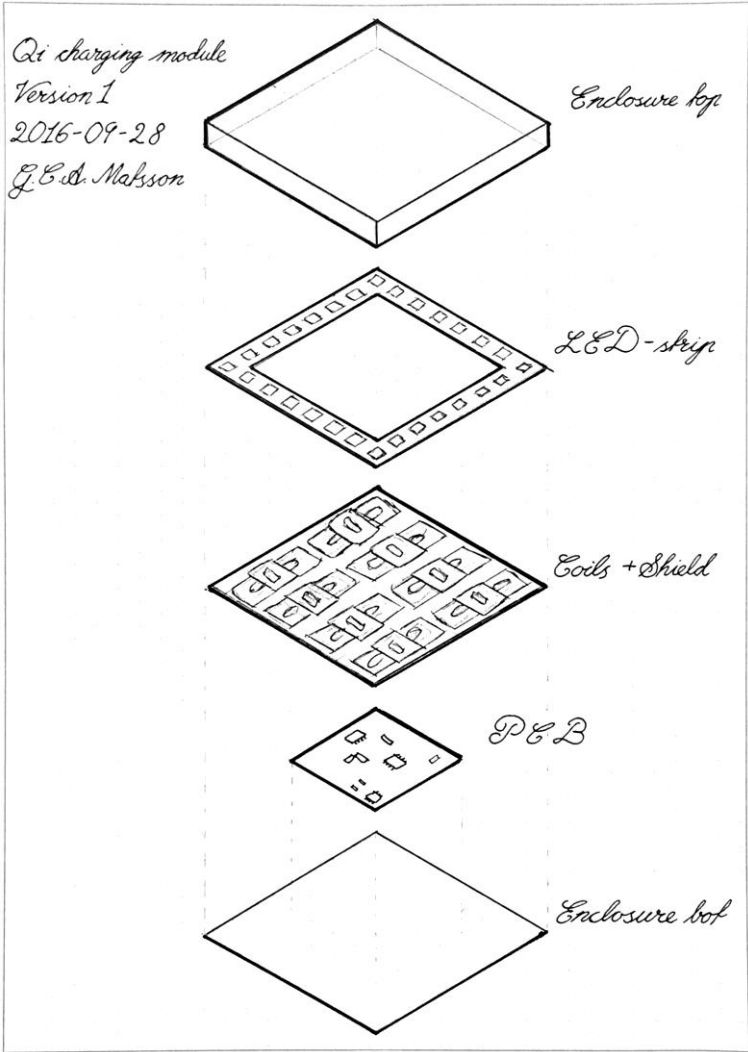


Figure 3.1: Transmitter module, exploded view.

3.1.1. ENCLOSURES

Over several iterations, the module enclosure underwent a number of changes in shape, size and material. The enclosure serves multiple purposes. First, the bottom part should contain all components and be attachable to any neighbouring modules. The top part acts as a lid, and should obscure the internal components yet be transparent enough to allow the LEDs to shine through and, of course, not block or otherwise disrupt the magnetic field of the charger.

Having the modules connect to their closest neighbours, in order to distribute power, opposed to connecting each individual module to a single power supply was considered crucial to the modular system. This way, an array of modules can be powered using a single cable leading off from it. The module connections assumed different implementations over several iterations. The first design involved connecting a ribbon cable across the edge between adjacent modules (Figure 3.2). The rubber non-slip pads would allow enough clearance between the module and the underlying surface. The main reason for having the connectors underneath the modules is that it allows the sides of the modules to be void of any protrusions or depressions, creating a very clean presentation.

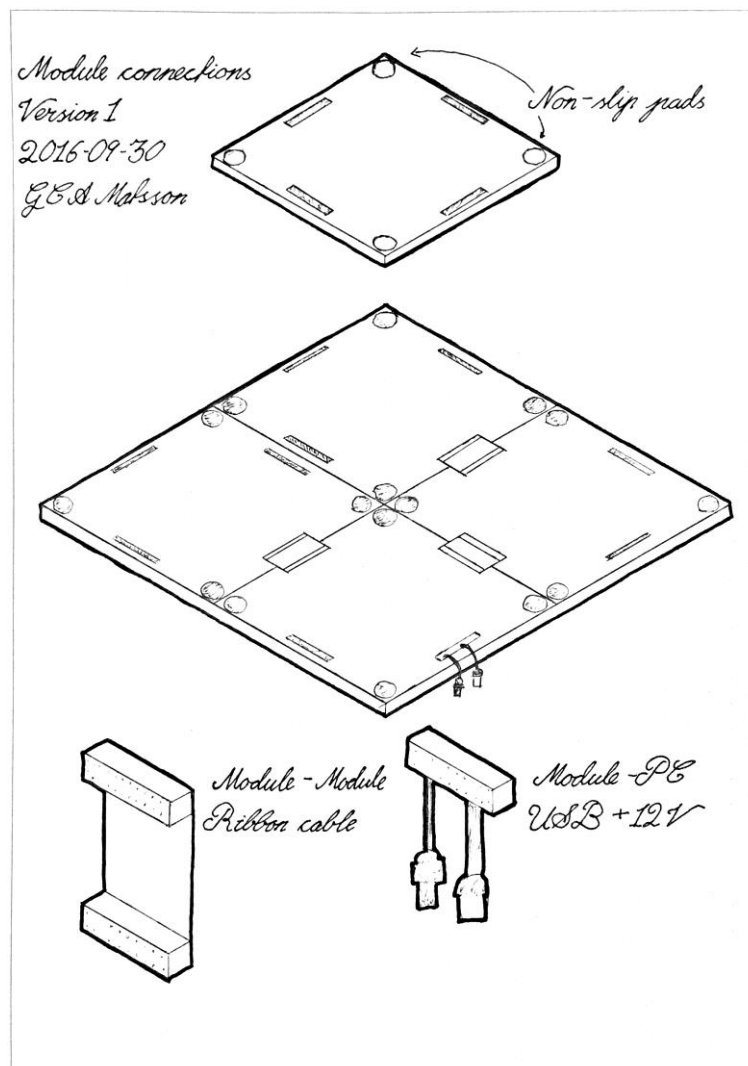


Figure 3.2: Square transmitter module connections.

The same connection method was also used after it was decided that hexagonal modules should be used. For comparison, see Figure 3.3.

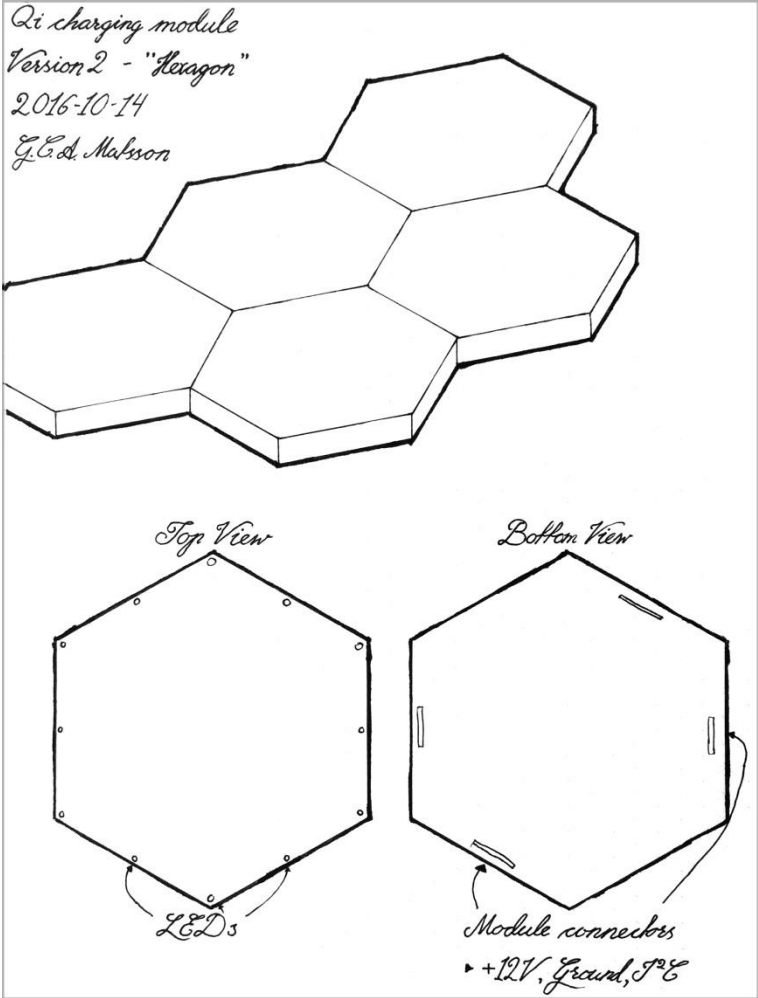


Figure 3.3: Hexagonal transmitter module connections.

Later iterations saw the introduction of magnets. In order to help users align the modules, magnets were installed inside each side of the modules. This aided alignment and produced a satisfying snap when two modules were brought together.

Upon further iteration, the use of cables underneath the modules were discarded as they added complexity and made adding new modules more difficult. Instead, the magnets used for alignment were allowed to protrude through the sides and act as electrical conductors. This change made installing new modules as easy as placing them next to another but sacrificed the previously flat sides.

Many different configurations of magnets and contacts were prototyped and tested – with the aim of striking a balance between aesthetics and functionality. Since the modules are symmetrical, it was stressed that the solution should allow them to be connected regardless of orientation. Three low fidelity prototypes can be seen in Figure 3.4.

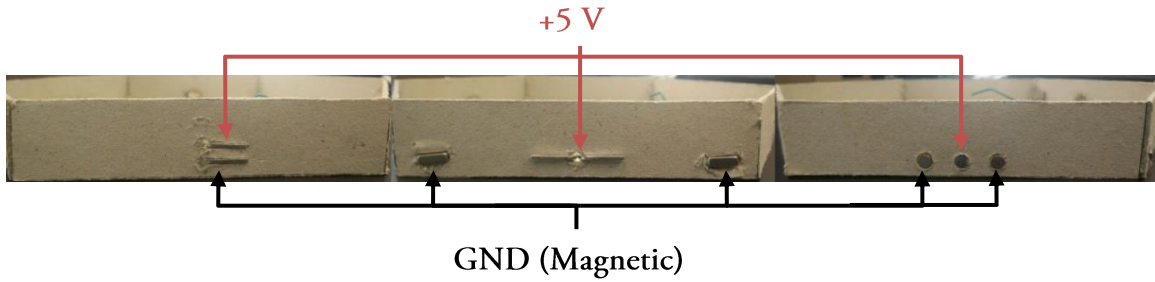


Figure 3.4: Three connector prototypes, made out of cardboard, side by side. The metallic contacts provide ground and 5V to connected modules.

The different solutions were evaluated based on aesthetics, function and ease of implementation. One solution – two magnets of opposite polarities, connected to ground, on both sides of a contact providing 5V – was deemed best for the intents and purposes. See Figure 3.5 for a diagram. Sketches, as well as 3D renderings (Figure 3.6), were produced in order to, more accurately, visualise how different magnet- and- contact locations affected the aesthetics of the modules.

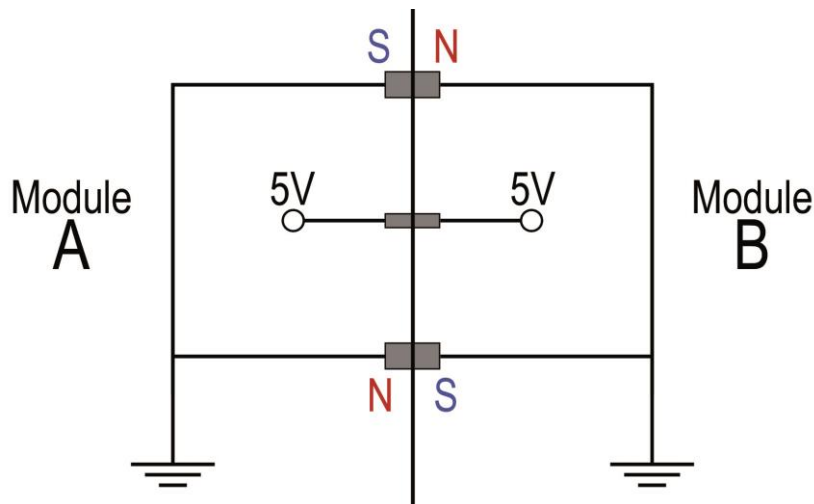


Figure 3.5: Diagram of magnetic and electric connection points between modules A and B.

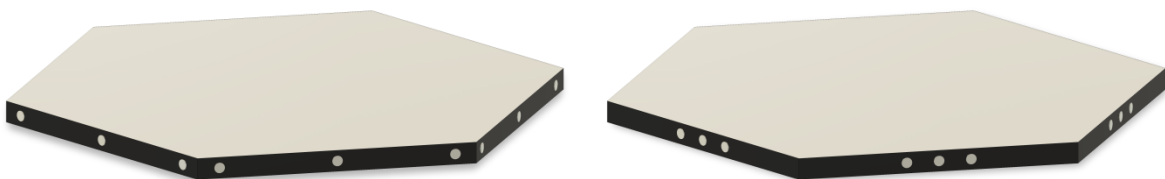


Figure 3.6: 3D renderings intended to aid evaluation of contact locations.

After deciding on using magnets, in order to supply the modules with power, it was necessary to design a supply module with a matching set of magnetic contacts. The supply module (Figure 3.7) was design to complement hexagonal charging modules in shape and size while accommodating for the electronics inside (see section 3.1.2). A cable, carrying 5V and ground, protrudes from the back of the supply module and ends in a male USB 'type A' plug. This plug can be con-

nected to the USB ports of a computer or a DC power supply granted that they could supply the required current.

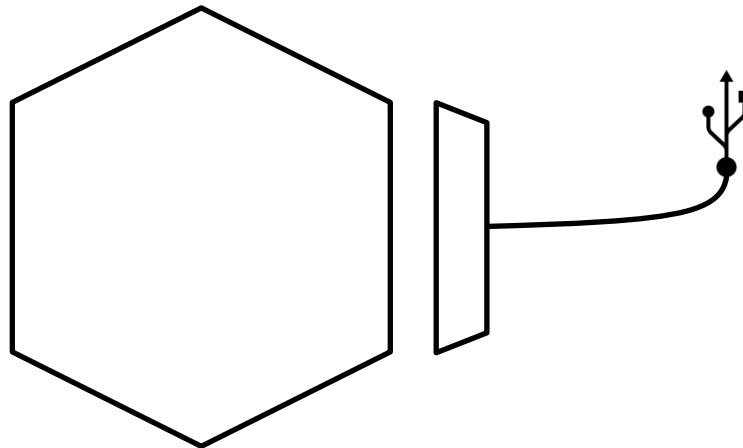


Figure 3.7: Top-down sketch of a charging module (left) and a supply module (right).

3D models (Figure 3.8) were created for 3D printing using Fusion 360¹, and later printed using a MakerBot² Replicator desktop 3D printer with biodegradable polylactic acid (PLA) filament. The printer was the limiting factor regarding the sizes of the modules. With its 295×195mm build area, the models were scaled to fill that area as closely as possible. The resulting prototypes were outfitted with the aforementioned contacts and electronics (see section 3.1.2).



Figure 3.8: Models of charging module (left) and power supply module (right) created for 3D printing. The two modules are not to scale – compare to Figure 3.7.

The charging modules' top surfaces were cut out of a semi-transparent acrylic sheet. For extra light diffusion, two layers of adhesive window diffuser film were added to both sides of the hexagonal acrylic pieces. The top surfaces were set in place on top of ledges inside the charging modules, acting as a lid sealing the modules.

¹ Autodesk Fusion 360 – official website: <http://www.autodesk.com/products/fusion-360/overview>

² MakerBot – official website: <https://www.makerbot.com/>

3.1.2. ELECTRONICS

After some testing, it was concluded that the power supply module needed higher capacitance in order to prevent momentary power dips upon connecting additional modules – causing them to reboot. It was established that 500 μ F of capacitance between the power terminals was enough to prevent this problem from occurring. Due to the limited space inside the power supply unit, no through-hole capacitor, or combination of multiple such capacitors, available to us, would fit that also met the 500 μ F requirement. Instead, we opted for a surface-mount technology (SMT) solution. An array of five 100 μ F surface-mount capacitors connected in parallel gave us the desired capacitance (Equation 1).

$$C_{total} = C_1 + C_2 + \dots C_n$$

Equation 1: Total capacitance when connecting capacitors in parallel.

A schematic (Figure 3.9) and PCB layout was created in CadSoft's *EAGLE*³ program, from which, a Gerber⁴ file was exported. The file was uploaded to a *Voltera V-One*⁵ – a PCB prototyping machine that prints circuits using conductive ink – and printed onto a PCB (Figure 3.10). The same machine was then used to dispense solder paste and finally reflow the PCB once the capacitors had been placed. The USB cable's, and module contacts', positive and negative leads were soldered to their corresponding terminals, labelled PAD1-4 in Figure 3.9.

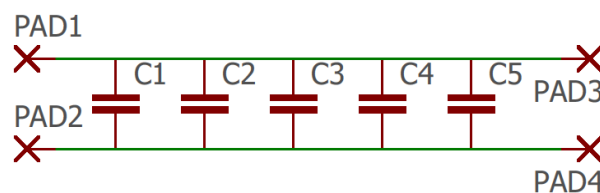


Figure 3.9: Power supply schematic.

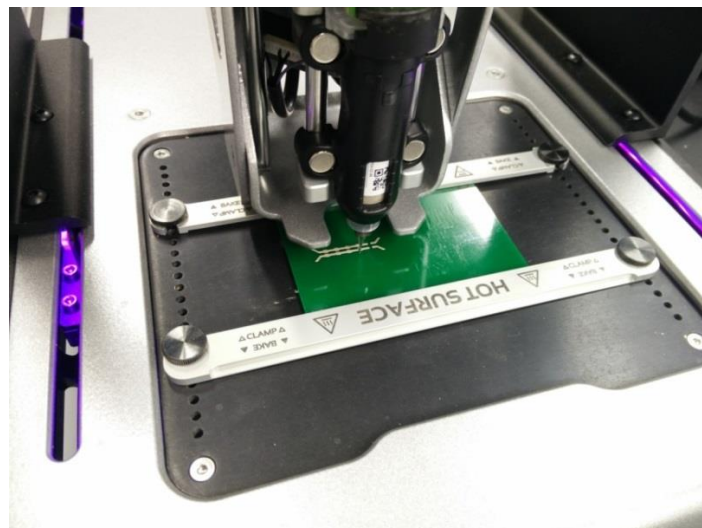


Figure 3.10: The *Voltera V-One* printing the power supply circuit.

³ CadSoft – official website: <https://cadsoft.io>

⁴ Gerber is an open vector image format commonly used for describing PCBs.

⁵ Voltera – official website: <http://voltera.io>

Inside each module there is an ATmega microcontroller controlling the individually addressable LEDs on the strip. Both an *Arduino Mini 5V 16MHz* and a Bluetooth controllable *DFRobot Blue Nano* was used, the latter for testing purposes (see section 5).

Inside a module, there is also the electronics of a *Belkin Qi Charging Pad* that was removed from its plastic enclosure in order to fit inside the module. By reading the voltage, compared to ground, at different points on the charger's PCB, a point was found at which the voltage was near 0V when the device was not charging and 4.8V when it was. This point was tapped and connected to an input pin on the microcontroller that continuously read that value. However, when connected to the microcontroller, the voltage no longer read 4.8V but much lower. Therefore, a voltage follower was created using an operational amplifier (Figure 3.11) that, owing to the nature of its high input impedance could provide the microcontroller with a stable input.

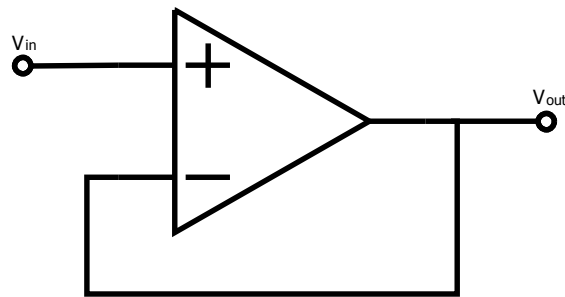


Figure 3.11: Voltage follower diagram.

3.1.3. SOFTWARE

The microcontrollers in the transmitter modules were programmed in the Arduino⁶ integrated development environment (IDE) using Adafruit's *NeoPixel* library⁷ for controlling the LEDs. The main program loop involved checking the wireless charging controller's status and playing the appropriate animation. Listing 3.1 shows a simplified example of the main loop.

```
void loop(){
  switch(checkCharger()){
    case idle:
      animation_idle(); break;
    case charging:
      animation_charging(); break;
    case fod:
      animation_fod(); break;
    case error:
      animation_error(); break;
  }
}
```

Listing 3.1: Simplified example of the transmitter microcontroller's main loop.

In order to provide instantaneous feedback for when the user places or removes a chargeable object above a transmitter, a custom delay function (Listing 3.2) was implemented. The standard

⁶ Arduino – official website: <https://www.arduino.cc/>

⁷ Adafruit – NeoPixel usage guide: <https://learn.adafruit.com/adafruit-neopixel-uberguide/arduino-library>

delay function⁸ of the Arduino does not allow code to run during the delay – except for interrupts. Since the check for changes to the charger is not an interrupt, a custom delay function that constantly checks the charging status was required. The function has two parameters – the duration of the delay and the current charging status. It returns ‘true’ if the charging status remains unchanged from the given status after the duration. If the status changes during the delay, it aborts and returns ‘false’.

```
/*
 * Function for handling state changes during LED animations.
 * Returns false if the status changed during the delay.
 */
bool LEDdelay(int duration, chargingStatus cs){
    float startTime = millis();
    float currentTime = startTime;

    while(currentTime - startTime < duration){
        if(cs != none && cs != checkCharger()){
            blackout();
            return false;
        }
        currentTime = millis();
    }
    return true;
}
```

Listing 3.2: Custom delay function that constantly checks for changes to the charging status.

The animations themselves are sequences of the aforementioned delays and assigning new RGB values to the LEDs. Listing 3.3 shows the source code for one of the animations implemented called ‘Pulsating’. As illustrated in Figure 3.12, the animation involves fading in all the LEDs at the same time and fading out again. This animation continues indefinitely or until the charger state is changed – in this case, from idle to charging.

```
void animation_pulsating(){
    while(true){
        for(int i = 0; i < 256; i++){
            for(int j = 0; j < nbrofLEDs; j++){
                strip.setPixelColor(j, i*R/255, i*G/255, i*B/255);
            }
            strip.show();
            if(!LEDDelay(7, idle)) return;
        }
        for(int i = 255; i >= 0; i--){
            for(int j = 0; j < nbrofLEDs; j++){
                strip.setPixelColor(j, i*R/255, i*G/255, i*B/255);
            }
            strip.show();
            if(!LEDDelay(7, idle)) return;
        }
        if(!LEDDelay(1000, idle)) return;
    }
}
```

Listing 3.3: Animation source code.

⁸ Arduino Reference – Delay: <https://www.arduino.cc/en/Reference/Delay>

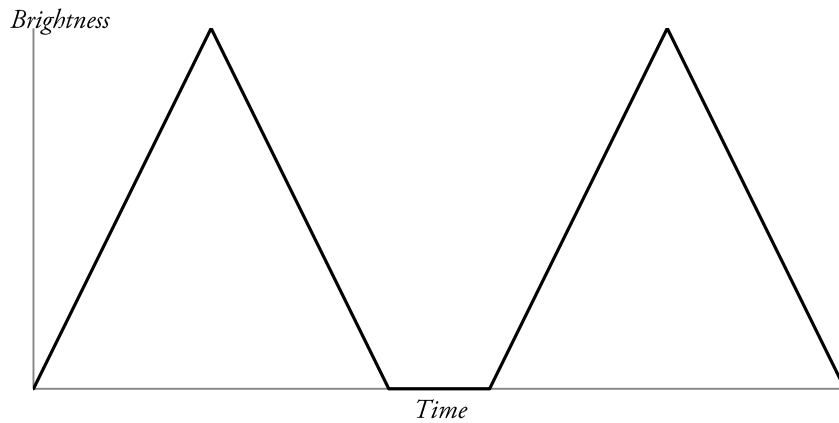


Figure 3.12: Graph illustrating the LED brightness over time during two cycles of the ‘pulsating’ animation.

Using Arduino’s ‘Wire’ library⁹, inter-integrated circuit (I²C) communication was implemented. I²C is a bus protocol that allows a master device to communicate with multiple slave devices. By enabling this type of communication, animations could be displayed across multiple transmitters. For example, an animation can start in one transmitter and seamlessly carry over to another, or simply allowing multiple transmitters to play animations in sync. Due to the nature of a bus, all devices were connected in parallel – meaning that transmitters cannot inherently know the addresses of their neighbours on the grid. Therefore, through I²C, all transmitters were assigned a position and provided with their addresses and physical positions of their neighbours. This had several consequences for the user experience, especially ease of use, which are discussed further in section 7. The transmitter positions were coordinates relative to the master module, which had coordinates (0, 0). Figure 3.13 shows how square modules were assigned their coordinates (indexes) and forming a matrix of modules.

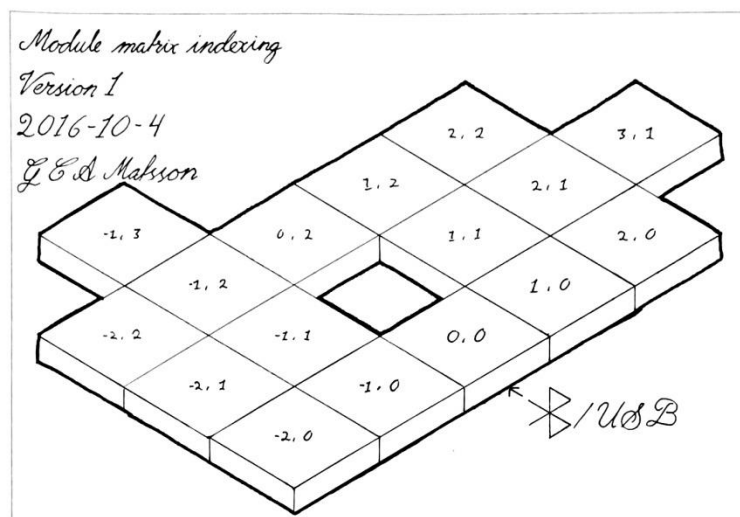


Figure 3.13: A sketch visualising matrix indexing of transmitter modules.

The same principle was later used for hexagonal transmitter modules. As shown in Figure 3.14, for ease of understanding, the hexagons were arranged in a square grid and assigned their address-

⁹ Arduino Reference – Wire: <https://www.arduino.cc/en/Reference/Wire>

es just like the square modules. Every odd row of modules was then shifted to the right and the resulting gaps closed – forming the hexagonal grid. In the same way as the squares, each hexagon have four neighbours – up, down, left and right – which simplified the animation programming but limited flexibility and possible configurations. This design decision was a compromise between cost and ease of implementation on one side, and user experience on the other. This design decision is discussed further in section 7.

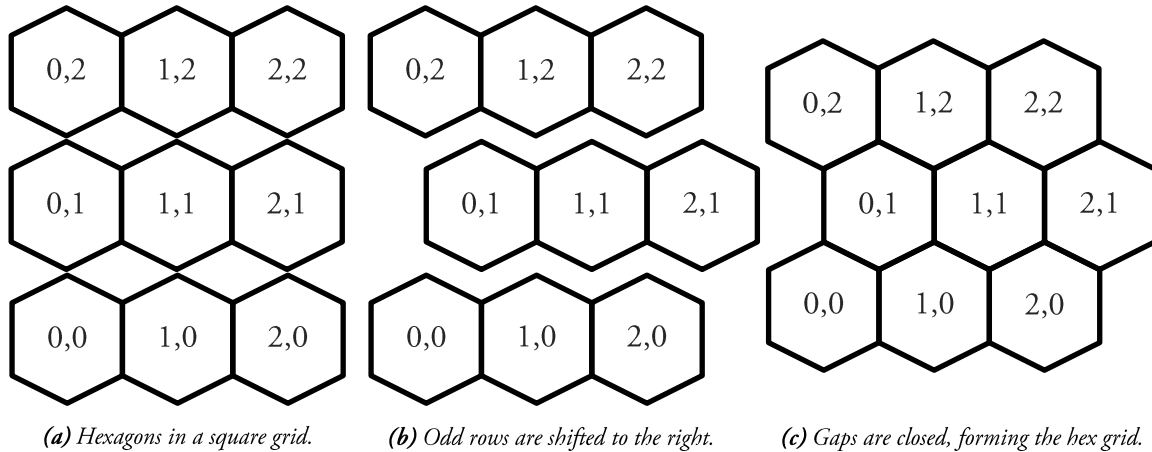


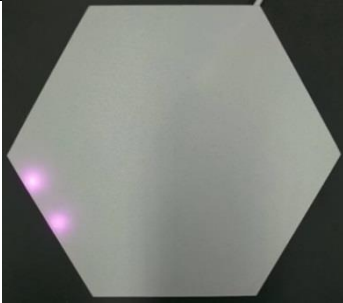
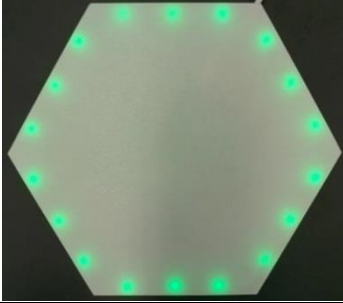
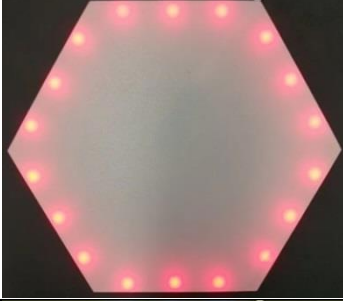


Figure 3.14: Visual representation of hexagonal matrix indexing in three steps.

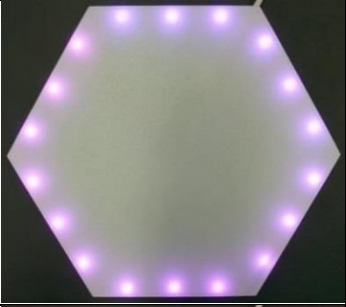

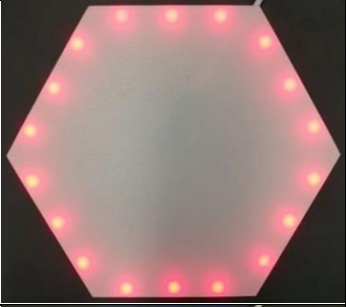
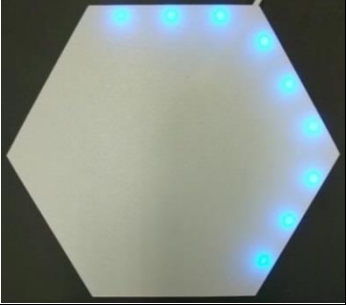
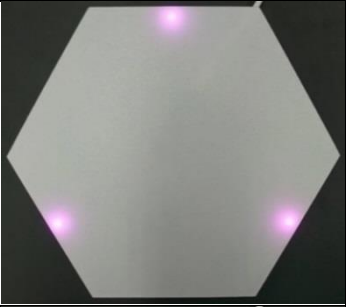
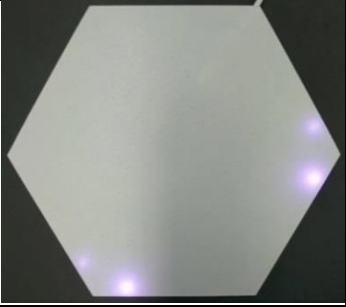
3.1.4. VISUAL FEEDBACK

In order to communicate effectively with the user, six states were identified that a wireless charger might assume:

- *Idle:* Waiting for something to charge
- *Start Charging:* A device has just been placed on the charger
- *Charging:* Charging a device
- *Stop Charging:* A device has just been removed from the charger
- *Error:* An error has occurred
- *Foreign Object Detected (FOD):* Power loss due to an unwanted metal object

Following the guidelines proposed by Matviienko et al. [6], eleven animations were designed with the six states in mind – some more ambiguous than others. For example, red and green animations were designed with positive and negative connotations in mind but not for any specific charger state. The most suitable animation for each state was later decided in an online survey (see section 4). Some animations were adaptations of, or inspired by, animations presented by Harrison et al. [5]. The created animations include:

| Animation | Colour | Behaviour | |
|------------------|--------|--|---|
| Going Around | Random | A single point moving clockwise, fading in the successive LED before fading out the current. Changes colour after each turn around the module. |  |
| Green Flash | Green | All LEDs turned on before fading out. Similar to Harrison et al.'s 'Fast In, Slow Out' [5] |  |
| Double Red Flash | Red | All LEDs blinking twice in unison. |  |
| Gauge Sweep | Random | All LEDs quickly fade in, moving slowly one after the other clockwise before turning off one by one in the opposite direction. |  |
| Pulsating | Random | All LEDs slowly fade in and out in unison, randomizing colour after each pulse. |  |

| | | | |
|-----------|--------|---|---|
| Rainbow | All | All LEDs slowly and smoothly cycle through the colour spectrum. |  |
| Sawtooth | Random | All LEDs slowly fade in before turning off – a sawtooth wave. Randomizing a new colour after each cycle. Called ‘Gradual Build’ by Harrison et al. [5] |  |
| Solid Red | Red | All LEDs red, no animation. |  |
| Throbber | Random | Half the LEDs, one after the other, clockwise, turn on before turning off in the same order. The animation is repeated on the other half of the module. |  |
| Triangle | Random | Three LEDs of fixed distance to each other fade in and out, rotating clockwise. |  |
| Ping Pong | Random | One LED and a trailing LED ‘bounces’ back and forth between two opposite corners of the module. This is mirrored on the other half. |  |

3.1.5. OUTCOME

Four, latest iteration, transmitter modules were created in total. The resulting prototypes (Figure 3.15 and Figure 3.16) measures 228×196 mm across their widest and narrowest sections respectively, including the slightly protruding contacts, and 10mm thick.

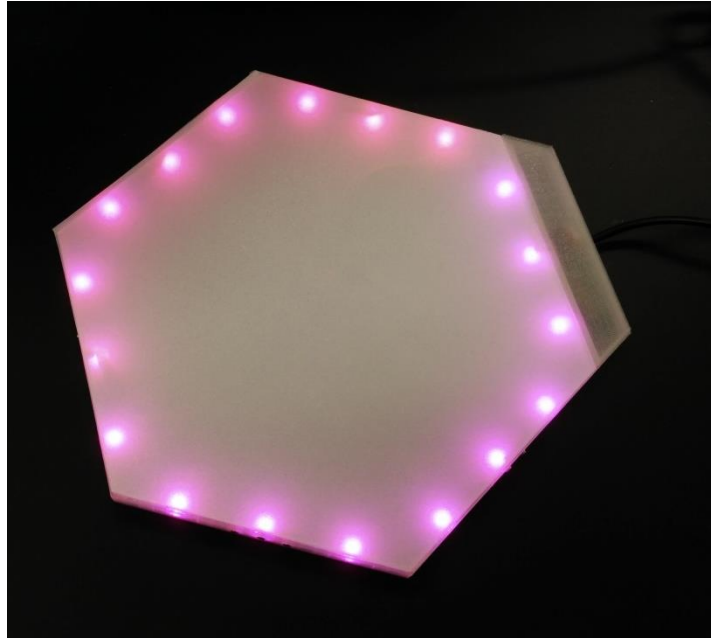


Figure 3.15: A single module with connected power supply.

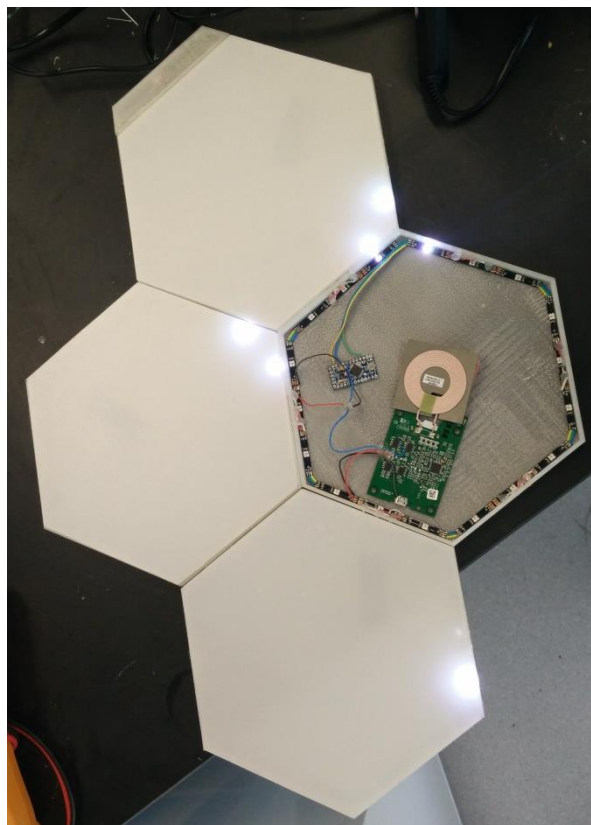


Figure 3.16: Four connected modules in a grid. One module has its top surface removed for demonstration purposes.

3.2. RECEIVERS

In order to facilitate evaluation of different applications, a number of technical gadgets were procured and modified to support wireless power. However, the choice of gadgets was limited by the power provided by the transmitters – namely five volts, one ampere.

3.2.1. KEYBOARD

The keyboard (Figure 3.18) communicates with a computer by radio, via a USB dongle. It was originally powered by two, 1.5 volt, batteries in series. In order to use the 3-volt keyboard with the 5-volt wireless charging system, a voltage divider, using two resistors, was created (Figure 3.17).

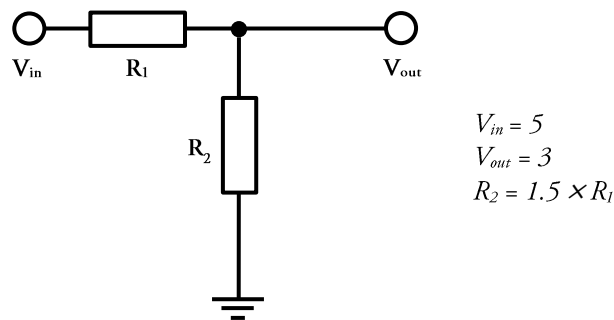


Figure 3.17: Voltage divider schematic and values.

After removing the batteries, wires were soldered to the exposed terminals and connected to the voltage divider and wireless charging receiver inside the now empty battery compartment. The charging receiver was then fastened under the keyboard.



Figure 3.18: The modified wireless keyboard.

3.2.2. LAMP

The lamp (Figure 3.19) was originally a 5 volt, USB chargeable, LED lamp. It was modified by drilling a hole in the bottom of the stand, extracting the rear facing power jack (Figure 3.20) and soldering the +5V and ground wires the corresponding terminals of a charging receiver glued to the bottom of the stand (Figure 3.21).



Figure 3.19: The desk lamp.



Figure 3.20: The hole left by the lamp's DC power jack.



Figure 3.21: A wireless charging receiver mounted underneath the stand.

4. STAGE C: ONLINE SURVEY

The purpose of the online survey was to evaluate how suited the animations were perceived for the six states of the wireless chargers. Two versions were created. For the pilot study, a custom website with an overview where all animations were displayed simultaneously was used. However, after the pilot study, it was replaced by *Lime Survey*¹⁰ – an online survey tool.

The website (Figure 4.1) consisted of all 12 animations, including all LEDs off, arranged in a grid – each with a corresponding five point Likert scale. The participants were presented with one of the wireless charger states at a time and proceeded to rate the 12 animations before clicking ‘Next’ upon the next state was presented and the Likert scales reset. This was repeated six times, rating all states. The results were first stored locally, using JavaScript, and on completion, a POST request was sent to a PHP file on the web server where the results were inserted into a MySQL database.

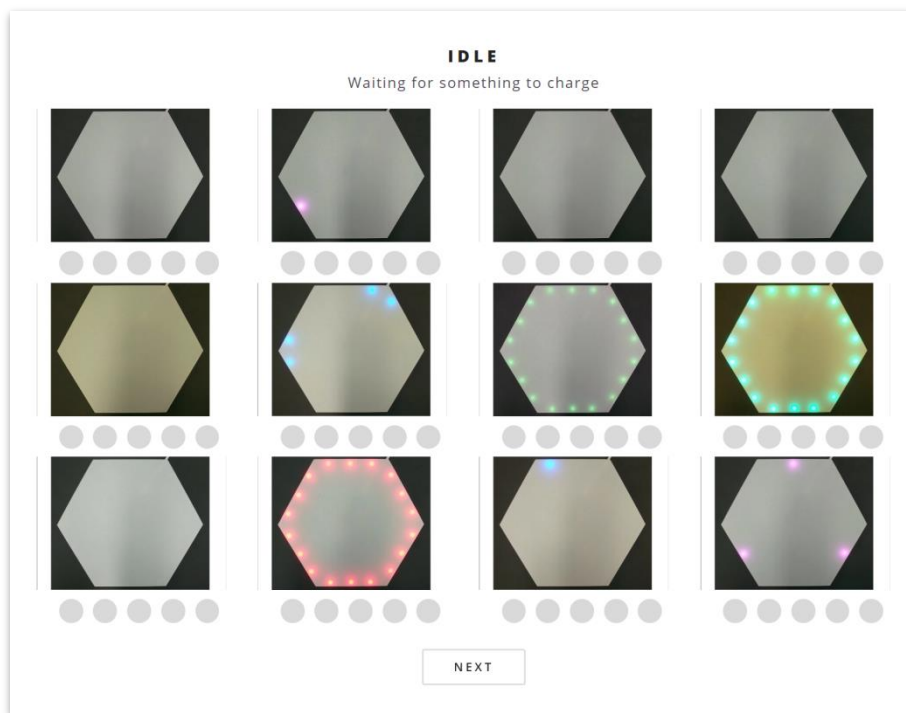


Figure 4.1: Screenshot of the website used during the pilot study.

After a pilot study (eight participants, mean age 26, two female) the survey format was changed to display one animation at a time where participants instead rated how suitable they found that animation for all six states. *Lime Survey* (Figure 4.2) was used instead of a custom website since the overview was no longer displayed making a traditional, sequential, survey suitable and faster to implement. This was also done in order to comply with the methodology used by Harrison et al. [5] and reduce page loading times and performance since displaying all 12 animations at once resulted in poor performance on slow connections and less powerful hardware. Another advantage

¹⁰ Lime Survey – official website: <https://www.limesurvey.org>

was that the order the animations appeared in could be randomized, which can reduce bias in the participant [10].

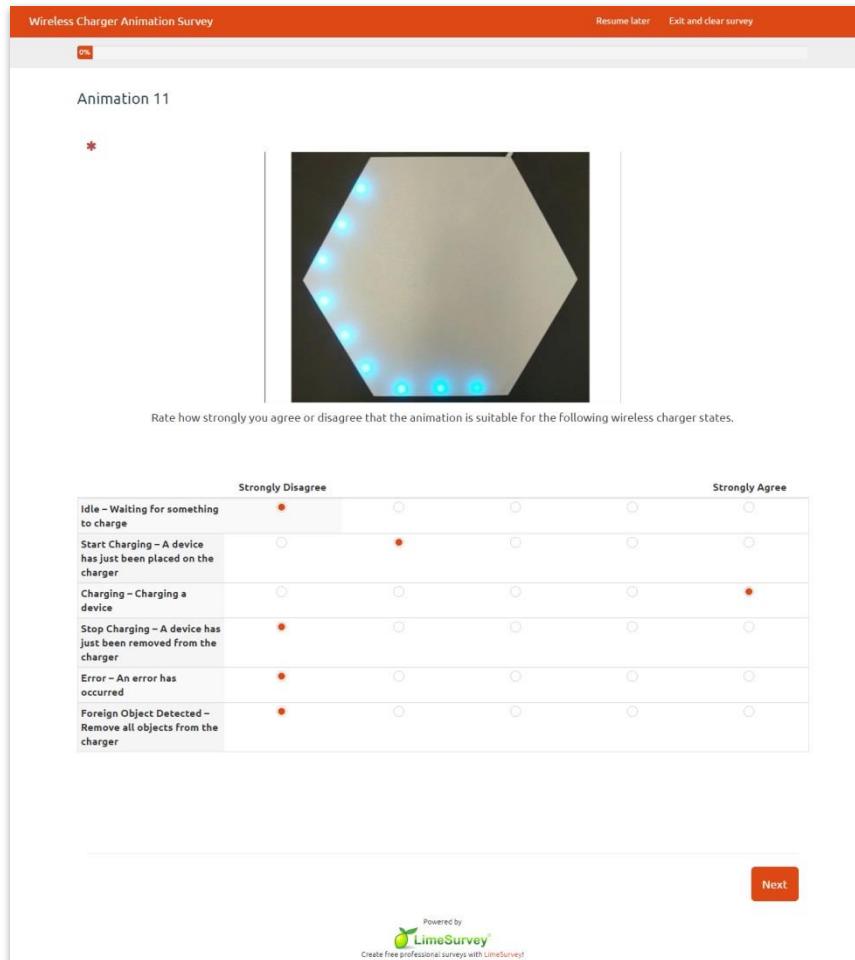


Figure 4.2: Screenshot showing the survey interface for one of the animations.

4.1. OUTCOME

18 participants (ages 22 to 38, mean 27) completed the survey. Eight of those were female and five reported previous experience with wireless charging. The education levels of the participants are shown in Figure 4.3.

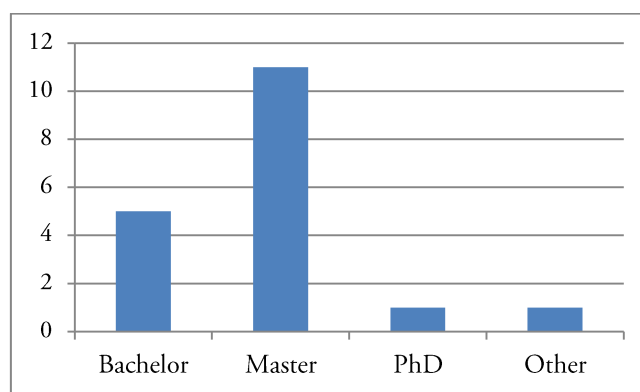


Figure 4.3: Survey participants' education levels.

For the idle state, participants showed a clear preference for having no animation i.e. all LEDs off with 5.53 average score. The closest contestants, 'Going Around' and 'Triangle', both scored an average of 3, see Figure 4.4.

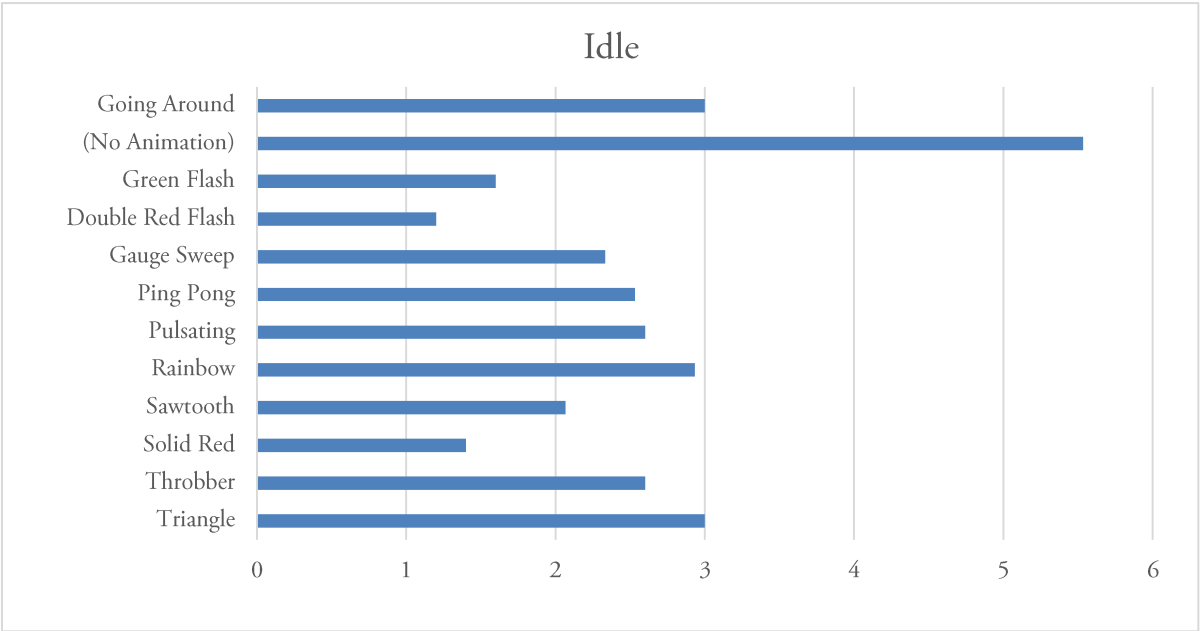


Figure 4.4: Ratings of animations for representing the 'idle' state.

'Green Flash' was scored highest for the 'start charging' state with an average score of 3.4, closely followed by 'Gauge Sweep' at 3, see Figure 4.5.

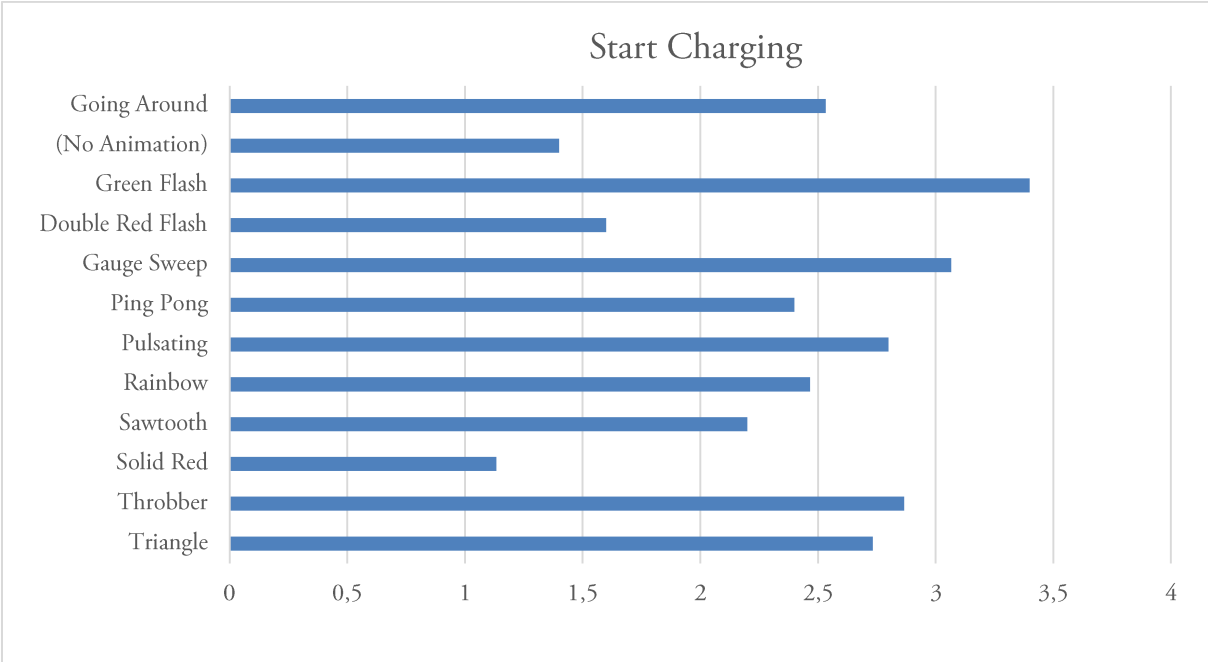


Figure 4.5: Ratings of animations for representing the 'start charging' state.

For when the charger is actively charging a device, participants scored 'Throbber' highest at 3.8, followed by 'Going Around' and 'Pulsating' at 3.3 and 3.25 respectively, see Figure 4.6.

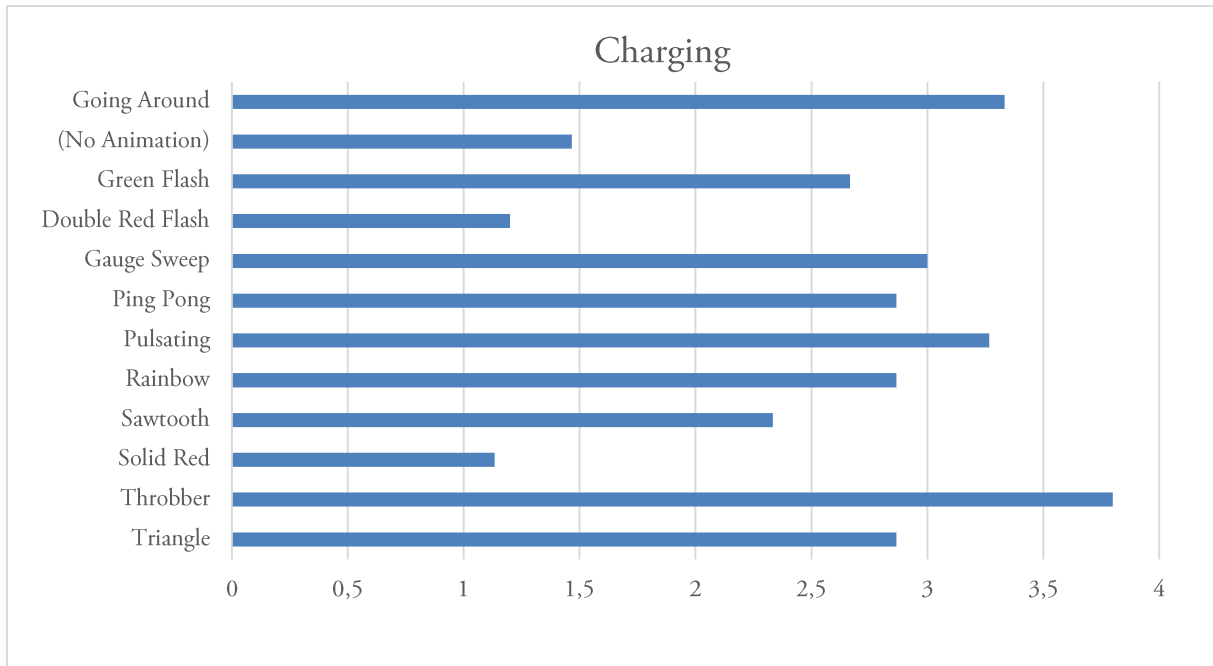


Figure 4.6: Ratings of animations for representing the 'charging' state.

For the 'stop charging' state, participants preferred no animation to be played with a score of 3. Note that all animations scored relatively low compared to the other states, see Figure 4.7.

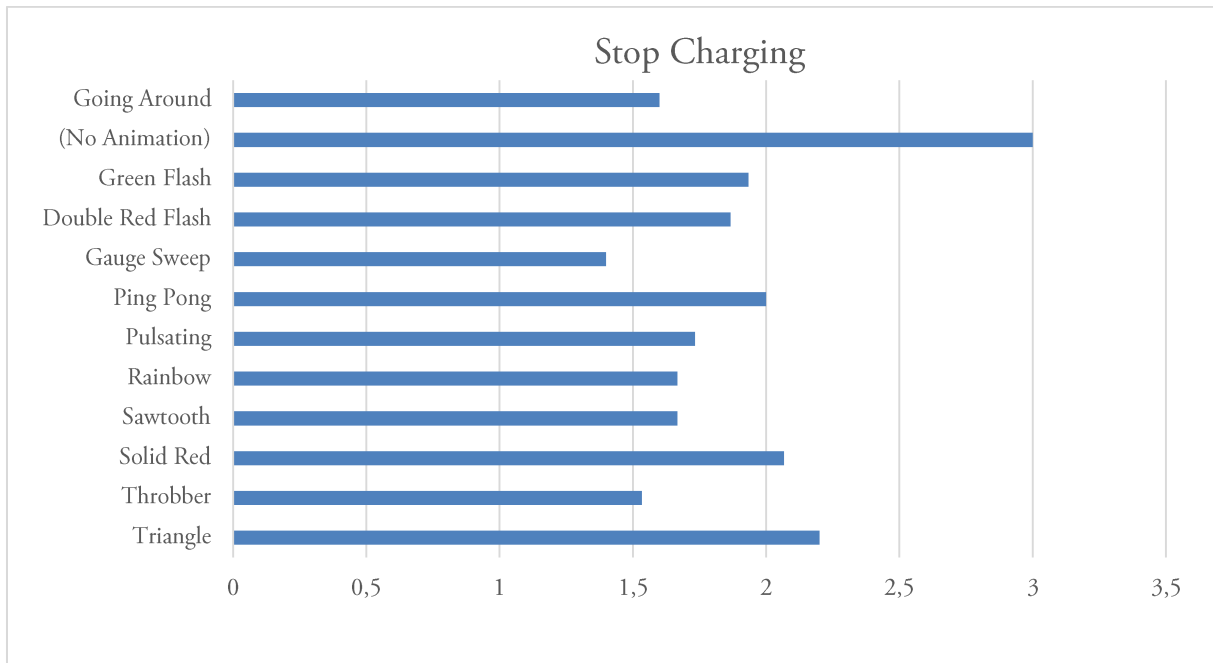


Figure 4.7: Ratings of animations for representing the 'stop charging' state.

The results for both error states were relatively similar with 'Double Red Flash' and 'Solid Red' being scored the highest by a large margin. For the generic 'error' state, 'Double Red Flash' scored highest at 4.53 (Figure 4.8), and for the 'foreign object detected' state, 'Solid Red' scored highest at 4.47 (Figure 4.9).

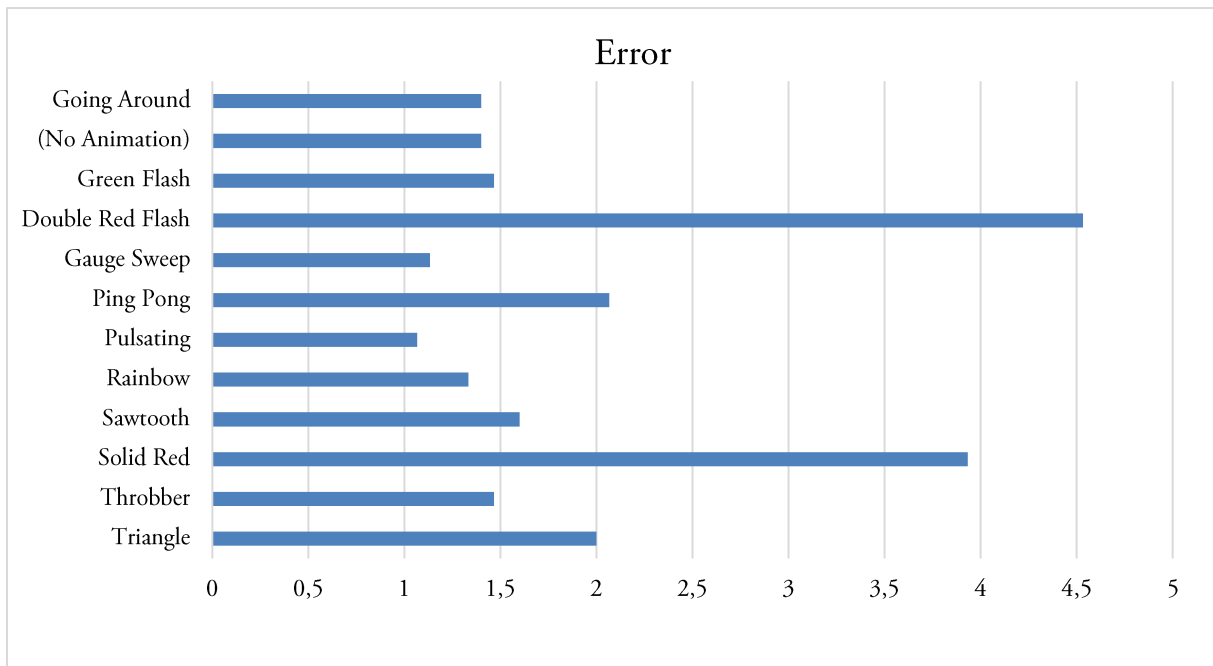


Figure 4.8: Ratings of animations for representing the 'error' state.

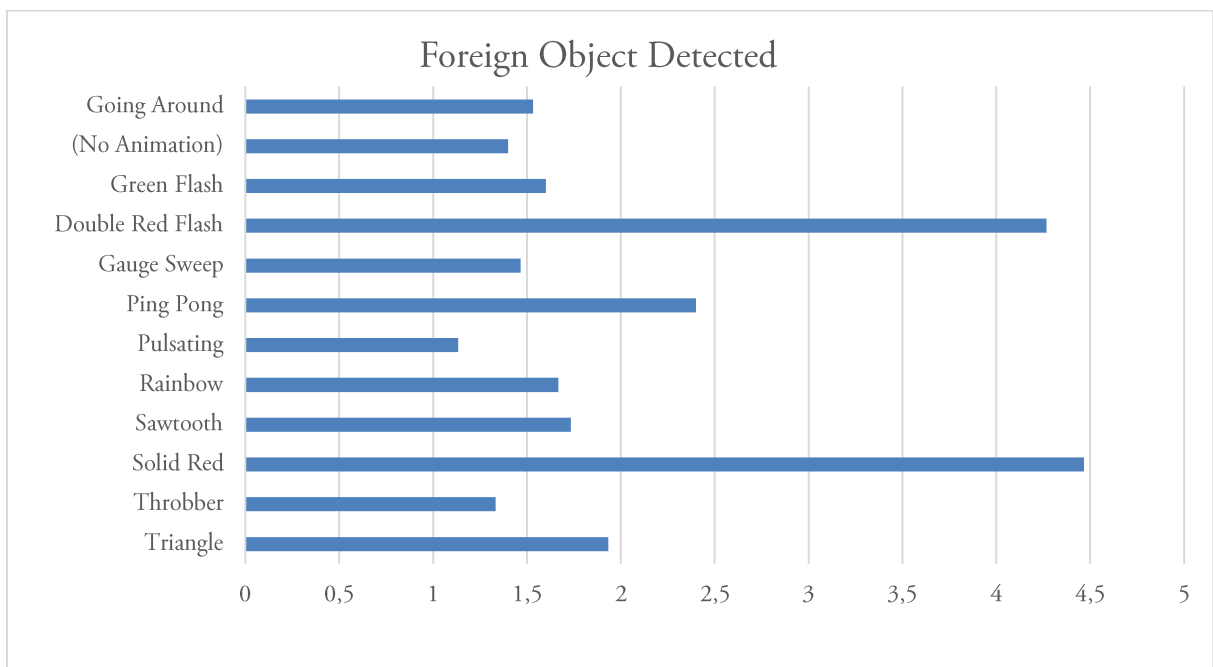


Figure 4.9: Ratings of animations for representing the 'foreign object detected' state.

5. STAGE D: PROTOTYPE EVALUATION

The aim of the prototype evaluation was to test the functionality of the developed modules – including size and proportions, magnetic contacts and feedback – as well as investigate what types of applications participants find suitable for wireless charging.

Each session started with sitting the participant down at a desk where the test was taking place and presenting them with consent forms and demographics information for them to fill out and sign. After an introduction to the study and our aim for it, participants were asked to complete two tasks followed by questionnaires and an interview. The participants were encouraged to think aloud during both tasks.

Because we did not possess the technology to fulfil the functional requirements, as stated in Stage A, concerning the ability to place a chargeable device anywhere on the charging surface, it was decided that the test should take the form of a Wizard of Oz¹¹ experiment using DFRobot Bluno Nanos – Arduino Nanos that can be controlled via Bluetooth. This way, signals could be sent to the charging modules to display the correct animation – simulating the required functionality.

In the first task, participants were presented with one charging module and a power supply. They were then asked to connect the power supply to the charging module. This part was aimed to determine how intuitive the participants found the module design. After successfully connecting the power supply, a smartphone (Samsung Galaxy S7) was given to the participant who was asked to charge it using the charging module.

Next, a second charging module was introduced and the participants were tasked to connect it to the other in any way they preferred. After connecting the second module, four additional receivers were introduced, including the modified lamp and keyboard as well as a wireless mouse and speaker. The participants were encouraged to try powering the different receivers and use multiple combinations of receivers.

For the second task, participants were asked to imagine two different scenarios of use – a bedside table and an office desk. In the first scenario, an area measuring 200×260 mm was outlined using masking tape on the desk – representing the bedside table. This area is large enough to fit a single module. The participants were provided a phone, wireless speaker and a lamp and asked to arrange the items, one two or all three, in a manner they saw themselves using on their bedside table.

In the desk scenario, two additional charging modules were provided resulting in four modules in total. A 21-inch monitor was placed on the desk to as a prop, as well as providing an obstacle around which the modules needed to be placed. In addition to the lamp, phone and speaker, the

¹¹ UsabilityNet – Wizard of Oz method: <http://www.usabilitynet.org/tools/wizard.htm>

mouse and keyboard were made available. The participants were asked to do the same thing as in the first scenario, but this time imagining their desk at work.

Upon completion of the second task, participants completed three questionnaires. The first, System Usability Scale (SUS) [11] [12] followed by select statements from Stage A (Figure 5.1), and finally Attrakdiff [13].

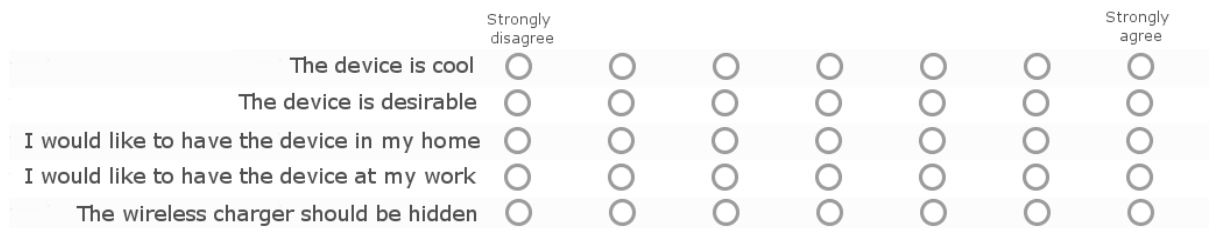


Figure 5.1: The five statements used, originally from Stage A, supplementing SUS and Attrakdiff.

The final part of the evaluation was a semi-structured interview. The aim of this part was to allow participants to share their views on the system, interaction and function. The interview included the following questions:

1. What types of devices did you find suitable for wireless charging?
2. Can you suggest more applications or devices to use with wireless charging?
3. What devices are not suitable for wireless charging?
4. Where would you like to have wireless chargers, inside your home / work / public space?
5. When would you typically use wireless charging if available?
6. What are your thoughts on the magnetic contacts – too strong or weak?
7. What are your thoughts regarding the power supply module?
8. Were the modules easy to arrange?
9. What do you think about the size of the modules – too big or small?

5.1. OUTCOME

There were five participants in total, one female, between ages 23 and 31. They were four graduate students and one undergraduate student. All had some previous experience with wireless charging but only one owned a wireless charger.

The average SUS score for the system was 83.5 with 75 being the lowest and 92.5 highest. The results indicate that the system is highly usable as the score is above the average rating of 68 [12]. The outlier statement that reflected poorly on the system was ‘I found the system cumbersome to use’ with two participants agreeing, one neutral and two disagreeing. Upon investigation, all participants, to varying degrees, expressed that connecting and rearranging the modules was unnecessarily cumbersome as they felt too light and slid around on the desk when two modules were disconnected. One participant cited the size of the modules as a source of frustration, arguing that smaller modules would have been ‘more easily arranged and less awkward to handle’.

The results for the statements, as seen in Figure 5.1, can be seen in Figure 5.2 and the scale distributions in Figure 5.3. From the results, we can see that the charging modules are considered ‘cool’ with two participants strongly agreeing, two agreeing and one somewhat agreeing. The modules are also desirable, however, in the ‘like to have’ statements they scored lower – much so at work. For having the modules at work, two participants somewhat agreed while two others were neutral and one disagreed. The interviewees in Stage A were not unanimous whether the chargers should be hidden from sight. That is reflected here although favouring a hidden charging solution.

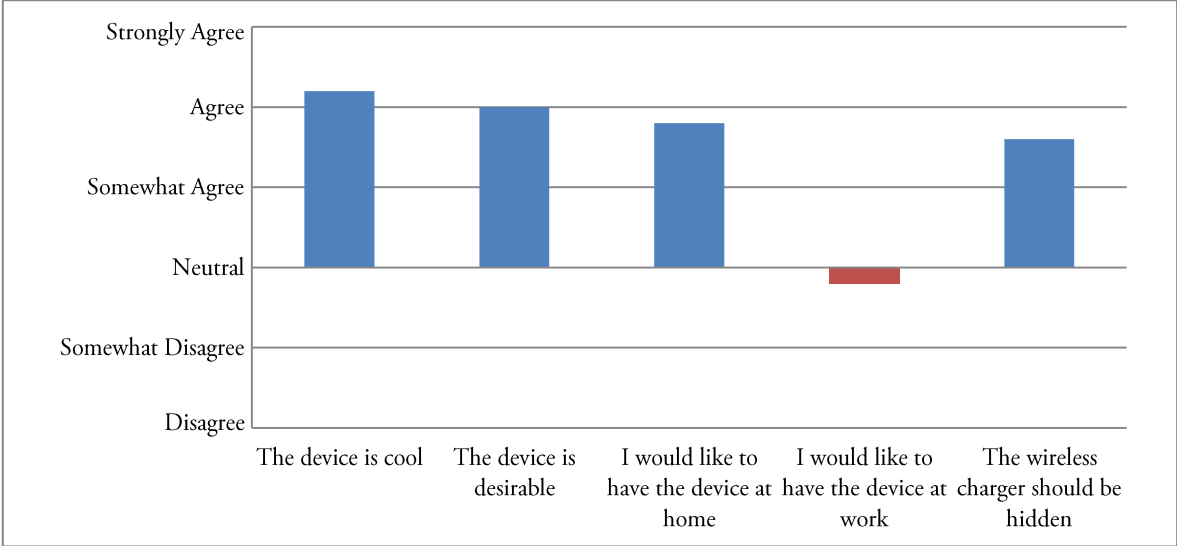


Figure 5.2: Average scores for the statements in Figure 5.1.

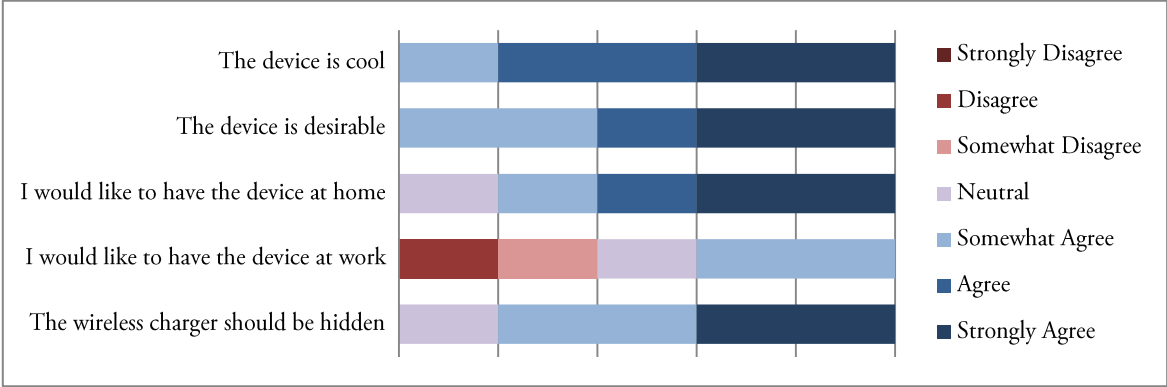


Figure 5.3: Distribution of responses regarding the statements in Figure 5.1.

The results for the final questionnaire, Attrakdiff, can be seen in Figure 5.4. As mentioned, the participants found the modules somewhat hard to disconnect and rearrange. This is also reflected in this questionnaire with moderately high scores towards ‘cumbersome’ and ‘unruly’. The modules were rated strongly towards ‘unprofessional’, which likely contribute to the disagreement towards the ‘like to have at work’ statement.



Figure 5.4: Line chart showing the average Attrakdiff ratings.

The types of devices participants found most suitable included the phone and the keyboard and mouse. The lamp and speaker was not regarded as highly as most of the participants stated that these devices were usually stationary and kept plugged in. However, as one participant stated, ‘getting rid of the wires would be most welcomed’.

In addition to the devices in the experiment, participants were asked to provide examples of other devices they would like to charge wirelessly. All participants considered laptops to be their first pick for wireless charging besides their phones. Other small devices, such as smartwatches and activity trackers were mentioned by several participants. Overall, the participants found that their experiences with wearables and small portable objects would be improved by wireless charging. Moreover, two participants mentioned charging electric vehicles such as cars and scooters using induction in parking lots and driveways. On the other hand, stationary object and products on which the participants relied heavily on were deemed unsuitable for wireless charging. Examples of such devices included desktop PCs, network routers, servers and refrigerators.

As to where participants wanted to use wireless charging, the home environment was all the participants first answer – their desk for laptops, keyboards and mice, and their bedside table for charging their phone during the night. However, during the second task of the experiment, one

participant stressed that they must be able to turn the LEDs off at night, as the light would disturb their sleep. At work or school, two participants wanted the wireless chargers mounted in or under the tables. It was pointed out that wireless charging technology needed to be present at most locations before they could leave the home without their laptop charger and not risk running out of battery before coming home.

All participants expressed that the magnetic contacts increased the overall user experience of the modules. However, the lightweight modules did not have enough friction on the table resulting in them sliding when participants attempted to disconnect them. All participants but one cited this as a major frustration.

Most participants were indifferent regarding the power supply. However, the ability to connect it to any side of any module in the grid was appreciated. Two participants wanted, in the desk scenario of the second task, to have two separated groups of two modules and were disappointed that only a single power supply was available. For examples of module layouts, see Figure 5.5.



Figure 5.5: Module layouts used by participants.

The modules were considered easily arranged although their low friction, low weight and large size had a negative effect on the user experience for most of the participants. They felt that using all four modules at once left too little desk space for stationery and other equipment.

6. RESULTS: DESIGN GUIDELINES

In this section, we will present our proposed user experience guidelines for wireless charging applications. The guidelines have been extracted from the outcomes of each stage and are meant to summarize and highlight the key findings of the studies. Moreover, the guidelines are placed under the user experience factors described in section 1.3.

6.1. FUNCTIONALITY

- §1. Charging areas should be large enough to allow users to place their device without having to care for alignment of the coils. In public spaces, a charging area must be indicated by, for example, outlining it.
- §2. Power transfer must be available over the whole area,
- §3. Ideally, integrate wireless charging transmitters in, or under, surfaces. The surface should be smooth and void of indentations.

6.2. FEEDBACK

- §4. When a charger is idle, no animation should be played.
- §5. When a charger starts charging, indicate this to the user with a short confirmation.
- §6. When actively charging, display an animation that communicates change or progression.
- §7. When an error has occurred, indicate this using attention grabbing colours and animations. Make these animations distinct from the others.
- §8. Users must be allowed to turn off the feedback of the wireless chargers.

6.3. APPLICATIONS

- §9. Design for portable receivers such as laptops, smartphones, smartwatches and other wearables. Additionally, computer peripherals, such as mice and keyboards are also suitable as wireless charging receivers.
- §10. Stationary devices, such as desktop PCs and lamps, are not suitable as wireless charging receivers.
- §11. Devices on which users rely heavily upon, such as network servers, or equipment in safety critical applications are not suitable for wireless charging.
- §12. Users prefer to use wireless charging in their home – at their desk or bedside table. For users to feel comfortable leaving their home, without fearing running out of battery, wireless charging must be available and accessible wherever on the campus, workplace or other place the user might over an extended period.

7. DISCUSSION

In this section, we will discuss our methods and findings. Points of interest, as well as shortcomings, concerning our work will be addressed here.

7.1. STAGE A: INTERVIEWS AND PARTICIPATORY DESIGN

The findings from the interviews greatly shaped the design of the prototypes. However, concerns must be raised regarding the small sample size and uniform population of the study. The participants in the convenience sample were all young students at Singapore University of Technology and Design. One could rightly argue that our findings would be different interviewing individuals of a different age group, culture and geographical location. Although preferable, the scope and budget of this thesis would not allow further inquiries as a prototype was deemed necessary to further test the applications of wireless charging technology and the feedback required.

Modularity seemed to be a concept that most participants found familiar – four participants even suggested a modular system before being introduced to the final part of the sessions. The size of the charging modules is something we did not include in the interviews. However, we strongly believe that the module size will greatly affect the perception of the products. Larger modules should reduce the cost of covering a large area. However, as one participant pointed out, small modules allow for higher adaptability as the ‘resolution’ increases for a given area compared to larger modules. We find it highly unlikely to be an optimal size for charging modules as consumers’ wants and needs varies, but further investigation could yield some indications as to consumer preferences.

We would also like to acknowledge how the four shapes chosen do not include all uniform, tessellating, shapes that could possibly be used for charging modules. The shapes chosen were primitives with low vertex counts: triangle, three; square and rhombus, four; and hexagon, six. For example, pentagons could be used. However, their asymmetrical nature limits the number of ways they can be oriented. Using two, or more, different shapes would allow for many interesting patterns, but would increase the complexity of manufacturing evaluation substantially.

The hexagon shape scored high in terms of both functionality and aesthetics. However, it was seen as rather unconventional. This was surprising, seeing as the shape is prominently featured in science fiction movies, video games and in nature – as honeycombs and graphite layers. The shape can also found in molecular diagrams and might evoke feelings of both the synthetic and the natural.

A grid of hexagons, as stated in the ‘honeycomb conjecture’, is the best way to divide an area into cells of equal size with the shortest total perimeter [14]. Although fine in theory, in practice when arranged on a rectangular table, they leave gaps around the grids perimeter and the edges of the table. For this reason, as rectangles are one of the most popular table shapes, square modules might be preferable after all.

As stated previously, the statements and Likert scales are inspired by Raptis et al. [8]. However, we removed the majority of the statements and added some of our own in order to address some shortcomings we found with the existing statements as well as investigate whether participants thought some shapes more suitable for home or work environments. The statements were meant to provide useful data on consumer preferences for developing a marketable product. Our major critique of the ‘Cool Questionnaire’ [8] is regarding the relevance for marketable product- and-service development. The authors cite three types of cool – ‘inner cool’, ‘outer cool’ and general ‘cool’. In the first, ‘inner cool’, there are three contributing factors namely ‘desirability’, ‘rebelliousness’ and ‘perceived usability’. We argue that the ‘rebelliousness’ is not necessarily contributing to the willingness to personally own or use a device or service and is therefore limited to one statement in our study. The results confirm our intuition as the lowest overall scoring shape, the rhombus, scored highest in unconventionality (4.1) whereas the square scored lowest (1.2). Moreover, the square scored lowest in ‘cool’ but scored high in both desirability and ‘like to have’ statements whereas the rhombus did not. The results from this study clearly indicate that coolness and desirability is not directly correlated.

7.2. STAGE B: PROTOTYPING

When designing the modules, there were many assumptions that had to be made due to the limited time available resulting in multiple potential features either being discarded or abandoned. For example, we would have liked to experiment with other types of feedback, such as auditory or tactile.

Having the modules make a sound or vibrate to communicate its current state would allow the modules to be mounted under, or in, surfaces – such as tables or desks. The outcome of Stage A showed that participants were not unanimous regarding the visibility of the charging devices. A solution where the chargers were hidden from sight would exclude the possibility of visual feedback, at least on the device itself, and would therefore require testing audio or tactile feedback.

However, we cannot assume that the transmitter is more suitable than the receiver is for providing feedback to the user. We chose to focus on the transmitters because they can detect errors and foreign objects, as well as being aware of multiple transmitters and receivers if connected. It was therefore thought to be a richer design space than that provided by receivers. Having the transmitters provide feedback also ensures consistency – at least within the same system. Users might have many receivers from different manufacturers – all providing feedback unique to their devices. The transmitters can provide the same feedback for all types of devices or, by using technology such as AirFuel [3], identify what device is charged and give feedback appropriate for that device.

We would also like to acknowledge how the technology limitations of the chargers, available to us, do not fulfil the requirement of being able to, haphazardly, place the receivers anywhere on a charging surface. This requires that the transmitter is capable of retaining a high enough output

even though the receiver is misaligned. There are three types of misalignment – lateral, vertical and angular [13]. For descriptions and visual representations, see Figure 7.1.

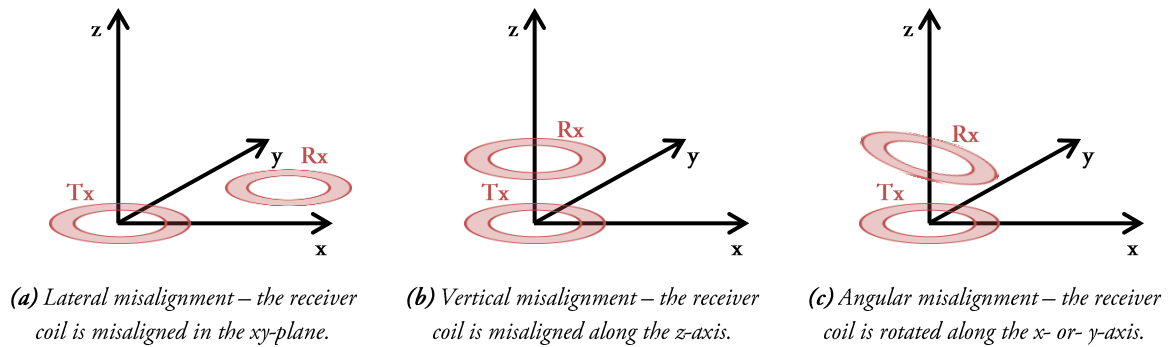


Figure 7.1: The three types of coil misalignment.

In an application such as wireless charging, there will always be some vertical misalignment as the both coils are inside some sort of enclosure. However, our main problem is that our transmitters do not allow for great enough lateral and vertical misalignment. The charging performance could be improved by adding more coils and control circuits inside the transmitter modules or using resonance technology. Sadly, this technology was unavailable to us at that time.

As mentioned, some features had to be abandoned – one of which is the I²C communication, which was implemented but never utilised. There were several contributing factors in the decision not to use I²C. Firstly, assigning addresses to each module was quite tedious and had to be redone each time the grid configuration changed – making it hard to test and evaluate, as well as affecting the user experience. Another issue was that the magnetic contacts could cause interfere – corrupting the data on the bus.

Besides making I²C unusable, we were pleased with the magnetic contacts. They provided a satisfying ‘snap’ sound as modules were brought together and holding them in place as well as acting as an electric conductor. The last iteration of modules was outfitted with two magnetic contacts carrying ground, and a non-magnetic contact carrying +5V on each side. A better solution would be to have four contacts – all four magnetic, two carrying ground and two power. This would improve the connection between the prototypes and making them easier to produce. Currently, it is hard to ensure that the non-magnetic, middle, contact is protruding the way they should for a reliable connection as they rely on the surrounding magnets to attract adjacent modules. Some form of short circuit protection is also needed since it is possible to misalign two modules.

The power supply module provided an easy way to connect a grid of transmitters to a power source. It could be placed on any available side of any module in the grid. However, having a USB connector is probably not a good idea since the current draw of multiple modules is potentially much higher than a standard USB jack allows and should only be mains powered using a high amperage DC power supply.

Naturally, there were many aspects we lacked the resources to prototype and test, such as different LED patterns and configurations and different enclosure materials. It is hard to determinate how our choices affect the overall user experience, let alone all other options. Therefore, further testing is required to assess how some of our design decisions affect the user experience and what changes could improve it.

The use of a modular system was considered from the start of the project and, after being suggested by multiple interview participants, decided worthy of pursuit. A modular system was deemed more easily implemented and the flexibility provided the opportunity for extensive testing of different configurations and applications by varying the size and shape of the charging area. However, seeing as the interview participants were not unanimous regarding buying new or modifying their furniture to support wireless charging, fixed sized, prebuilt, wireless charging furniture should also be explored.

7.3. STAGE C: ONLINE SURVEY

Using the prototypes developed in Stage B, we conducted an online survey in order to investigate what animations were suitable for the six states of the chargers. Our main concern after performing this study was the low number of participants who completed the whole survey. We must understand that the data will not be fully representative and has been treated as such. Many variables could affect the results of the study and controlling for them all was not an option due to our budget – in terms of both time and finances.

The variable of colour was particularly hard to control. Some animations had a fixed colour where others were assigned a new random colour at different points in their animations. Communicating this was challenging and we believe it could have been better executed by having longer videos and descriptive texts for each animation. Presenting the animations without their colours, i.e. in black and white, was considered. However, removing the colours from the animations would result in inaccurate data since combinations of colours and movement patterns could yield different results. Ideally, every animation should be presented in multiple colours – however, this would greatly increase the complexity of the test.

The number of evaluated animations is also a point of concern. Just as Harrison et al. [5], we designed a number of animations, which were later presented to participants. Seeing, as there are six charging states, two of which are transitional, 12 light patterns is a very small sample size and must therefore not be seen as the definitive, or correct, animation for any state. However, for creating guidelines, we can try to extrapolate and find common characteristics for the animations rated highest for any given state and draw our conclusions.

An interesting observation is how, contrary to Matviienko et al. [6], we found that the green animation was thought of as good and the reds as bad. In their paper, the authors state “red light is often perceived as something negative, but only when green colour is present in the pattern”. Our findings contradict this statement in both the pilot study, where multiple animations were dis-

played at the same time, and in the survey – where animations were displayed one at the time. If true, that would lead us to believe that the animations in question (‘Double Red Flash’, ‘Solid Red’ and ‘Green Flash’) communicated their state more in light pattern than colour; however, we find this improbable. Note that red and green without different light patterns pose problems for people suffering with red-green colour blindness. More research is needed to assess how light patterns and colour affect perceived meaning and how they should best be combined.

As for the outcome of the study, participants highly preferred no animation [all LEDs off] when the device was in the idle state. In a home environment, this would not be a problem, as the inhabitants would know what the device was and how it works. In a public space, however, some form of indicator would probably be preferable. For when charging, the ‘Throbber’ animation scored highest, followed by ‘Going Round’ and ‘Pulsating’. Here, we see a strong correlation with faster, energetic animations.

7.4. STAGE D: PROTOTYPE EVALUATION

For the prototype evaluation, we chose to do the ‘Wizard of Oz’ method. In Stage A, it was established that users required the charging areas to be large and allow charging anywhere on it. Unfortunately, we did not possess such technology that would make this possible – therefore we argue that, in this case, a Wizard of Oz test would provide data on user experience more accurately. The chargers we used in the modules do not allow for lateral misalignment (Figure 7.1) more than a few centimetres, which, in conjunction with the large modules, make aligning receivers both difficult and frustrating. By performing a Wizard of Oz test, we could simulate the requirement of high lateral misalignment tolerance with the downside of not having a notification in the receivers when charging. Additionally, as some participants did, we could simulate charging multiple receivers on a single transmitter module – something that is currently not possible.

To familiarise participants with the technology and applications, they were asked to perform two tasks, one of which presented two scenarios of use. We introduced the transmitter modules and receivers gradually and increased the number of modules in each new stage of the tasks. In the first task, a single module and power supply was presented to the participants. Apart from observing the participants’ first reaction, this was done to introduce the technology without overwhelming them with multiple receivers and modules. The two scenarios of use, the bedside table and desk, were meant to exemplify different applications of the technology – both in terms of time and space.

Comparing to the outcome of Stage A, we can see how the ‘cool’ and ‘desirable’ statements for the hexagon shape are similar to the outcome of Stage D – with cool being slightly higher, and desirable slightly lower than in Stage A. The ‘like to have at home’ statement also scored similarly between both stages. However, we see a big difference for ‘like to have at work’ statements in the two stages. In Stage A, the hexagon shape was rated high for both home and work – 4.4 and 4.6 respectively. In Stage D, however, the prototypes scored very differently for home and work – for

comparison: 4.8 for home and 2.8 for work. The modules were rated towards ‘unprofessional’ in the Attrakdiff questionnaire. In Stage A, the square shape was rated as more suitable for both the home and work environment but was, however, rated lower in desirability compared to the hexagon. Having square modules to test could have provided some interesting insights as to why the modules were rated as low as they were in for the work environment.

Some participants voiced the opinion that, at least in public spaces, the modules should be hidden from sight – integrated in or under furniture. Besides the benefits of protecting the modules from damage and theft, integrating them would allow for a completely smooth surface. The modules, although only 10 mm thick, make placing large objects, such as keyboards, difficult unless the whole area is covered by them due to the difference in height.

The major complaint towards the modules was regarding their build quality and material. The thin, light, 3D printed plastic enclosures were regarded as cheap and not too stylish. The interaction with the modules was perceived as rather cumbersome and impractical. There were many complaints regarding the low friction with the table – something that could have been prevented using rubber non-slip pads. However, this would have added more height to the modules. Either very thin rubber pads or having indentations in the enclosures for the pads could be possible solutions.

Higher voltages should be explored for charging devices such as laptops – seeing as all participants considered them as the one device that they wanted to charge wirelessly besides the devices in the test. Future development might also provide possibilities for charging electric vehicles and other high voltage, high power devices and machinery.

Overall, the impression of the charging module was positive. As an emerging technology, it was no surprise to see the ratings tend towards ‘novel’ and ‘innovative’. Moreover, the modules were also rated strongly towards ‘good’, ‘inviting’ and ‘presentable’. Further development of the enclosures, and the electronics within, should address the major complaints found in this study and provide an even better user experience.

7.5. DESIGN GUIDELINES

The user experience design guidelines proposed in this thesis are based on the findings of each stage of the study. Therefore, it follows that the guidelines are only as strong as the studies. The guidelines are meant to aid designers in creating appealing products and systems. Our ambition is that the guidelines will provide designers with reliable points of data, on which to develop the wireless charging technology of tomorrow.

However, the guidelines are, at their nature, contemporary. Wireless charging technology, in consumer electronics, is not as widely used as we hypothesise it will be in the future. As more such technology is introduced to the market and bought, consumers’ comfort levels, expectations and

requirements will change. We expect that some guidelines will be less relevant and others rendered redundant.

With such high demand, and with technology in development, we expect to see large charging areas with complete coverage on the market within the near future. Seeing as users might prefer integration in furniture to buying standalone chargers, the technology and furniture industries might converge into products such as Jysen from IKEA. We hypothesise that, in the near future, furniture manufacturers will start offering products with full wireless charging integration in compliance with both §1 and §2. For an example of an outline, as suggested in §1, see Figure 7.2.

As wireless charging technology develops and starts being adopted into the market, new types of products will emerge and current technology will adapt to comply with future wireless charging standards. The application guidelines can assist in the development of new products and spaces where wireless charging is desired. However, these guidelines are highly capricious, as new products will be introduced that might change how users feel towards wireless charging technology.



Figure 7.2: Example of a charging area indicator, in accordance with §1.

7.6. FUTURE WORK

Aside from development of the technical aspects, wireless charging is still a relatively unexplored area of research – especially from a user interface and experience perspective. There are many potential research subjects available – both immediate and further in the future. Not related to wireless charging per se, further investigating the relationship between light patterns and colours and its effect on perception and user experience should prove an interesting research topic.

An area that we did not cover in this thesis is the application of wireless charging in the automotive industry. The trend of having wireless charging in the glove compartments and centre consoles of cars is beginning to emerge. However, driving, and other safety critical activities, require different types of notifications and thus require further, and more targeted, research.

A natural continuation of the research presented here is investigating charger integration and the implications on UI design. For example, other types of feedback, such as tactile or auditory, is required if chargers are mounted underneath an opaque surface. Finally, the inclusion of higher voltage devices, such as laptops as well as electric vehicles and household appliances, will further increase the design space regarding both complexity and potential.

8. CONCLUSION

The aim of this thesis was to explore and find user experience design guidelines that should be considered when designing for wireless charging applications. Our approach was an executed and presented in four stages, A to D. In stage A, we conducted interviews and participatory design sessions in order to familiarise ourselves with the design space and investigate what expectations users had on wireless charging technology. Using the data from Stage A, in Stage B, we created a modular charging system. We hosted an online survey in Stage C in order to determine what animations should be displayed on the modules, which were tested in Stage D.

The outcome of each stage shaped the execution of the next, and in the end, we presented guidelines based on our findings. The guidelines concern three aspects of user experience namely function, feedback and applications. The guidelines can serve designers in creating appealing products and spaces for wireless charging.

REFERENCES

- [1] Wireless Power Consortium, “Qi Specification,” 2016.
- [2] L. Shi, Z. Kabelac, D. Katabi and D. Perreault, “Wireless Power Hotspot That Charges All of Your Devices,” in *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*, New York, NY, USA, 2015.
- [3] Air Fuel Alliance, “Airfuel Alliance Specification,” 2016.
- [4] J. Jadidian and D. Katabi, “Magnetic MIMO: How to Charge Your Phone in Your Pocket,” in *Proceedings of the 20th Annual International Conference on Mobile Computing and Networking*, New York, NY, USA, 2014.
- [5] C. Harrison, J. Horstman, G. Hsieh and S. Hudson, “Unlocking the Expressivity of Point Lights,” in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 2012.
- [6] A. Matviienko, V. Cobus, H. Müller, J. Fortmann, A. Löcken, S. Boll, M. Rauschenberger, J. Timmermann, C. Trappe and W. Heuten, “Deriving Design Guidelines for Ambient Light Systems,” in *Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia*, New York, NY, USA, 2015.
- [7] S. Jordà, G. Geiger, M. Alonso and M. Kaltenbrunner, “The reacTable: Exploring the Synergy Between Live Music Performance and Tabletop Tangible Interfaces,” in *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*, New York, NY, USA, 2007.
- [8] D. Raptis, A. Bruun, J. Kjeldskov and M. B. Skov, “Converging coolness and investigating its relation to user experience,” *Behaviour & Information Technology*, vol. 0, pp. 1-18, 2016.
- [9] V. Yussuff, “Wireless Charging Consumer Insights Report,” IHS Markit, 2015.
- [10] I. S. MacKenzie, *Human-computer interaction: An empirical research perspective*, Newnes, 2012.
- [11] J. Brooke, “SUS-A quick and dirty usability scale,” *Usability evaluation in industry*, vol. 189, pp. 4-7, 1996.
- [12] U. S. Department of Health & Human Services, “System Usability Scale (SUS),” [Online]. Available: <https://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html>.

[Accessed 20 March 2017].

- [13] J. Hantschel, “Wireless Energy Transmission: Coils as Key Components,” Würth Elektronik, 2013.
- [14] T. C. Hales, “The Honeycomb Conjecture,” *Discrete & Computational Geometry* 25(1), pp. 1-22, 2001.
- [15] S. L. Sravana Kumar, S.-Y. Chang, S. Viswanathan and Y.-C. Hu, “Demo: Free Data Communication Using Wireless Charging,” in *Proceedings of the 14th Annual International Conference on Mobile Systems, Applications, and Services Companion*, New York, NY, USA, 2016.
- [16] M. Hassenzahl, “The interplay of beauty, goodness, and usability in interactive products,” *Human-computer interaction*, vol. 19, pp. 319-349, 2004.