Physicalizing electromagnetic spectrum for tangible learning

Bachelor Thesis Creative Technology

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Abstract

Despite being widely used, the concept of electromagnetic waves is often difficult to comprehend by the majority of people. This includes students and teachers both from high school and the university. Teaching students about this topic is a challenging yet important task as electromagnetic waves (also referred to as EM waves) are a part of everyday life and are the basis of any wireless communication technology. This thesis focuses on developing a new teaching approach that can help students understand EM waves in an easier and more enjoyable manner. For this, a prototype has been developed through the CreaTe Technology Design Process and it has been evaluated against traditional teaching methods. The results suggest that the learning gain is the same for both the prototype and the traditional method, but students seem to be more engaged and involved in the learning process while using the prototype. Overall, the prototype has been well received and it meets its purpose.

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Chapter 1 - Introduction

Despite being widely used, the concept of electromagnetic waves is often difficult to comprehend by the majority of people. This includes students and teachers both from high school and university. In physics, electromagnetic waves are oscillations in an electric and magnetic field. These waves need no propagation medium, and they can carry electromagnetic energy. This includes radio waves, microwaves, infrared, (visible) light, ultraviolet, X-rays, and gamma rays. All of these waves are part of the electromagnetic spectrum, and they have multiple applications in everyday life such as: the development of solar panels, microwave technology, wireless communication technology and so on.

Teaching students about this topic is a challenging yet important task as innovation in engineering requires a clear understanding of physics on the concerned phenomena. The bachelor thesis focuses on developing a prototype for physicalization of dynamic data with the purpose of teaching students about basic principles of the electromagnetic waves and their spectrum. It is explained that data physicalization (or simply physicalization) is a physical artefact whose geometry or material properties encode data. [1] Despite its multiple benefits, which include leveraging our perceptual exploring skills, making data accessible, cognitive benefits and engaging people, physicalization of dynamic data is a rather new field which has not been researched a lot in the past years. Data physicalization shows great potential for bringing data into the real world for educational purposes.

1.1 Background

Definition and Importance of the Electromagnetic Waves

In physics, electromagnetic waves are oscillations in an electric and magnetic field. These waves need no propagation medium, and they can carry electromagnetic energy. [4, p.430] This includes radio waves, microwaves, infrared, (visible) light, ultraviolet, X-rays, and gamma rays.

The electromagnetic spectrum and its waves are a constant part of everyday life. From cellphones, to microwave ovens to the internet itself, satellites and X-Ray machines, most technology is dependent on the electromagnetic waves. They have applications in telecommunications, remote sensing, food processing (microwaves), medical instruments, energy harvesting, etc. [10,14] It is one of the broadest fields in physics and the focus of many engineering degrees [16,15]. Despite being widely used and a part of everyday life, a large part of the population, adults and children alike, still have misconceptions about the electromagnetic waves [20, 14, 10].

Misconceptions

The discovery of the electromagnetic waves started as early as 1800 with the discovery of infrared radiation [5] and it culminated with the findings of gamma radiation in 1910 [5]. Electromagnetic waves have since been widely implemented in telecommunications and with that, the first misconceptions about them started to surface. The general public was worried about possible health effects of electromagnetic radiation coming from radio towers and telephone towers. [17] While these concerns have been proven to be ungrounded time and time again [17,18,19], people and especially children are still sometimes misinformed about this subject [10]. In a recent study conducted in the Netherlands it was found that students see radiation as something dangerous and unnatural [10] This is expanded upon by a study from 2011, where it was found that high school students do not differ significantly from middle school students in their understanding of UV (ultraviolet light) and both teachers and students struggle with the understanding of EM waves. [24] This trend continues in honours physics too, where 50% of the students and 45% of the teachers still struggle with different aspects of the nature of light and its propagation. [20,21] Other sources also show that it is common for university students to have misconceptions when it comes to electromagnetic waves and their nature, as well [22, p.260].

It is generally agreed that one of the reasons for these misconceptions is the lack of teaching material that could support teachers and keep students interested in the topic. [10,24] In order to assess what kind of teaching materials would be best suited for teaching students about the electromagnetic spectrum, a literature review has been conducted on the topic of teaching approaches in relation to EM waves.

Teaching approaches and struggles

In pedagogy, there are various approaches being used and studied for effective teaching. Some of these approaches include guided notes during lectures, collaborative learning, project-based learning, printed materials, questionnaires, graphics, images, animations, analogies, etc. [27, 28, 15]. Videos, animations, images, graphics and component concepts, “score overall better than the printed books” [4]. Unfortunately, the main method used for teaching is still the traditional way of explaining things through equations, books and examples. While this can work quite well for some people, there have been studies that show that analogies between different subjects in physics (including electromagnetic waves) can enhance learning for students [29]. Furthermore, multiple research papers published in the past couple of years point toward the advantages of alternative teaching methods. [28 to 33]

The main difficulty students face when it comes to learning about the electromagnetic waves is the visualisations of these waves. [32] Since there is no easy analogy in their daily life, students have difficulties in understanding about the propagation, applications, danger, or benefits of EM waves.

One of the possible solutions to improving teaching methods is tangible learning. Tangible learning is currently explored by researchers for it's outstanding results when it comes to engaging students and explaining abstract concepts.

1.2 Objective and Research Question(s)

The objective of this research is to study more in-depth an alternative teaching method for the electromagnetic spectrum. Based on an in-depth literature review and state of the art research, the teaching method chosen is tangible learning through the means of data physicalization. A prototype is built based on this. The prototype is then tested against the means of traditional teaching methods for effectiveness, learning gains, and user friendliness (understandability, user satisfaction, ease of use and usability).

Through all this, the primary objective of this research paper is to answer the question. The research question for this study has been formulated as:

How does tangible learning of the electromagnetic spectrum through data physicalization compare to traditional learning?

1.3 Thesis Outline

This research report tries to find a way to further innovation of teaching methods for the electromagnetic spectrum. This has been done by doing an in-depth background research on current teaching methods and approaches used for EM waves, which will be presented in chapter 2. Following on that, a small description of the methods and techniques used for the development of the prototype has been discussed in chapter 3. Next, an extensive ideation phase, has been presented in the fourth chapter. This covers the multiple ideas and reshaping of the prototype design before the final form has been reached. From there on, specifications of the requirements have been discussed in chapter 5, while chapter 6 presents a detailed explanation of the building phase. In chapter 7, the prototype is being evaluated and the results of said evaluation are presented. Finally, the thesis wraps up with a discussion on limitations, recommendations and future work in chapter 8 and an answer to the research question is given in chapter 9.

Chapter 2 - Background

Alternative Teaching Methods with a focus on Tangible learning

What is tangible learning?

For the purpose of this research, tangible learning has been defined as teaching through the means of tangible user interfaces or through physical objects. This is the case for many innovative studies that treat the subject of teaching children or teens about the electromagnetic spectrum such as: “Superheroes of the Electromagnetic Spectrum: A Non-Traditional Way of Teaching Ionising Radiation” [10], “A Do-It-Yourself (DIY) Light Wave Sensing and Communication Project: Low-Cost, Portable, Effective, and Fun” [24], “Exploring the electromagnetic spectrum with superheroes.” [30], “Experimenting with electromagnetism using augmented reality: Impact on flow student experience and educational effectiveness” [32], “Hands-on activity using the amplitude and frequency of electromagnetic waves to demonstrate the principle of information transfer” [33].

What are the main benefits of tangible learning?

It is generally agreed that tangible learning used in the right way improves students' understanding of abstract concepts. [8, 9, 31, 34] A study conducted by Zuckerman, Arida and Resnik (2005) identifies three main advantages of tangible learning: sensory engagement, accessibility and group learning.[8] This lines up with an educational paper from 2007, Marshall argues that if perception and cognition are closely interlinked, then using physical materials in a learning task might change the nature of the knowledge gained relative to that gained through interacting with virtual materials. [31] Manches and price back this up in their paper from 2011, explaining that tangibles can be useful for teaching (children) about different topics as generating hand movements may help children recollect informal experiences and build novel motor representations to support cognition. [9] However, they also mention that this is not always the case and it depends on the taught concept. [9] This type of learning will be further explored for the case of the electromagnetic spectrum.

Literature Review and state of the art

In a study conducted in 2021, a light wave sensing (LWS) prototype has been built into a do it yourself (DIY) kit that allows the user to send and receive information through the means of light modulation.[24] This way students can learn about the use of EM waves in a more easily understandable manner since light is visible to the naked eye and the principle works the same as radio transmitter and receivers since radio waves and visible light are both electromagnetic waves. A picture of the setup can be seen in figure 1. It contains an amplifier, LED, battery, an audio player and some small solar panels. Through this setup and a list of small tasks, the students learned about EM propagation, the strength of a signal depending on different wavelengths (using different LEDs), reflection and noise which can be present in a signal.

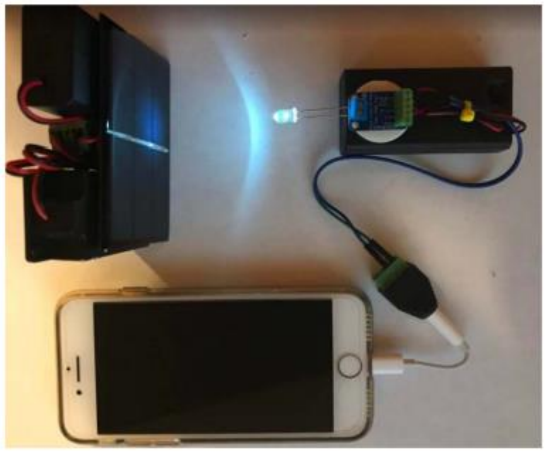


Figure 1: Light wave sensing prototype setup [24]

Most students (81%) agreed that the experience of learning about EM telecommunications using the kit was enjoyable. One of the key implications drawn for this is that, in line with the previously discussed benefits, tangible learning can improve the enjoyability and therefore engagement of the students. It is also important to note that the student's knowledge of the EM transmissions has improved after the use of the toolkit. This goes to show that analogies and tangible learning can be an irreplaceable add in learning about a, what is considered to be, challenging topic.

A similar study uses a more complex setup for the same purpose of teaching students about EM transmission. This study focuses on the principle of information transfer, where students learn to use the given setup (figure 2) for information encoding and decoding. [33] The setup schematics can be seen in figure 2 (part a). As described by the researchers, "the transmitter unit consists of a coil connected to a Pico Scope to generate the input signal while the receiver unit consists of a multi-layered coil connected to a receiver circuit for signal acquisition" [33]. For the testing, the students were given a small 15-minute introduction on the EM waves followed by a pre-test for knowledge, prototype testing and finally a post test for knowledge.

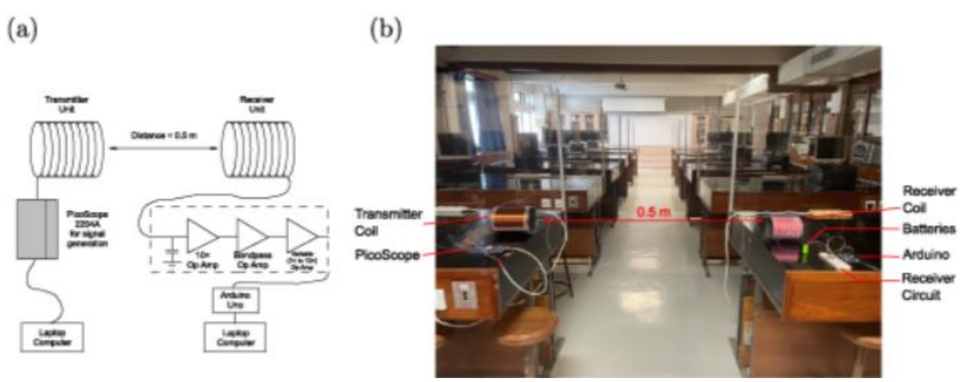


Figure 2: Setup for EM information decoding prototype [33]

Students did seem to have a better understanding of EM wave shapes and propagation after the prototype testing with only 5% of students giving the correct answer in the pre-test and 15% of students giving the correct answer in the post test. Unfortunately, this is not a great result and does not have as big of a knowledge gain as the previously discussed study. This may have to do with the 15-minute lecture as it is possible that it did not properly explain the functionality or theory behind the setup. It is possible that a combination of lessons and hands-on experience with the prototype could provide way better results.

When comparing the approaches of Ekin et al. [24] with Sin and Leung [33] it could be speculated that one of the reasons why Ekin's approach was more successful is that because they have been using easily understandable analogies when it came to the EM propagation and information transmission while Sin and Leung used a setup very similar to real life with no visualisation of the EM waves. This could be the reason why students still struggled with their understanding of EM waves at the end of the testing in Sin and Leung research [33] since students already have trouble visualising the EM spectrum and its behaviour as discussed in [32] and the research did not help in clearing those visualisation issues.

Other types of learning developed in recent years specifically for the electromagnetic spectrum include teaching high school children about the electromagnetic spectrum through the means of superhero analogies or descriptions. This has been developed by Fitzgerald [30] and it promises a novel approach of teaching to the difficult subject of EM radiation. Fitzgerald proposes a worksheet for different superheroes that is being shown in figure 3.

In the 2011 film *Captain America: The First* Avenger, Steve Rogers becomes a super-soldier after he is injected with an experimental serum that changed how his cells react to radiation after which he is radiated with vita-rays, a fictional form of radiation.

You are a research scientist hired by Howard Stark and Abraham Erskine to evaluate Captain America's super-soldier treatment. Stark and Erskine want you to assess the effect of vita-rays on Captain America's body. In addition, they want you to estimate the properties of vita-rays such as the frequency, wavelength, and energy, and make suggestions for further applications of vita-rays.

1. List some of the changes to Steve Rogers' body after being exposed to vita-rays

____

____

2. Steve Rogers was treated with vita-rays in an isolated container such that Stark, Erskine, and their team were not exposed to vita-rays. What does this tell you about vita-rays?

____

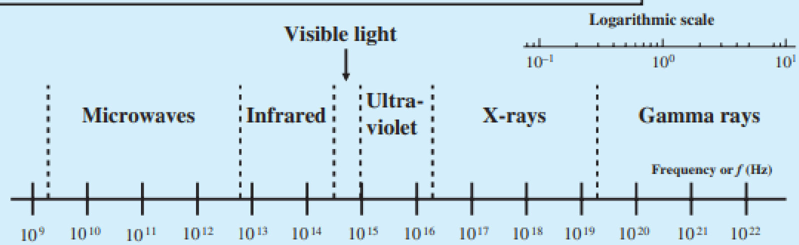
____

3. In your opinion, which type of radiation are vita-rays most similar to? Give reasons for your answer.

____

____

Using your answers, it is time to estimate the frequency, wavelength, and energy of vita-rays.



4. Mark the approximate frequency of vita-rays

5. Write down the frequency of vita-rays ______________________ **Hz**

6. Categorisation of vita-rays based on frequency ☐ **Non-ionising radiation** ☐ **Ionising radiation**

7. Calculate wavelength in metres (m) of vita-rays ______________________

____

8. Calculate energy in eV of vita-rays ______________________

____

9. If vita-rays were real, how do you think they might used in modern society (besides in the creation of possible super-soldiers)?

____

10. If you have concluded that vita-rays are ionising, suggest measures to protect against over-exposure to vita-rays. If you have judged that vita-rays are non-ionising, support your conclusion.

____

Figure 3: Worksheet using Captain America, teaching about EM waves (Fitzgerald, 2018) [30]

While this could prove to encourage critical thinking of students, this has not been tested in classrooms yet. Furthermore, since vita-rays (rays associated with the powers gained by captain America) are a fictional type of electromagnetic radiation, unless properly explained, this approach could potentially confuse the students during a lecture. It is also important to note that this has not been back checked by a teaching professional or tested in a classroom setting. This approach of teaching could prove to be useful if the researcher managed to develop his idea and conduct research on it. Which is exactly what he did in cooperation with Plotz.

In their pivotal, long-term study conducted on Austrian high school students, Plotz and Fitzgerald built up on the previously discussed teaching idea and came up with an improved concept that has also been backed up by numerous teachers and educational experts [10]. Besides a lesson plan based on pop culture, this also includes the uses of ID cards for EM waves (as shown in figure 4) as well as group working. Their research shows that this particular

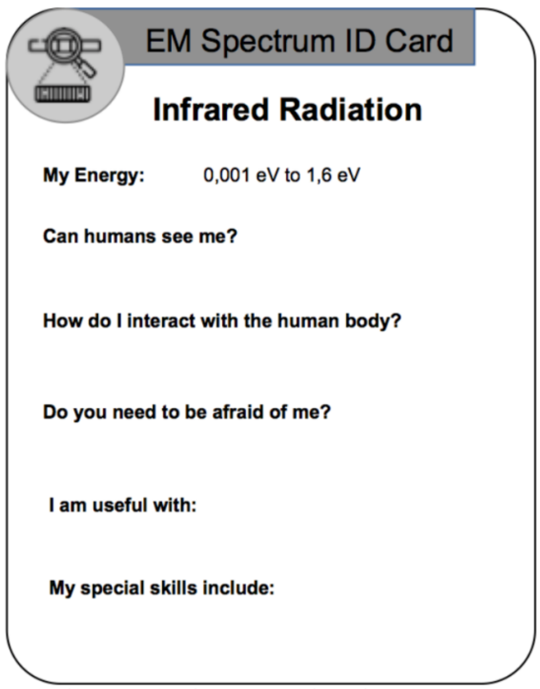


Figure 4: Example of an ID card for EM waves [10]

approach shows statistical significance results when it comes to improving students' knowledge on the topic of EM waves. However, it is important to note that even though the lesson was effective, 22% of students said they were confused about the addition of superheroes in the classroom. It overall seems that students did enjoy the lesson and using superheroes motivated them to complete the exercises. However, the study does not seem to show a comparison between the new teaching method vs the traditional teaching methods used in Austria. Therefore, it is not known how the students' knowledge after the superhero lesson compares to their peers who got taught through traditional teaching methods. The student's engagement is also not tested, although the study does show promising results and it has the potential to be more engaging than traditional lessons.

Conclusion

This literature review aimed to give insights on the novel teaching approaches used in high schools, on the topic of electromagnetic waves. While designing for an interactive or tangible teaching method, it is important to be aware of the already existing designs and the benefits each of these bring. It is maybe even more important to know what the current limitations of the research are and in which direction it could be developed.

The current alternatives to traditional teaching methods when it comes to electromagnetic waves are still in development and come with certain drawbacks. It has been noted that the most important aspects of successfully teaching this subject are clear visualisations of the EM waves, easily understandable analogies and, if possible, interactive lessons. Furthermore, group work also seems to be a recurring theme and has been found out to be quite effective when learning about challenging subjects.

Chapter 3 - Methods and Techniques

3.1 Creative Technology Design Process

The Creative Technology Design Process [35] was used to design and evaluate the proposed system. This process consists of four phases: Ideation, Specification, Realisation and Evaluation which can be seen put into perspective in figure 5. For each of these phases the following has happened:

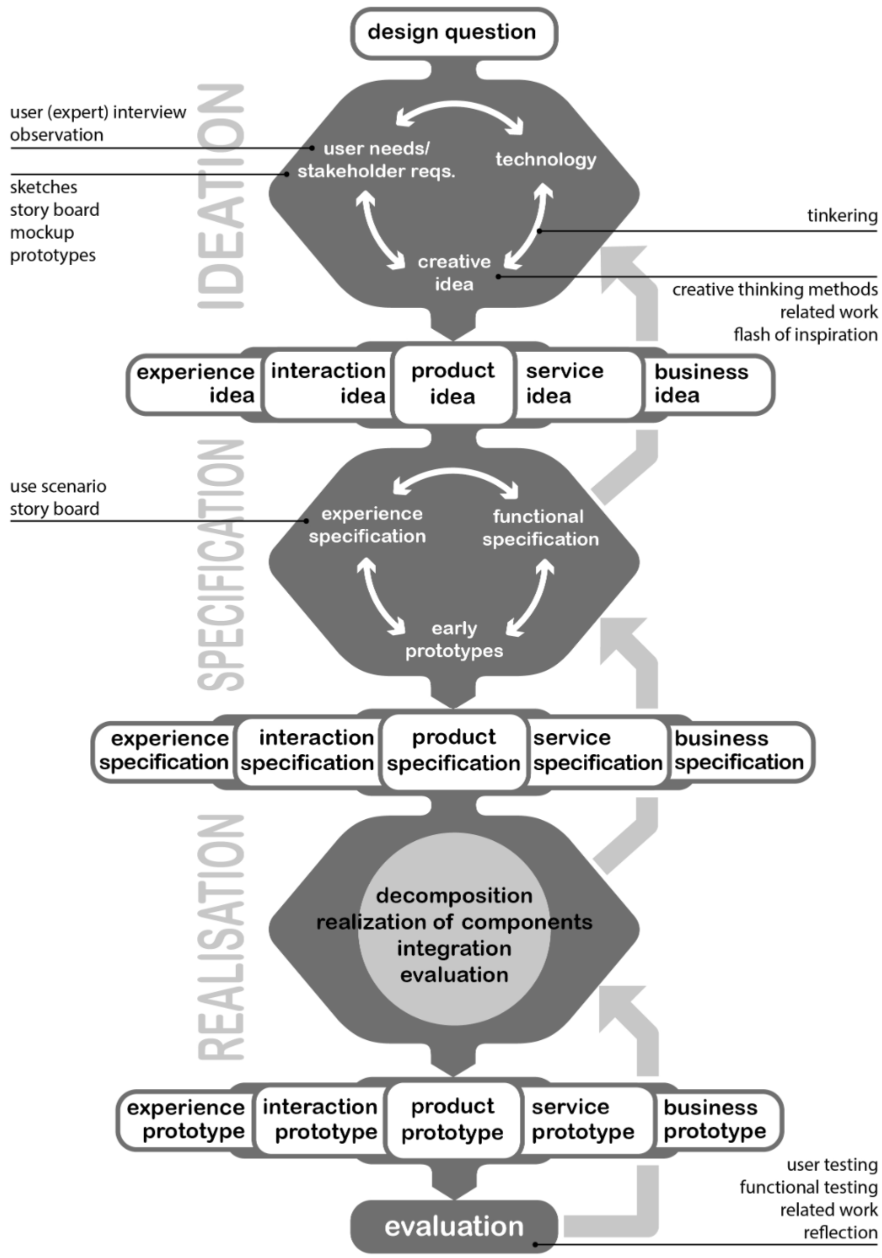


Figure 5: A Creative Technology Design Process. [35]

Ideation:

The ideation's phase focuses on developing high level ideas for a prototype focused on teaching people about the EM spectrum. This is done through brainstorming and developing a mind map of possible interactions. The direction of these ideas has been heavily influenced by the background research and state of the art. Another tool used in this phase is the principle of divergence and convergence. has been used multiple times until a satisfactory product idea has been reached. During this process, other different methods have been incorporated like brainstorming, mind mapping and iterations based on feedback from experts in the field. This will be further discussed in chapter 4.

Specification:

In the specification phase, the final idea from the ideation phase is explored and a building plan is established. This is done through setting project requirements which come from the potential users needs and the utility of the prototype. Users' needs are developed through the use of personas while the utility of the prototype is strongly driven by the core of user experience and tangible learning methods. An in-depth Specification phase and description is presented in chapter 5.

Realisation:

The realisation phase is the practical part of the project. In this phase the researcher focuses on building the prototype and some last iterations may occur due to technical necessities. In contrast with the previous two phases this process is linear and leaves little to no space for further improvements. The technical background knowledge of the researcher and, new acquired skills if needed, are employed in this phase. Chapter 6 is the one containing all the practical discussions.

Evaluation:

At the end of the cycle, the prototype is evaluated. This evaluation is presented in depth in chapter 7. The evaluation focuses on retrieving data relevant to the research question that has been defined at the beginning of this paper. This is done through a user research study that aims to compare the performance of users through tangible learning vs traditional learning. At the end of this phase, the researcher will be able to answer the research question.

Chapter 4 - Ideation

The initial step in this phase is to determine the end user of the product and the other stakeholders of the project. This is essential as the end user must always be kept in mind during the development of the product.

4.1 Users and the context of use

According to Varvasovszky (p. 341) [36] “Stakeholders can be defined as actors who have an interest in the issue under consideration, who are affected by the issue, or who because of their position have or could have an active or passive influence on the decision-making and implementation process.”. In other words, anyone who is involved or impacted by the present project can be regarded as a stakeholder. For this research, the main stakeholders are the users. The users are also the only stakeholders considered.

The users of this prototype are any people who are learning about the EM spectrum. These users can mainly be high school or university students, but that does not necessarily exclude any other people without a background on the EM waves.

4.2 Product Requirements

The prime users of the installation will be first year university students who are enrolled in an engineering program. When designing the installation, the following facts have been assumed:

- The users have basic knowledge of sinusoidal wave properties, such as frequency, wavelength and amplitude
- The users will be interacting with the installation mainly for gaining basic insight on the electromagnetic spectrum. For more in depth information they should study the subject on their own

The aim of the product is to convey insight on the following aspects of an electromagnetic wave: propagation medium, propagation speed, wavelength size, basic medical implications, types of electromagnetic waves and energy. This has been based on the literature review and expert interviews.

The requirements of the design are as follows:

- Easy to use
- Output of the installation is understandable
- Low cost components (<75 euros)
- Sensory experience (for tangible learning)
- Physical interaction (for tangible learning)
- Limited amount of text

Finally, after the stakeholder analysis and after the product requirements have been decided, the next step is the ideation phase.

4.3 Divergence and convergence of product ideas

While working on the design process for the product, the model of divergence and convergence defined in '*A design process for Creative Technology*' by A. Mader [1] has been used. This is a classical model where the design space is opened by the divergence phase and then reduced in the convergence phase until a certain solution has been reached. This particular design process consisted of one instance of divergence and convergence and a second phase where the chosen idea has been iterated in order to better fit the product specifications. The process will be described in the following sections.

4.3.1 Divergence phase

The first instance of divergence was based on the previous literature review and state of the art research. The base of the ideation is physicalization of data and tangible learning. For this, the ideation first focused on ideas centred around different output options such as haptic, visual, or auditory. To generate the ideas, a mind map has been developed which can be seen in figure 6. This has been done to put into perspective the interaction methods which are available currently. Afterwards, an independent brainstorming session has been conducted where different interaction methods are combined. The most relevant ideas that resulted from this process are presented in this section

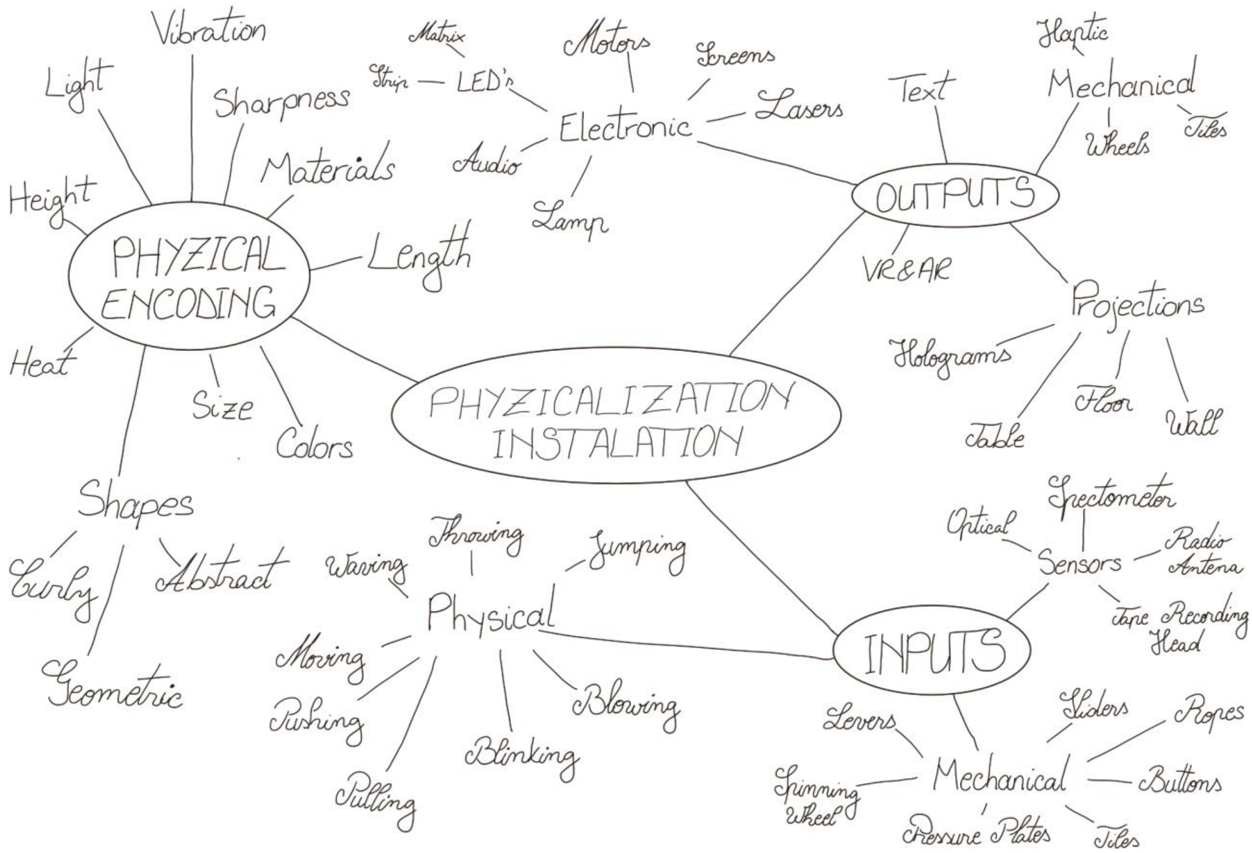


Figure 6: Mind map of physical interactions

Idea 1: Wavelength to object size analogy

An installation where several objects is being displayed. The size of the objects is representative of the size of the wavelength of certain electromagnetic waves. Upon picking up said object the installation will produce the type of electromagnetic wave which has a similar size with the given object. Of course, this will only work for a couple of wavelengths as X-rays or Omega-rays cannot be easily reproduced (nor it is safe to do so). This will give the user a better understanding of the size of wavelengths for each type of electromagnetic radiation.

Idea 2: Controller with display

The second idea has been inspired by the state of the art research (specifically reference [24]) and it would be a device that you can point in one direction and it would tell you the type of waves it can detect coming from that way. The feedback could be visual (LED's or a screen display), haptic (including a vibration motor that will represent the intensity of each wave) or audio (assigning each wavelength a sound and playing it when the certain wavelength is present). All this can be connected to a screen display where information is given regarding the certain types of waves.

Idea 3: Iteration of the second idea:

The reverse would also work where users point a certain type of radiation towards an installation, for example a remote that works with infrared light or the light coming from a phone. Based on the input the installation could display the type of wave that it is receiving. The frequency could be represented through one or more types of physicalizations. This would entail, like in the previous idea, visuals, sounds or haptic outputs. Furthermore, the size of the wavelength can, again, be represented by small objects or a model of bigger ones.

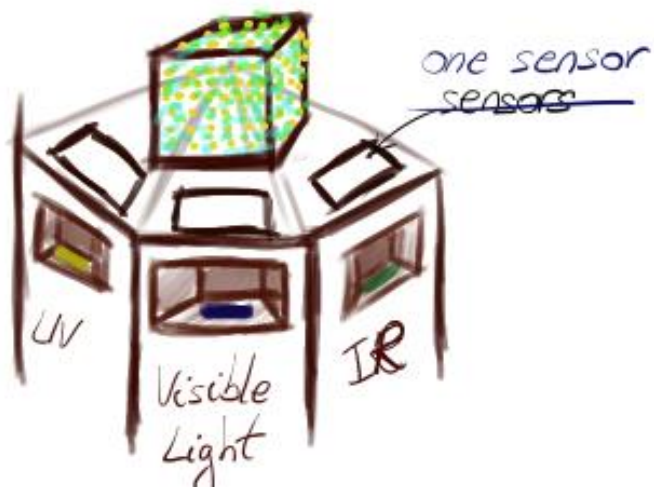


Figure 7: Sketch of the second iteration of idea 2

Idea 4: Interactive art installation

Figure 8: Interactive Art Installation [42]

For the purpose of teaching people about the nature, behaviours and effects of the electromagnetic spectrum on the human body, an interactive installation similar to the one in the picture above can be built (figure 8). The idea behind it is that the installation can show the user which type of electromagnetic waves can travel through the human body. At the bottom of the display there would be a slider that allows the user to choose what type of electromagnetic wave to visualise.

Idea 5: Mechanical waves analogy

For teaching people mainly about propagation and frequency, the electromagnetic waves can be represented through physical waves. Electromagnetic waves behave similarly to any other mechanical wave and thus, an installation that makes an analogy between the mechanical waves and electromagnetic waves could teach people about their propagation and frequency. A specific installation for this could contain water (or another liquid) that can be disturbed by vibrations which would make waves on the surface. The frequency of the waves would be proportional to the frequency of the electromagnetic wave that it needs to represent. On the side of the installation there would be a slider that would allow the user to choose which wave should be represented.

Idea 6: Sensor gloves

To focus more on the physicalization of data, a new idea has been developed based on haptic feedback. This takes advantage of the tactile sense of people. The prototype should ideally be usable completely remotely.

A set of sensory gloves hooked up to a small hexagonal display where the type of electromagnetic waves can be displayed. The gloves contain the sensors and a small vibration motor which gives feedback based on the EM waves present. The higher the intensity of the waves, the more vibration will the user feel. One glove will be focussed on the radio waves while the other glove will focus on the light spectrum (here this includes the UV and IR waves). This setup can be seen in figure 10. The wiring will be connected to a small heptagonal display where the type of waves recorded by the sensor will be displayed by LEDs. The same heptagonal box will also contain the microcontrollers needed for these sensors and LED control.

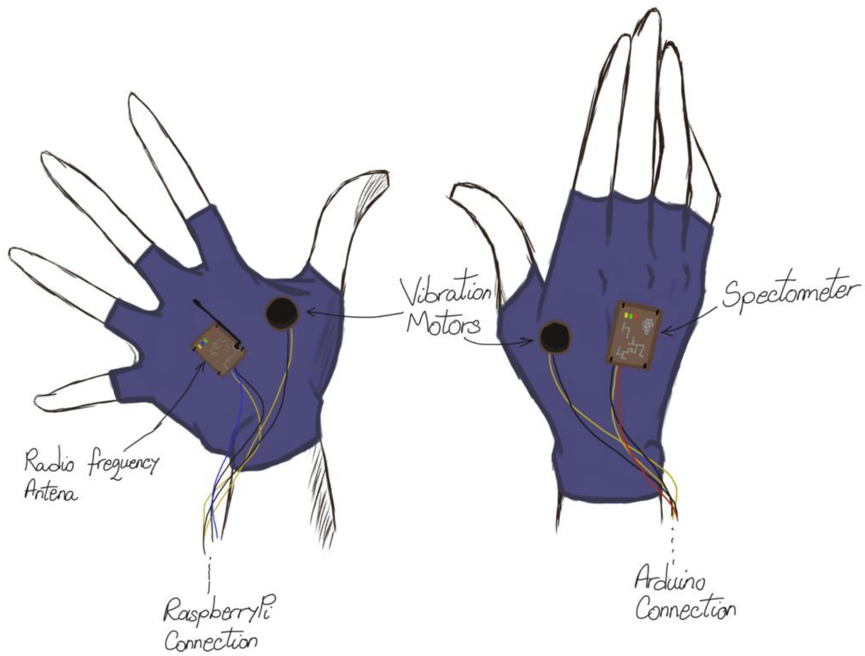


Figure 9: Sketch prototype of idea 5 (Sensor Gloves)

4.3.2 Convergence

After the ideas have been laid out, the convergence process can begin. In order to decide which ideas would best work out for the purpose of the project, they have been evaluated against a set of aspects. The aspects are as follows: interactivity, tangibility, output/feedback and learning goals. The 'interactivity' refers to how much interaction is possible between the user and the prototype whereas 'tangibility' refers to how much will the user need to touch the installation and how much tactile or haptic feedback can they get back from the prototype. The 'feedback' aspect mainly refers to how much feedback a user can get from the prototype; this includes visual, audio, and haptic feedback. Finally, in the 'learning goals' column it will be checked how many of the learning goals (defined in chapter…) are met by the prototype idea. For this a 5-point grading system is used where '++' is great, '+' is good, '+/-' is average, '-' is insufficient and '--' is terrible. The evaluation can be seen in table 1.

Ideas	Interactivity	Tangibility	Feedback	Learning goals
First idea	+/-	+	-	-
Second idea	+	+/-	++	+/-
Third idea	+	-	+/-	+/-
Fourth idea	+	-	+/-	-
Fifth idea	+/-	+/-	+	-

Sixth idea	+	++	+/-	+/-

Table 1: evaluation of initial ideas

From the table, the second and the fifth idea scored the most and have the same score. To decide which one to continue to develop, a small practical look is taken at the two ideas. While they seem to score similarly, the development of the second idea would be preferred as it includes less wiring, albeit this is because the cables and necessary sensors will be encased, and it is less likely to have technical problems because of that. Furthermore, it is unlikely that there is an antenna which can be as small as the one sketched and therefore and may become uncomfortable for the users to interact with this type of prototype. Finally, the gloves prototype may not fit all users because of the different hand sizes. Thus, the concept for the prototype will be further developed based on the second idea.

4.3.3 Idea iterations

At the end of the first divergence and convergence phase a final idea has been chosen based on the best overall score. Since the initial ideas were not developed fully and all the ideas had aspects which could have been improved on, the final concept underwent an iteration phase. This happened to ensure that the prototype met all the requirements described in section 4.2 and to improve on the aspects from table 1.

First, the most important aspect which needs to be improved is the learning goals. For this purpose, the installation needs to convey information about the harmful effects of some of the electromagnetic waves. This can be done by minimal text and using colour codes: red - dangerous, yellow - potentially dangerous and green - safe. Therefore, when the type of electromagnetic waves will be written on the installation, they will be colour coded accordingly. Furthermore, it will be indicated whether a certain wave is ionising or not as that is the property that can make them dangerous or not. The speed of an electromagnetic wave and its propagation medium will also be mentioned as these aspects have been found to be important during the literature review research. Finally, the wavelength range of each electromagnetic wave will also be written down on the final prototype and the users will also be given information about what wavelength certain household items use (e.g phones, microwaves, Bluetooth devices, TV’s, Wi-Fi, radio etc.).

Now that the improvement points have been decided on, the next divergence phase mainly focused on the shape of the installation. Since it is important to represent all the electromagnetic waves, the heptagonal form has been kept as a base for the installation since each side can hold information about one type of an electromagnetic wave. Knowing this, the following ideas have been developed:

First iteration: Museum like installation

Here, the prototype is a big installation like a museum one. The users are encouraged to walk around it and read the information given on the different types of electromagnetic waves. With the wireless sensors encased in a special casing (hereby referred to as a remote), the users can walk around and find out the type of radiation they are currently being exposed to. The remote that they are holding will indicate which type of electromagnetic waves are present now using a set of LEDs. For more feedback, the remote will also vibrate based on the intensity of the electromagnetic radiation which is present. Finally, each type of electromagnetic wave can be coded using a musical note. The musical note will play when that certain electromagnetic wave is present. The users can go back to the main installation and read more about their findings.

Second iteration: Portable measurement tool and interactive information heptagon

The prototype design discussed before could raise issues because of the wiring of the setup. Furthermore, if everything needs to be displayed on the heptagon box then it could quickly become an issue since cluttered information is hard to read. This could be fixed by increasing the size of the heptagon but could end up being difficult to be carried around. Thus, a last iteration is needed for an optimal solution.

The final iteration of the idea contains the same type of sensors bundled into two different remotes. Like before, one of the remotes will be used for tracking the radio wave spectrum while the second one will be used for the visible light, UV, and IR waves. The user will receive feedback consisting of visual, haptic, and audio elements as discussed in the previous ideas. What is done differently is the heptagon which is not connected to the remotes, and it returns the present EM waves independently via LEDs. The size of the heptagon is similar to a purse, and it is made such that the user can turn it around and explore the information written on it. This design allows the user to interact with the installation in two different ways: walking around with the bundled sensors or playing/ turning around the heptagon. This increases the tangibility and interaction the user can have with the prototype.

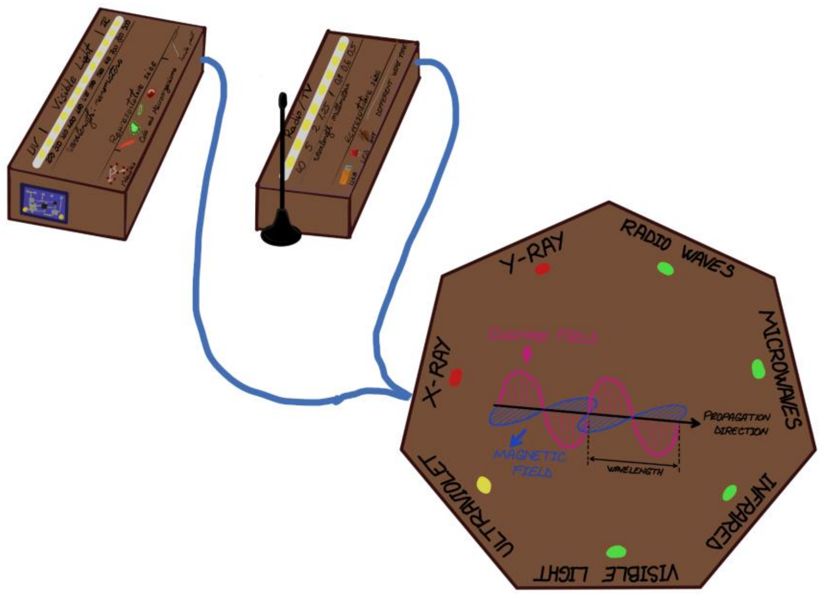


Figure 10: Sketch of final prototype idea

At this point, it has been decided that the concept accommodates all of the requirements in a satisfactory way, and it can proceed to the next phase: specification.

Chapter 5 - Specification

In the specification phase, the final idea from the ideation phase is built upon by setting functional and non-functional requirements. This is done using user case scenarios that will reflect the needs of the main users of the system. The shape of the prototype will no longer change drastically, but instead it will evolve gradually by adding important details and testing the design through visualisations and prototyping. Since prototyping is an iterative process, small adjustments can still be made and tested while building the prototype.

5.1 Formulation of requirements

Based on the final ideation idea, building plans and an initial evaluation plan, part of the requirements become evident. Firstly, since the budget of the project is rather limited and the components needed for the realisation of the prototype should not exceed 75 euros. Secondly, the final prototype should be intuitive to use as it would be ideal for the users to be able to use it with little to no initial explanations. Finally, the prototype should be mobile as its aim is to be used in a classroom setting.

5.1.1 Personas and scenarios

To gain further insights on the exact user needs, a couple of personas have been developed for the prototype. A study from 2011 [37] suggests that personas offer multiple benefits when it comes to the design process. Persona's use has been linked to an increased focus on the needs of the target users, enhancing identifications with the users and a reduction in changes at the end of the product development process. [37]

Scenario 1: high-school student with no background knowledge on EM

Name:	Ellon
Age:	15
Experience with tangibles:	High, has probably used tangibles before and has experience with technology

Ellon is quite good when it comes to technology. His many gadgets and games use all kinds of interactions for inputs. He can quickly figure out how a new controller works or what kind of interactions you can have with new technologies. However, when it comes to his background on physics, things are not that bright. Ellon struggles with basic concepts and has trouble visualizing abstract concepts. He only heard about electromagnetic waves from some of the shows he watched and, of course, he knows about gamma radiation from the famous Chernobyl incident.

When faced with the prototype, Ellon quickly figures out how it works with little explanation. He takes quite some time to understand and process the information given by the LEDs but at the end of the exploration he figures it out. He enjoys learning about EM waves through this device.

Scenario 2: university student with limited background knowledge on EM

Name:	Chalina
Age:	19
Experience with tangibles:	Medium, hasn't used tangibles, but she has a good grasp on technology

Chalina hasn't had a lot of experience with different types of controllers, but she studies user interface interaction at her university and has a pretty good understanding of the concept behind them. Although not experienced, she can easily grasp how a new type of interaction functions. When it comes to the electromagnetic spectrum, she doesn't remember a lot from her high school years. She still has misconceptions that she isn't aware about, but some of her background knowledge is solid.

When interacting with the prototype she takes a minute to figure out what it does, but afterwards she easily uses it to explore the world of EM waves. Some things she recognizes from her high school years, while some things that she learns about through the prototype are new to her. Some things are even contradictory (due to the misconceptions) and she ends up asking the teacher about it. At the end of the day, Chalina has cleared her misconceptions, learned new things and refreshed her knowledge on EM waves.

Scenario 3: teacher who holds a lesson on EM waves

Name:	Clementine
Age:	35
Experience with tangibles:	Low, has not used tangibles before and has limited experience with technology

Clementine is a middle-aged woman who has limited experience with technology and has never used tangibles before. On the other hand, she is an experienced physics teacher and has a good understanding of the concepts and theory behind electromagnetic waves, their purpose, their use and their dangerous potential.

When given the prototype, Clementine can immediately read and figure out the purpose of the heptagonal design that presents the EM waves. However, it takes her a bit of time to figure out exactly what the remotes are showing her about the light spectrum and radio spectrum. After a couple of explanations, she gets it and, given her physics background, she can easily use the prototype now. She is happy with the discussion opportunities that this prototype brings in her classroom.

5.1.2 Non-functional requirements

- The prototype should be easily used by any users
- The information written on it should be easily readable
- In a classroom setting, it should allow for multiple people to look at it
- For inclusiveness, the prototype should not be physically demanding to use
- Be enjoyable

5.1.3 Functional requirements

- Be suited to teach people about EM waves: include important and useful information on EM
- Be able to run for a long period of time (at least an hour)

5.1.4 Requirements found during the building phase

- The heptagon should be big enough to display all important information that has been discussed in chapter 2
- The LEDs should be colour coded for the different wavelengths of the visible light spectrum
- The sensing remotes and heptagon should be separate to allow the user to walk around with the remotes while learning about the electromagnetic spectrum
- The devices should be able to be powered on and off by the user to avoid overheating

Chapter 6 - Realisation

In this chapter the realisation of the prototype is discussed. The result consists of three different parts which will be presented separately: the radio sensing remote, the uv, light and infrared sensing remote and the electromagnetic spectrum display.

6.1 The radio remote

Sensing of the radio waves is best done through the means of a radio antenna. For this, a small antenna needed to be chosen to fit it in the relatively small encasing of the remote. The antenna also needed to cover as big a spectrum as possible with relatively low costs. It has been found that Rafael Micro R820T/2/R860 is a good choice with a frequency range between 25 MHz to 1750 MHz and with a cost of approximately 20 euros. A radio antenna only works with a computer and such, a Raspberry Pi has been chosen to retrieve data from the antenna and to control the display LEDs.

Raspberry Pi is a small-scale computer and has been developed by a British company in hopes to inspire young people to learn more about computers and coding. Raspberry Pi has its own IOS called Raspberry Pi OS, previously called Raspberian. A user can easily write and implement code on Raspberry with Python.

In order to make the remote work as intended, first the Raspberry Pi needed to be set up. This has been done by following the steps offered at the following website: https://www.tomshardware.com/how-to/set-up-raspberry-pi.[39] After the setup was complete, the code implemented has been based on a project by Tony DiCola [40].

The antenna picks up the radio waves present (between 25 MHz to 1750 MHz), in the the code sectioned it into 7 different ranges and when a signal is picked up from a certain range, it lights up the corresponding LED on the remote. This shows the user, with a low accuracy, which radio waves are present now.

It should be noted that, despite the initial design, where the remotes were designed to be wireless, the Raspberry Pi has very strict requirements when it comes to the input voltage and current it receives. It needs a 5V DC power source which is difficult to obtain through batteries without using a converter. Therefore, in the current design, the Raspberry Pi needs a USB computer connection to act as its power supply.

Finally, the encasing of the remote is made from wood. The outline has been laser cut, assembled together and then painted. For the circuitry, a small breadboard has been used in order to make it easy for the circuit to be taken apart if needed. The insides of the radio remote looks similar to the insides of the UV, Visible Light and Infrared remote which can be seen in figure 12.

6.2 The UV, Visible Light and Infrared remote

After the completion of the radio remote, the next step would be the building of the UV, Visible Light and Infrared remote. For this, sensors were needed that would be able to detect UV rays, different wavelengths of the visible light spectrum and infrared light. Finding all three of them combined was rather difficult and as such, it has been decided to choose two sensors that would be able to cover the desired spectrum. The sensors chosen are SI1145, used for UV light sensing, and AS726x, used for visible light and infrared sensing.

For implementing and using the sensors, a microcontroller was needed. For this purpose, an Arduino was used. Arduino is an open-source electronics platform based on easy-to-use hardware and software. [41] In addition, the sensors mentioned above already have an Arduino library that could be used for interfacing them with the microcontroller.

The casing of this remote is made in the same way as the radio remote casing. It has been laser cut based on the same model. The placement of the LEDs is also similar to that of the radio remote with the difference that the LEDs for the UV, Visible Light and infrared remote have been colouring coded to match the colours of the wavelength they are representing.

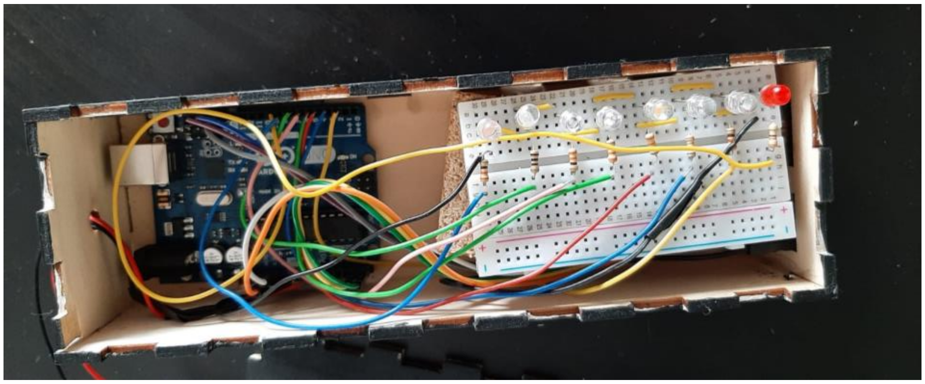


Figure 11: UV, Visible Light and Infrared remote circuitry

The software part for this remote has been coded in C++. A flowchart displaying the steps of the code can be seen in figure 13 and the code can be found in appendix 8.

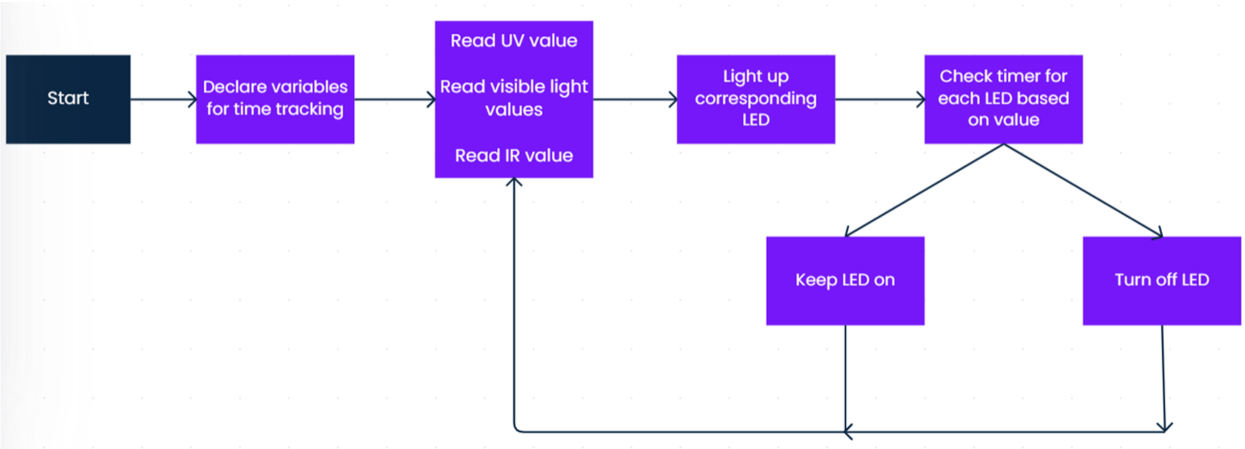


Figure 12: Flowchart of the Arduino code for the UV, Visible Light and Infrared remote

6.3 The display of the spectrum

Lastly, but not the least, the display with all the electromagnetic spectrum waves has been built. It has been made from wood through laser cutting and then pieced together. To give it a nice aesthetic, it has been painted the same colour as the remotes. Each side of the heptagon represents a different type of electromagnetic wave. They are written down in order from the longest wavelength (Radio Waves) to the shortest wavelength (Gamma Waves). On the side of the heptagon information is given about their wavelength and whether they are ionising or non-ionising. In the centre of the heptagon, their shape is drawn (transverse waves) and information about their speed and propagation medium is given.

Figure 13: Heptagonal display of the electromagnetic spectrum

Lastly, a small selection of household items has been chosen to be written down on some paper in order for the user to gain more insight on what household item generates what type of electromagnetic waves.

6.4 Total overview

The result can be seen in figure 15. As it can be seen, the heptagon and the UV, Visible Light and infrared remote are completely wireless which means the user can easily manoeuvre them and walk around holding them. This is especially important for the remote as the user is able to test it in different lighting conditions. However, for the usage of the radio remote, the user needs to remain in close proximity to the laptop since it acts as a power supply.

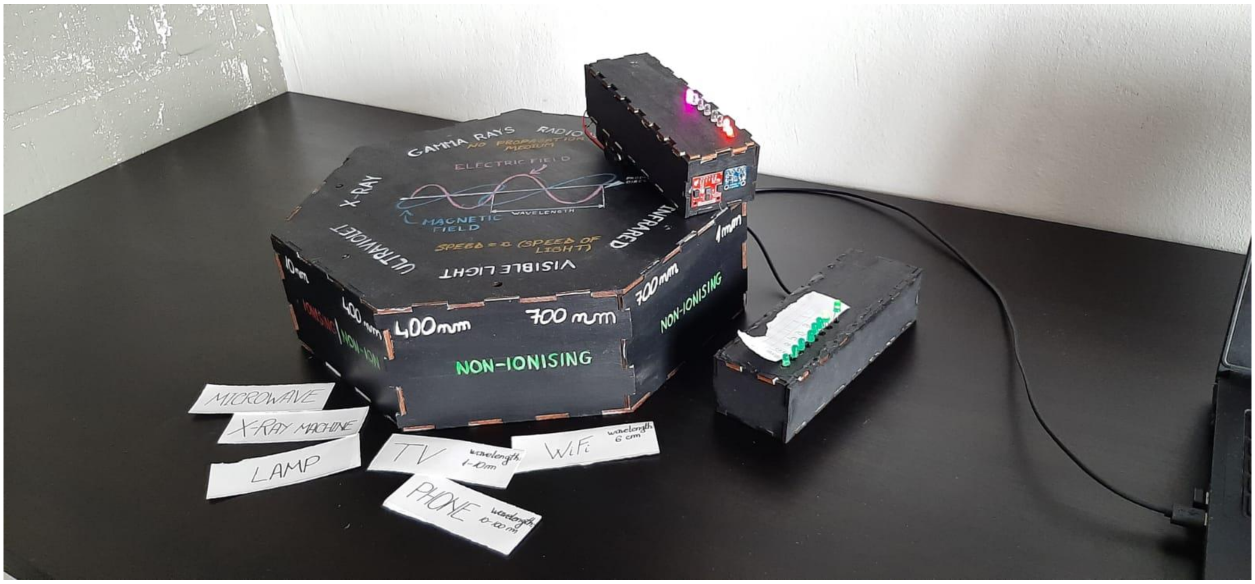


Figure 14: The final realised prototype

The setup from figure 15 is also the one that will be used for the evaluation.

Chapter 7 - Evaluation

In this chapter the evaluating of the prototype will be described. The first part of this chapter describes the goal and user study while the second part focuses on the results of the evaluation.

7.1 Goal of the study and Hypothesis

The goal of the study is to help answer the research question: How does tangible learning of the electromagnetic spectrum through data physicalization compare to traditional learning? To be more precise, the study will test how well do people grasp newly taught concepts, in this case the basics of the electromagnetic spectrum, through the means of physicalization of data vs the traditional teaching methods.

Based on the previously conducted literature review it is expected that people who are using the developed prototype to learn about new concepts will be more engaged in the experience and will be able to grasp abstract concepts better than people taught through traditional methods. It is expected that at the end of the experiment the students who interacted with the prototype will have a better level of understanding of the topic (or at least the same level of understanding) as people who were taught the same concepts through a lecture.

7.2 User Study

To evaluate the effectiveness of the prototype a between group study design has been used. This has been chosen based on previously reviewed literature where the researchers had a similar approach [10, 24, 32, 33] and based on discussions with more experienced researchers. Furthermore, by having a between group study design, the modality of the lesson can be tested without introducing any bias in the results as each user will only use one type of learning. The study has been first approved by the Ethics committee of the Faculty of EEMCS at the University of Twente.

The variables tested during the study are the effectiveness, the learning gain, the understandability, the user satisfaction, the ease of use and the usability of the prototype. These have been based on the research question since they will show how the two different methods of learning score against each other. Additionally, a small section has been dedicated to additional findings based on observations made during the testing process.

Independent variables are variables that are changed in the experiment in order to study their effect. For this research, the independent variable is the type of modality of the lesson: only through slides or through slides and the prototype. Dependent variables are that which is measured during the experiment. For this experiment, the dependent variables are, the correctness of the answers and the subjective experience of the user.

7.2.1 Study Design and Apparatus

The study design will follow a between group design where the participants knowledge will be tested before and after evaluating the prototype. This is being done by asking the participants to fill in two tests in the form of online quizzes: one before the testing of the prototype and one afterwards. The purpose of the tests is to test the knowledge of the participants on the subject that is being taught, namely the electromagnetic spectrum and its waves. It should be noted that for the rest of this paper these two tests will be referred to as the pre-test and post-test.

This being said, the apparatus of the study consisted of 6 elements: (1) Pre-test; (2) Familiarization and learning task list; (3) The prototype developed; (4) Lecture slides; (5) Post-test; (6) An altered version of UMUX.

The pre-test and post-test are focusing on the correct order of the waves in the electromagnetic spectrum, the health risks of exposure to certain waves, the correct wavelength, the classification of the waves, the speed of the waves and their propagation medium. The pre-test and post-test each have one or two questions for each of these topics. The difference between the pre-test and post-test is that the multiple choice options are different (except for the correct answer which stays the same). Another difference is that in the third questions of the pre-test asks about the wavelength of radio waves while the post-test third question refers to the wavelength of the visible light. Finally, in the fourth question, the pre-test asks about the speed of microwaves, while the post-test asks about the speed of a radio wave. Since all electromagnetic waves travel at the same speed (the speed of light), the answer is the same for both questions. The pre-test and post-test can be found in appendices 5 and 6 respectively. The pre-test and post-test have been built in a google form that has been shared with the participants when needed.

The prototype that was being tested has been thoroughly described in chapter 6 of this report. During the testing of the prototype, participants also had access to slides containing the same information they could collect using the prototype (the same slides used for the control group). The slides have been retrieved from the website of a school and they contain information on the wavelength and frequency of the waves, the order of the waves and classification, their propagation medium, the propagation of the waves (transverse waves), their speed and a small description of each wave of the electromagnetic spectrum. The slides can be found in Appendix 4.

The user study for this research has been made using the UMUX. UMUX is “a short qualitative assessment designed to measure the general usability of a system.” [38] “Developed at Intel in 2010 by Kraig Finstad and his colleagues, the UMUX questionnaire was intended to offer a shorter alternative to the 10-item SUS questionnaire. Additionally, it was meant to address the new definition of usability set forth by the International Organization for Standardization or ISO. Whereas SUS assesses perceived usability and learnability, UMUX targets usability by assessing effectiveness, efficiency, and satisfaction.” [38] The UMUX used for this research has been slightly modified in order to match the requirements of this research. Therefore, the four statements have been changed from this:
“1. This website/ product/ tool/ software/ prototype capabilities meet my requirements.
2. Using this website/ product/ tool/ software/ prototype is a frustrating experience
3. This website/ product/ tool/ software/ prototype is easy to use.
4. I have to spend too much time correcting things with this website/ product/ tool/ software/ prototype” [38]
To this:

1. *The prototype indicates the presence of EM waves in an easily understandable manner*

2. *Using the prototype is a frustrating experience*

3. *The prototype is easy to use*

4. *I have to spend too much time correcting things with the prototype*

Lastly, it should be noted that users could give a score to the statements based on their own experience with the prototype. For this purpose, a Likert scale has been used. The Likert scale used has 7 points and it was mapped from 1 - strongly disagree up to 7 - strongly agree.

The users had an explanation about the prototype before getting to use it. During the experiment, the users had to complete a set of tasks in order to gain insight on the electromagnetic spectrum. The tasks were designed in such a way that, by performing them, the user would get the same insight on the electromagnetic spectrum as somebody who only read the slides. The task that each participant from the test group had to complete are as follows:

1. *Identifying at least 4 types of electromagnetic waves and seeing where they fit on the spectrum*
2. *Comparing the intensity of different waves (this will be done by comparing the intensity of different waves between them as the prototype does not show a numerical value for the intensity of each wave)*
3. *Identifying at least two different sources of electromagnetic waves (examples of sources are: the sun, a lightbulb, LED's, walkie talkies, radio towers, phones, laptops etc.)*
4. *Identifying two sources of electromagnetic waves which produce the same type of wave (example: light is produced by both the sun and a lightbulb)*
5. *Identifying the wavelength size for each of the electromagnetic waves discovered in the previous tasks*
6. *Identifying the travel medium of the electromagnetic waves*
7. *Identifying the speed of an electromagnetic wave*
8. *Matching different household items (Phone, TV, WiFi, Microwave, Lamp and X-Ray machine) with the correct electromagnetic wave that they produce*

The researcher made notes on the approach each participant took while solving the tasks and it has also been noted when a participant went to the slides in order to find an answer to one of the tasks. The notes can be found in Appendix 2.

7.2.2 Participants

A total number of 21 participants have been gathered for the testing procedure. Most of the participants were students of the university while a couple of people were college graduates. There was a mix of people with background knowledge on the subject and without any knowledge on the subject. In both the control group and the test group, there were 4 out of 10 people who had prior knowledge on the electromagnetic spectrum. The recruitment of the participants has been made through personal contacts, word of mouth and social media.

7.2.4 Procedure

In this section the procedure for testing will be explained. First of all, it should be noted that the participants have been randomly split into two groups. One of the groups will be testing with the prototype and will also have access to the slides. This group is the control group and will be referred to as the *tangible learning group* through the rest of this paper. The second group will be testing with the slides. The second group is the test group and will be referred to as the *conventional learning group* for the rest of the paper.

7.2.4.1 Procedure for the tangible learning group

The procedure used for the tangible learning group can be summarised by figure 16. The participants have been asked to have their own phone on them or a laptop on which they can fill in the tests and UMUX questionnaire. In case anyone forgot their device, an alternative has been provided.

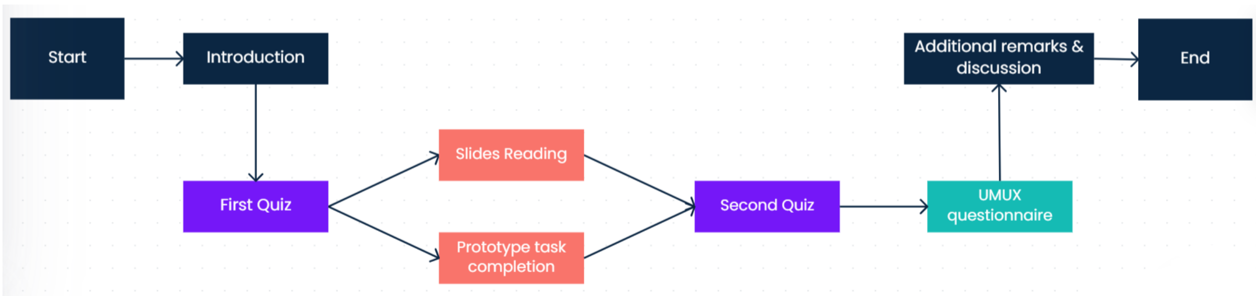


Figure 15: Flowchart of the testing procedure for the tangible learning group

At the beginning of the study, the participants will be informed of the purpose of the study, and they will be given a consent form that they will need to sign before taking part in the experiment (consent form can be found in appendix 1). Afterwards, the participants's background knowledge will be tested through the pre-test (appendix 6). Following that, the participants will receive a brief explanation on how the prototype works and will be given the set of tasks discussed in the previous section. The participants will also have the chance to refer to the slides for a better understanding on the topic, however, this is not mandatory and it's up to the user to decide if they require extra information besides what the prototype provides. Next step is for the participants to fill in the post-test. This will give an insight on the things that they learned during the experiment. Finally, the participants will take part in a small discussion where they can give their thoughts and feedback on the experience.

The researcher has been present all the time to keep track of the procedure. Furthermore, the researcher has been monitoring the participants during the completion of the tasks, taking notes, and answering any additional questions.

7.2.4.2 Procedure for the conventional learning group

The procedure used for the conventional learning is very similar to the tangible learning group and it can be summarised by figure 17. The participants have been asked to have their own phone on them or a laptop on which they can fill in the tests. In case anyone forgot their device, an alternative has been provided.

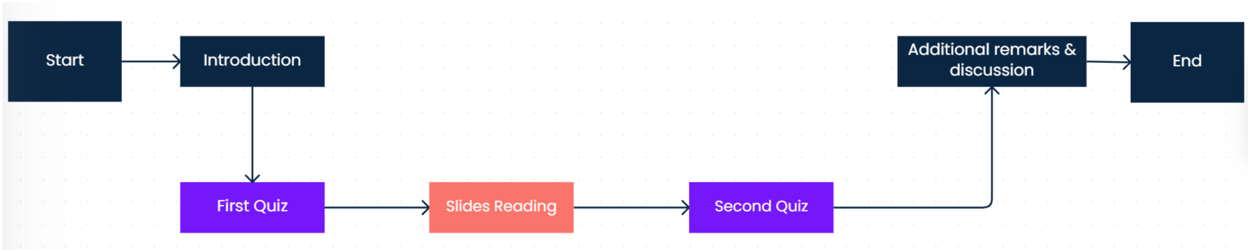


Figure 16: Flowchart of the testing procedure for conventional learning group

Upon arrival at the designated meeting place, the participants will be informed of the purpose of the study, and they will be given a consent form that they will need to sign before taking part in the experiment (consent form can be found in appendix 1). Similar to the tangible testing group, the participants's background knowledge will be tested through the pre-test (appendix 6). Following that, the participants will read through the slides. Next step is for the participants to fill in the post-test (appendix 7). This will give an insight on the things that they learned during the experiment. Finally, the same way as the tangible learning group, the participants will take part in a small discussion where they can give their thoughts and feedback on the experience.

The researcher has been present all the time in order to keep track of the procedure and to answer any questions.

7.3 Results

Results are centred around the dependent variables: effectiveness, learning gain and usability. Additionally, a section where the data gathered by notes and discussions with the participants has been added.

7.3.1 Effectiveness

For this study, effectiveness is simply defined as the number of correct answers vs the number of wrong answers while looking at the post quiz results between the prototype group vs the slides group. The results have been plotted in two different pie charts (figure 18 for the prototype group and figure 19 for the slides group). It can be seen that the prototype group scored better by 3%.

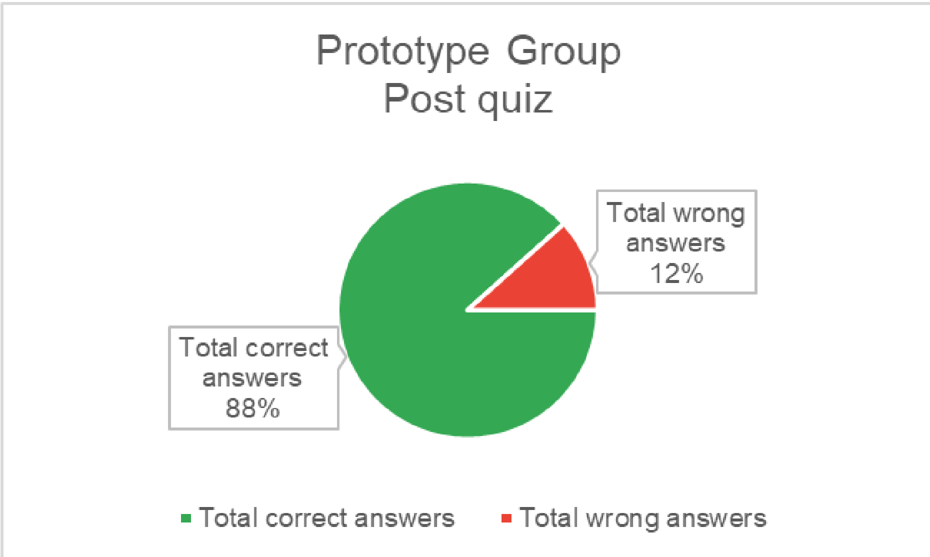


Figure 17: Plotted results of the correct vs wrong answers of the post test in the tangible learning group

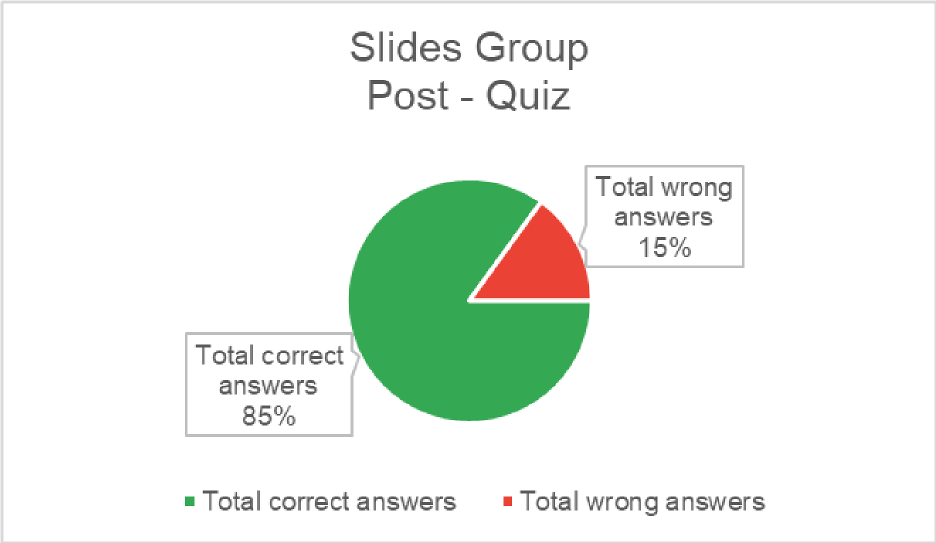


Figure 18: Plotted results of the correct vs wrong answers of the post test in the traditional learning group

It is desired to find out whether there is a statistical difference between the results of the slides group and the results of the prototype group. For this a t-test has been conducted with an acceptable margin of error of 0.05. It should be noted that before conducting the test, it had to be determined whether the variances of the two groups are different from each other. For this an f-test has been used and it has been found out that, indeed, the variances of the groups are different from each other. The two tailed t-test has been conducted with the use of Microsoft Excel and the results show a p-value of 0.43. This is significantly bigger than the margin of error which can be accepted and, therefore, it can be said that there is no statistically significant difference between the effectiveness of the slides and the effectiveness of the prototype. In other words, using the prototype to learn about the electromagnetic spectrum will yield the same results as learning using the slides.

7.3.2 Learning Gain

Learning gain has been defined as the increase in knowledge before and after testing with the prototype or reading the slides. In order to calculate this, the results of the pre-test and post-test have been compared to each other from each group. To be more precise, in order to calculate the learning gain for each individual, the result of the pre-test has been subtracted from the result of the post-test. Therefore, the maximum learning gain a person could have is 7 since there are 7 questions in each quiz.

It should be noted that the variances between the groups for both the pre-test and post-test are statistically different. This has been determined by conducting a F-Test two sample for variances between groups. However, when conducting a t-test between the two groups, it is evident that there is no significant difference between groups as the p-values for both tests are significantly bigger than 5%.

The individual learning gains for the prototype group and slides group can be seen in figure 20 respectively. The full results can be seen in appendix 5.

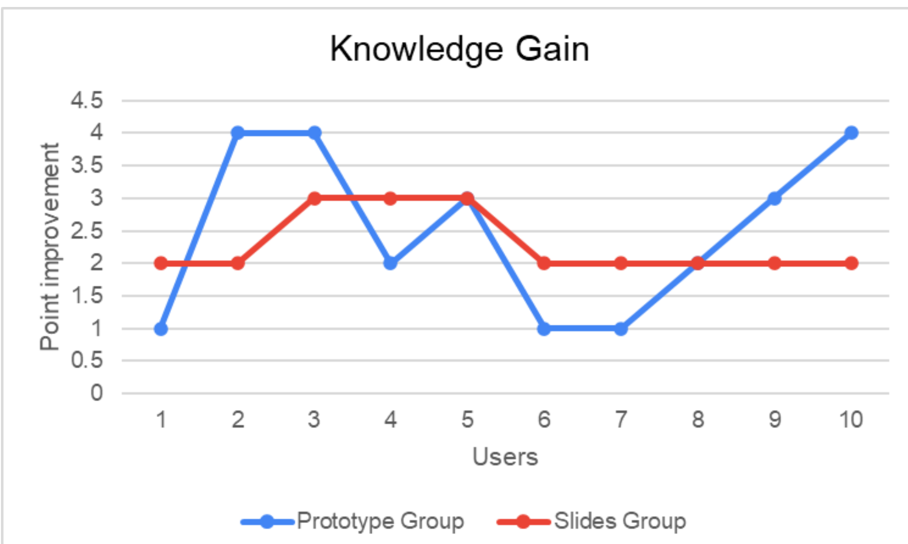


Figure 19: Individual learning gain of the group who tested with the prototype and slides

As it can be seen in figure 20 (figure above), the prototype group performed rather high, but varied. The maximum learning gain per person was 4 while the minimum one was one. The mean of this knowledge gain is 2.5 while the variance is about 1.6. The slides group got more stable results with the maximum learning gain per person was 3 while the smallest one was two. The mean of this knowledge gain is 2.3 while the variance is about 0.23.

Statistical analysis:

Ho: There is no significant difference between the prototype group and the slides group when it comes to the learning gain.

H1: There is a significant difference between the prototype group and the slides group when it comes to the learning gain.

Margin of error: It is considered that a cut off value of 0.05 will suffice. If the p-value is less than 5% then we can reject the null hypothesis and conclude that there is a significant difference between the prototype group and the slides group when it comes to the learning gain.

The T-test has been done with the use of excel and the result gave a p-value of 0.647. Therefore, the null hypothesis can not be rejected. This means that there is no statistical difference between the slides group and the prototype group when it comes to the knowledge gain.

7.3.3 UMUX results

The tangible learning group had to fill in a usability questionnaire (described in section 7.2.1) at the end of their test. Furthermore, a small discussion has been conducted with each participant in order to receive feedback and other comments regarding their experience with the prototype.

7.3.3.1 Understandability

For the purpose of this research, understability is being defined as the ease with which the user can understand the feedback of the installation. This has been measured by asking the participants to rate the following statement: '*The prototype indicates the presence of EM waves in an easily understandable manner* '. This has been measured on a Likert scale from 1 to 7 where 1 is mapped as 'strongly disagree' and 7 is mapped as 'strongly agree'. The results can be seen in figure 21. From these results, the average score is found to be 5 out of 7.

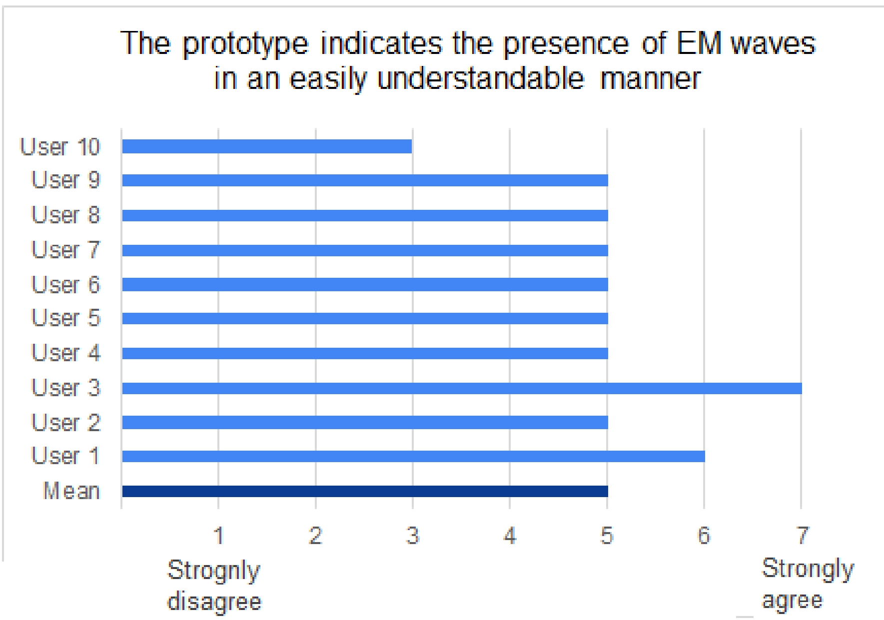


Figure 20: Understandability ranked on a Likert scale (1 to 7)

7.3.3.2 User Satisfaction

For the purpose of this research, user satisfaction is being defined as the ease with which the user can manipulate and use the prototype.This has been measured by asking the participants to rate the following statement: '*Using the prototype is a frustrating experience*'. This has been measured on a Likert scale from 1 to 7 where 1 is mapped as 'strongly disagree' and 7 is mapped as 'strongly agree'. The results can be seen in figure 22.

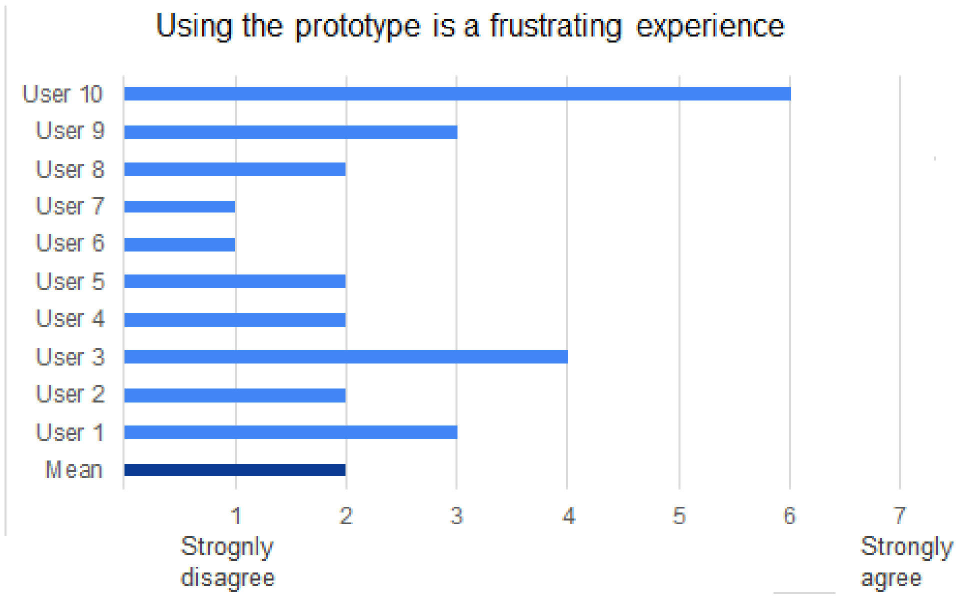


Figure 21: User satisfaction ranked on a Likert scale (1 to 7)

It can be seen that the average score is 2 out of 7. This means that most users did not find the interaction frustrating with a notable outlier for user 10 who seems to have struggled with the prototype.

7.3.3.3 Ease of Use

For the purpose of this research, ease of use is being defined as the ease with which the user can manipulate and use the prototype. This has been measured by asking the participants to rate the following statement: '*The prototype is easy to use*' .This has been measured on a Likert scale from 1 to 7 where 1 is mapped as 'strongly disagree' and 7 is mapped as 'strongly agree'. The results can be seen in figure 23. It can be seen that the average score is 5 out of 7.

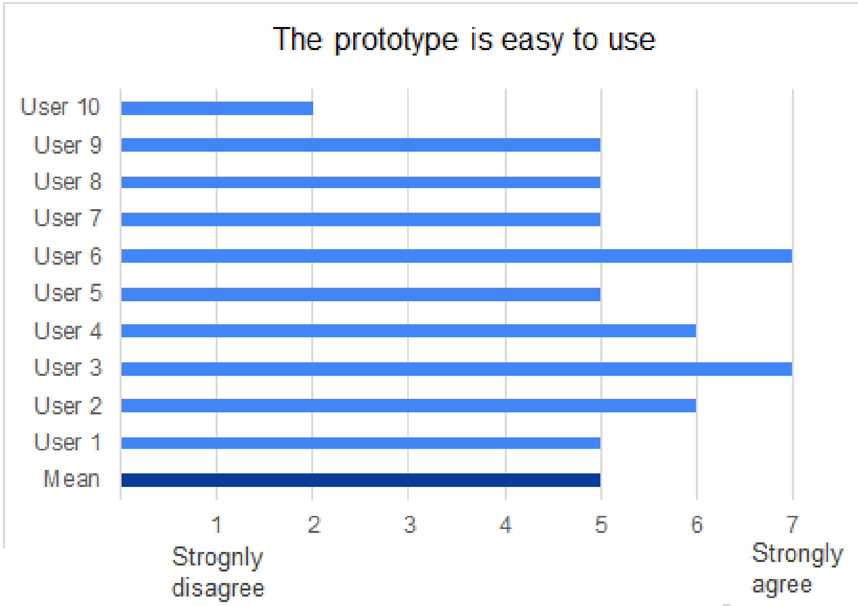


Figure 22: Ease of use ranked on a Likert scale (1 to 7)

It can be seen that the average score is 5 out of 7. Similarly to the previous question, user 10 did not find the prototype easy to use.

7.3.3.4 Usability

For the purpose of this research, usability is being defined as the ease with which the user can use the prototype. In other words, the users need to mention if they felt like they needed too much time to correct things with the prototype. This has been done by answering the question '*I have to spend too much time correcting things with the prototype*' .This has been measured on a Likert scale from 1 to 7 where 1 is mapped as 'strongly disagree' and 7 is mapped as 'strongly agree'. The results can be seen in figure 24.

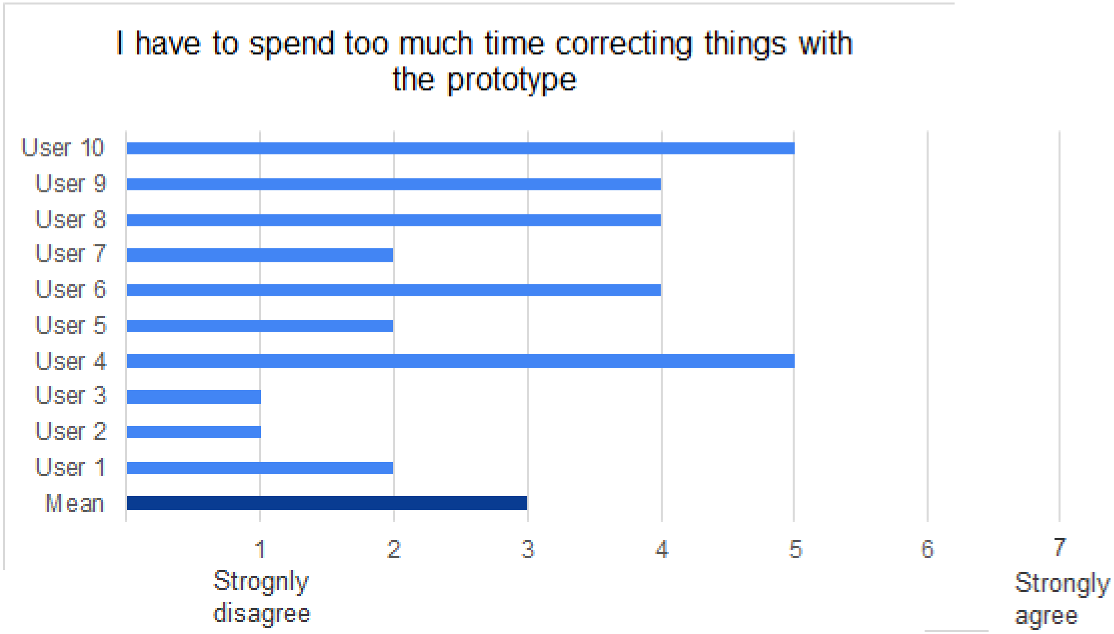


Figure 23: Usability ranked on a Likert scale (1 to 7)

It can be seen that the average score is 3 out of 7. For this particular statement, it seems that the user's opinions are evenly distributed.

7.3.4 Additional Findings

In addition to the UMUX questionnaire, the researcher took notes and conducted a small interview at the end of the test. These notes can be found in appendices 2 and 3. Based on this, a couple of additional findings can be discussed.

It has been noted that the participants who tested with the prototype mostly only used the prototype, even though they also had access to the slides (only 1 out of 10 participants read through the slides in addition to using the prototype). The participants with background knowledge on the subject have used said knowledge to answer some of the task questions instead of using the prototype. Most of the participants said they found the experience quite engaging, but they were confused with the blinking pattern of the LEDs. A couple of participants complained about the heptagon shape, saying that they found it difficult to manoeuvre it in order to find information. In contrast to that, some participants found it really fun and enjoyed using it. Some participants felt like the prototype was not well put together because the sensors and heptagon were not connected and it felt like two different prototypes.

For the slides group, most of the participants read through the slides without engaging with the researcher. Two of the participants asked clarifying questions on the material. From the discussion afterwards it has been found out that most of the participants enjoyed the slides and had fun learning about a new subject. The participants who weren't interested in the subject also found the experience rather boring. Multiple participants mentioned that it was difficult for them to remember exact numbers (for example the wavelength of microwaves or visible light). It should also be noted that some participants mentioned that because of the pre-test they were already anticipating what they should be paying attention to in the slides.

Chapter 8 - Discussion

8.1 Limitations

The study had multiple limitations throughout the research, building and evaluation of the prototype. In this section, each of these limitations will be discussed.

It would be worth noting that the research done in this paper is rather novel and it covers two different areas that have not been combined before: tangible learning and physicalization of dynamic data. Due to this, the literature review has been rather challenging and it is possible that certain aspects have been accidentally excluded. This is due to the fact that it is a new area of research and, therefore, what is truly important to it is yet to be established firmly, so it is possible that aspects that may have been important were excluded. Furthermore, since the time allowed for research in a graduation project is limited this could have also affected the quality and depth of the literature review.

For the building phase of the prototype there have been financial and time limitations. Since the study has not been financed, the quality of some of the components used is low and some features needed to be excluded from the final product. Due to that, the resolution of the sensors is not very high and as such, only a limited part of wavelengths can be displayed. On the same note, it should be mentioned that the prototype only includes visual displays of the EM spectrum and this could potentially be improved on by using supplementary actuators. Additionally, due to time constraints, the software of the prototype could not be improved upon and there have been quite a number of participants that commented on the fact that they found the blinking of the LEDs confusing. This could have potentially also influenced the results of the research.

Talking about the research, that also contains a number of limitations that should be mentioned. Firstly, since this is a novel research, the method of testing may not have been the most efficient. The quizzes used have had limited question design (only multiple choice). It would have been better if the questions were formulated in a more engaging way (see Superheroes of the Electromagnetic Spectrum) and cover more knowledge. The tasks could have also been improved on as there were a couple of participants mentioning that the radio remote is only used once. Secondly, the number of participants was rather small with only 10 testers for each group and thus, the statistical significance of this study is rather low. Finally, the research results could be improved by adding other dimensions such as the time it takes to complete each task, the time it takes to read through the slides and the engagement for the prototype testing. All this could bring new insights into the study.

8.2 Recommendations

For the improvement of the current prototype multiple recommendations can be given. First of all, an addition of actuators to the current prototype could improve the physicalization of data. Right now, the data is only expressed through LED's and the shape of the heptagon, but the users could benefit from an additional actuator. For this, a small vibration motor could be used similarly to what has been described in section Z of the background research. Secondly, the prototype could be made completely wireless as now part of it still needs to be connected through a laptop for the power supply. While none of the users had complaints about this, it would be a good feature to have for a final product as it could improve the ease of use. Lastly, the current design of the information displayed on the heptagon could be improved upon as some of the users found it confusing and thought that certain information only applies to certain sections of the EM spectrum instead of all of it.

The components used could also be improved upon. For example, for making the sensing remotes smaller, a smaller arduino could be used, like an arduino nano, which would decrease the size of the casing. Furthermore, the wiring could also be soldered on a small soldering board as right now a simple breadboard is being used and this could potentially be unreliable for longer periods of time. Additionally, investing in a converter for the Raspberry Pi power supply could make the whole setup completely wireless and therefore easier to use in a classroom setting. Finally, choosing sensors with a higher resolution could prove to be useful to improve the range display of the EM spectrum.

8.3 Relevance and Future Work

Firstly, the research is relevant for a variety of reasons. People's misconceptions about electromagnetic radiation are prominent throughout the population, even in the higher education institutions. [10, 20, 21, 22, 24] This could be due to either pop culture [10], but it can also be attributed to the difficulty of the subject. A natural solution is improving the current educational approaches on the topic; making the learning process more entertaining and the subject easier to understand. Upon a background research, tangible learning has been found to be the most efficient solution. Due to the nature of the subject being taught, visualisation has also been found to be an important variable to take into account. Therefore, this research has theorised that physicalization or visualisation of data can also play a role in tangible learning of the EM waves. The usage of data physicalization for tangible learning is a rather new approach and there exists no previous study done on this topic. Therefore, there exists a multitude of improvements and future projects which can be done on this subject.

A framework for testing the physicalization of data as a means of tangible learning should be developed in the future. Besides an in-between group design, it should contain a measurement of the time to complete tasks, accuracy of the users while using the prototype, but also a perceived task load and fatigue which have not been taken into account in this research. This would help better structure future work in this domain and keep the variables tested relatively consistent.

Another improvement which could be included to this particular study is adding a new method of data physicalization. At the moment, only LEDs are being used and the shape of the display which encapsulates the essence EM waves. By adding a new method of physicalization, the users could also benefit from haptic feedback which could prove to be more efficient than only presenting data through visualisations.

Chapter 9 - Conclusion

Based on the results of the evaluation and the background research, conclusions can be formulated in regards to the research question:

“How does tangible learning of the electromagnetic spectrum through data physicalization compare to traditional learning?”

It has been noted that there is no significant difference in the knowledge gain of the users between the tangible learning group and traditional learning group. However, interviews indicate that the users testing with the prototype seemed to enjoy the learning process more than the users who only had the slides.

The results of the UMUX user study also show that the prototype performed rather well, with an average score of 5 out 7. Users overall enjoyed learning about the Electromagnetic Waves through the means of the prototype with a small exception. As a whole, this serves as a validation for the fact that data physicalization can serve as a means of tangible learning.

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Appendices

Consent Form for Physicalizing the Electromagnetic Spectrum for Tangible Learning

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated [……./……./………….], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	O	O
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	O	O
I understand that taking part in the study involves filling out two questionnaires: one before and one after taking part in a mini lecture/ prototype testing. (please cross with a line the option which DOES NOT apply to you). I understand that the questionnaires focus on my knowledge gain and I am aware that the questionnaires will not be shared with anybody besides the researching team and they are stored securely according to the guidelines of the AVG.	O	O
This sections only applies to prototype testing. If you take part in the mini lecture you can skip this		
I am aware that testing the prototype entails completing different tasks which have been described in the information brochure attached to this document.	O	O
I am aware that the researcher will take observation notes during the testing session and these notes can be used in the research paper. The notes will not be shared with anybody besides the researching team and they are stored securely according to the guidelines of the AVG.	O	O
Use of the information in the study		
I understand that information I provide will be used for the thesis report of the researcher.	O	O
I understand that personal information collected about me that can identify me, such as [e.g. my name or signature], will not be shared beyond the study team.	O	O
I agree that my comments can be anonymously quoted in research outputs.	O	O

Signatures

______________________ ______________________ ________

Name of participant [printed]

Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

________________________ __________________ ________

Researcher name [printed] Signature Date

Study contact details for further information:

Clara Draganuta **c.draganuta@student.utwente.nl** **+40743707777**

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Information & Computer Science: ethicscommittee-CIS@utwente.nl

Appendix 2: Interview & Notes - Test Group

User 1:

They thought that an extra task concerning the radio waves could be introduced as the radio remote has only been used once.

They really enjoyed the shape of the prototype and also had a lot of fun interacting with it.

They found the propagation music confusing.

They thought the prototype could be a bit more put together. The fact that everything is separated right now (two different sensing devices plus the information heptagon) is a bit confusing.

They used the prototype for all tasks.

They found the prototype very engaging. Engagement: 7

User 2:

Already had a lot of background knowledge on the subject. As a result they didn’t use the prototype for any of the tasks and just stated the answers. Completely opposite to the previous participant, they were annoyed by the fact that they needed to move around the heptagon to retrieve certain information.

They didn’t find the prototype very engaging. Engagement: 2

User 3:

Walked around the room quite a lot while using the prototype and enjoyed looking for information on the heptagon.

Engagement: 6

User 4:

Due to the fact that the information displayed on the heptagon was closer to certain rays than the others, they assumed that the information only applies to the rays closest to it. Found the blinking of the rays a bit counterintuitive.
Overall they had fun using it. Engagement: 6.

User 5:

Found the first task very confusing. Also found the blinking confusing. For tasks 5 and 6, the heptagon was used.

Engagement: 6

User 6:

Task 1,2 & 3: Used both the installation and previous knowledge in order to complete the tasks.
Task 4,5,6 & 7: Answered mostly from memory but also double checked their knowledge with the prototype.

Engagement: 7

User 7:

Task 1: Used installation and previous knowledge to complete it.
Task 2: There were technical issues with the radio sensor and such, the wizard of oz was used for this. The user correctly completed the task.
Task 3 to 7: answered from the top of their head
Task 5: A bit unsure about the UV but used intuition instead of checking the information written on the heptagon.
Task 8: Used the heptagon.

They found the blinking hard to interpret.

Overall they had fun using the prototype. Engagement: 7

User 8:

Tasks 1 to 4: made using the prototype.
Tasks 5: from pre-knowledge and looking at the heptagon.
Task6: looking at the heptagon
Task 7: they thought the information concerning the speed on the heptagon was only for the IR, visible light and UV
Task 8: Had small issue due to them struggling with the handwriting.

Engagement: 5

User 9:

First they went through the slides before looking at the prototype.
Mostly used the prototype in order to complete the tasks. For some of the tasks (tasks 5 and 6) they already knew the answer but checked the heptagon to confirm.

The blinking of the LED’s took a bit of time to figure out but in the end it was understandable.

Engagement: 6

User 10:

All tasks were completed using the prototype. Small mistake was made in task 7 (placing the lamp in the radio wave section).

Overall they found the prototype fun to use.

Engagement: 5

Appendix 3: Interview notes - Control Group

User1:

Already had some knowledge about this from highschool physics. Compared to the other users they went quite quick through the pre-test.

They enjoyed getting a refresh on the subject, however they felt like they should have already know more about the subject. They found it difficult to remember number related information. They found the acronym ROYGBV quite helpful.

They enjoyed the yellow highlighted parts of the slides as it helped them to know what the important information is.

User 2:

They didn't find the experience interactive. “No good vibes”. Overall they did not enjoy the experience too much.

User 3:

They think things like numbers are especially hard to remember. Asking questions and thinking/associations helped them remember things easier. Information that wasn't related to only numbers was easier to remember.

They found it difficult to focus sometimes.

“Once I filled in the first questionnaire I felt kind of stupid. But it kind of gave me a purpose to pay attention to the slides as I knew what to pay attention to. There was also a bit of pressure as I knew I had to fill in a second questionnaire.”

User 4:

They didn't enjoy the experience as they felt the slides are a boring way to learn a new subject. They were also not particularly interested in the subject that was being taught so that made it a bit difficult to focus.

They tried to remember some numbers/ information by heart as they knew that there was going to be a second questionnaire and they wanted to score better in it. Overall they didn’t enjoy the experience too much.

User 5:

They found the topic interesting. They thought the pre-test influenced the things they payed attention to during the slides reading.

“Since there was no time limit, I actually tried to learn everything written on the slides”

They didn’t find the slides that exciting.

User 6:

Regrets that their highschool teacher didn’t use slides for their lectures. They found the slides quite nice and interesting. “Mildly interesting presentation.”

They already had a good grasp on the information presented, but their knowledge wasn’t ordered too well in their head. This helped them organize it a bit better in their head.

For them this was just “basic physics”. They didn’t feel like they learned anything new.

User 7:

They had fun learning about the subject. They found the slides quite informative.

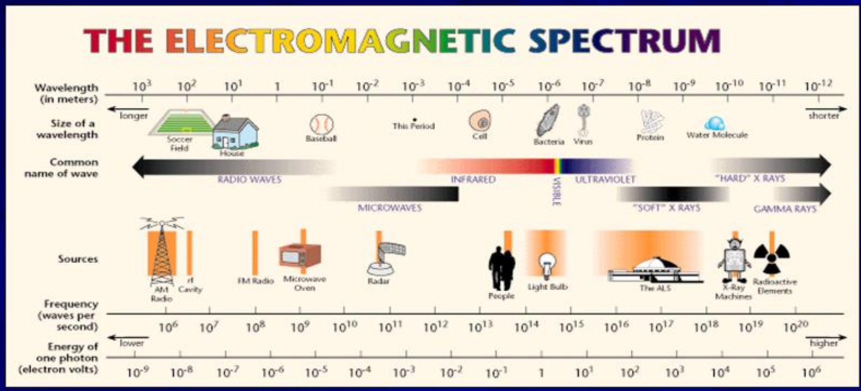
They didn’t ask any questions as they though the slides were clear enough and didn’t require any extra explanations.

User 8:

Didn't have previous experience with this except one highschool lecture. She did enjoy the topic as it sparked interest.

User 9:

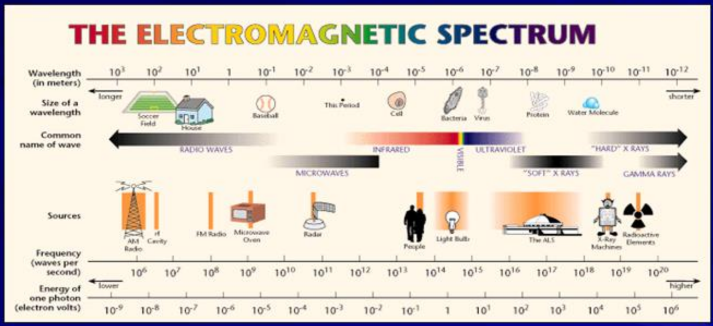
The slides are pretty nice. “I at least know that the wifi is a microwave and that they didn't need a medium to travel.” They enjoyed the materials. Didn't find the experience very interactive.



The Electromagnetic Spectrum

The Electromagnetic Spectrum

- The EM spectrum is the ENTIRE range of EM waves in order of increasing frequency and decreasing wavelength.



- As you go from left → right, the wavelengths get smaller and the frequencies get higher. This is an inverse relationship between wave size and frequency. (As one goes up, the other goes down.) This is because the speed of ALL EM waves is the speed of light (300,000 km/s).

Things to Remember

- The higher the frequency, the more energy the wave has.
- EM waves do not require media in which to travel or move.
- EM waves are considered to be transverse waves because they are made of vibrating electric and magnetic fields at right angles to each other, and to the direction the waves are traveling.
- Inverse relationship between wave size and frequency: as wavelengths get smaller, frequencies get higher.

The Waves (in order…)

Radio waves: Have the longest wavelengths and the lowest frequencies; wavelengths range from 1000s of meters to .001 m

- Used in: RADAR, cooking food, satellite transmissions

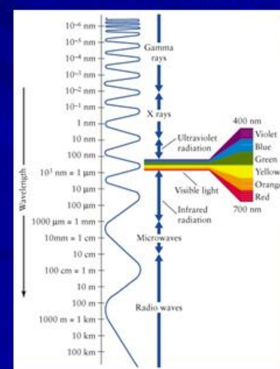


Infrared waves (heat): Have a shorter wavelength, from .001 m to 700 nm, and therefore, a higher frequency.

- Used for finding people in the dark and in TV remote control devices

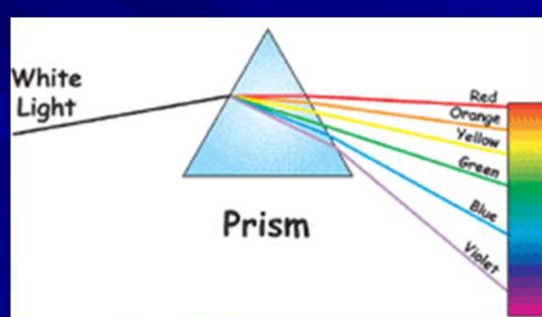
Visible light: Wavelengths range from 700 nm (red light) to 30 nm (violet light) with frequencies higher than infrared waves.

- These are the waves in the EM spectrum that humans can see.
- Visible light waves are a very small part of the EM spectrum!



Visible Light
Remembering the Order

- ROY G. BV
  - red
  - orange
  - yellow
  - green
  - blue
  - violet



Ultraviolet Light: Wavelengths range from 400 nm to 10 nm; the frequency (and therefore the energy) is high enough with UV rays to penetrate living cells and cause them damage.

- Although we cannot see UV light, bees, bats, butterflies, some small rodents and birds can.
- UV on our skin produces vitamin D in our bodies. Too much UV can lead to sunburn and skin cancer. UV rays are easily blocked by clothing.
- Used for sterilization because they kill bacteria.

X-Rays: Wavelengths from 10 nm to .001 nm. These rays have enough energy to penetrate deep into tissues and cause damage to cells; are stopped by dense materials, such as bone.

- Used to look at solid structures, such as bones and bridges (for cracks), and for treatment of cancer.

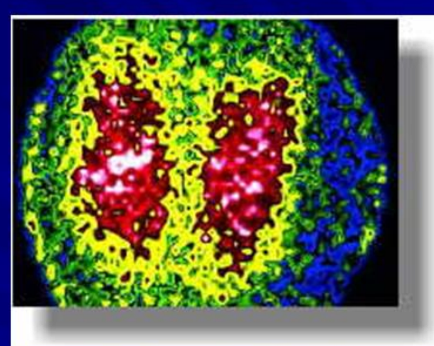
Gamma Rays: Carry the most energy and have the shortest wavelengths, less than one trillionth of a meter (10^{-12}).

- Gamma rays have enough energy to go through most materials easily; you would need a 3-4 ft thick concrete wall to stop them!

- Gamma rays are released by nuclear reactions in nuclear power plants, by nuclear bombs, and by naturally occurring elements on Earth.
- Sometimes used in the treatment of cancers.

Gamma Rays

- This picture is a “scintigram” ➔
- It shows an asthmatic person’s lungs.



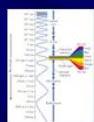
- The patient was given a slightly radioactive gas to breath, and the picture was taken using a gamma camera to detect the radiation.
- The colors show the air flow in the lungs.

Image Sources

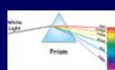
Micro Worlds, Lawrence Berkeley National Laboratory.
http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html




2004 Microsoft Corporation, One Microsoft Way, Redmond, WA 98052-6399 USA.

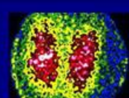


NASA http://science-edu.larc.nasa.gov/EDDOCS/Wavelengths_for_Colors.html



NASA http://spaceplace.nasa.gov/blue-sky/


NASA http://missionscience.nasa.gov/ems/11_xrays.html

Andy Darvill, Broadoak Community School, Radioactivity Uses
http://www.northallertoncoll.org.uk/science/Additional%20Physics/Nuclear/Nuclear/Radioactivity/uses.htm

Appendix 5: Test Results

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Pre-test: Prototype Group	1	1	1	1	0	1	1
	0	1	0	0	0	0	1
	1	0	0	0	0	1	1
	1	0	0	1	0	1	1
	0	1	0	0	0	1	1
	1	1	0	0	0	1	1
	1	1	1	1	0	1	1
	1	1	0	1	0	1	1
	0	1	1	1	0	1	1
	0	0	1	0	0	0	1
	0	1	0	0	0	1	1
Post-test: Prototype Group	1	1	1	1	1	1	1
	1	1	1	1	0	1	1
	1	1	1	1	1	1	1
	1	1	1	1	0	1	1
	1	1	0	1	1	1	1
	1	1	1	0	0	1	1
	1	1	1	1	0	1	1
	1	1	1	1	0	1	1
	1	1	1	1	1	1	1
	0	1	1	1	0	1	1
	1	1	1	1	1	1	1
Pre-test: Slides Group	0	1	1	0	0	0	1
	1	1	0	0	1	0	1
	1	0	0	0	0	0	0
	1	0	0	0	0	0	1
	0	0	0	1	0	1	1
	0	1	0	1	1	1	1
	1	1	0	0	0	1	1
	0	1	0	1	0	1	1
	1	1	0	0	0	1	1
	1	1	0	1	0	1	1
Post-test: Slides Group	1	1	1	0	0	1	1
	1	1	1	1	1	1	0
	1	1	0	1	0	1	0
	1	1	1	0	0	1	1
	1	1	1	1	0	1	1
	1	1	1	1	1	1	1
	1	1	1	1	0	1	1
	1	1	1	1	0	1	1
	1	1	1	1	0	1	1
	1	1	1	1	1	1	1

Appendix 6: Pre-test Questionnaire

I already have a background regarding the electromagnetic wave spectrum.

- ◯ Yes
- ◯ No

The correct order of the waves type (based on their wavelength) in the electromagnetic spectrum is as follows:

- ◯ Gamma rays, Radio waves, X-Rays, Microwave waves, Ultraviolet (UV), Visible light, Infrared waves (IR)
- ◯ Gamma rays, X-rays, Ultraviolet, Visible light, Infrared waves, Radio waves
- ◯ X-Rays, Gamma rays, Infrared waves, Visible light, Ultraviolet, Radio Waves
- ◯ X-Rays, Gamma rays, Ultraviolet, Visible light, Infrared waves, Radio Waves

The following waves can be dangerous on exposure:

- ◯ Gamma rays, Microwaves, Infrared waves
- ◯ Ultraviolet, Microwaves, X-rays
- ◯ Radio Waves, Infrared waves, Gamma rays
- ◯ X-rays, Gamma rays, Ultraviolet

The radio waves wavelength is between:

- ◯ 1 km - 100 km
- ◯ 10 nm - 100 km
- ◯ 10 m - 100 000 km
- ◯ 100 mm - 100 000 m

The speed of a microwave is:

- ◯ 100 km/s
- ◯ Speed of light
- ◯ Speed of sound
- ◯ 100 000 m/s

Knowing that a wifi router transmits and receives signals at 5 GHz (about 6 cm wavelength), what type of wave would the wifi signal be?

- ◯ Microwave
- ◯ Radiowave
- ◯ Infrared
- ◯ Ultraviolet

What medium does an electromagnetic wave need for propagation?

- ◯ Air
- ◯ Plasma
- ◯ They don't need a physical medium
- ◯ Grass

All electromagnetic waves can be easily blocked by a solid object.

- ◯ True
- ◯ False

Appendix 7: Post-test Questionnaire

The correct order of the waves type (based on their wavelength) in the electromagnetic spectrum is as follows:

- ○ Gamma rays, Radio waves, X-Rays, Microwave waves, Ultraviolet (UV), Visible light, Infrared waves (IR)
- ○ Gamma rays, X-rays, Ultraviolet, Visible light, Infrared waves, Radio waves
- ○ X-Rays, Gamma rays, Infrared waves, Visible light, Ultraviolet, Radio Waves
- ○ X-Rays, Gamma rays, Ultraviolet, Visible light, Infrared waves, Radio Waves

The following waves are safe for human exposure:

- ○ Gamma rays, Microwaves, Infrared waves
- ○ Ultraviolet, Microwaves, X-rays
- ○ Radio Waves, Infrared waves, Visible light
- ○ X-rays, Gamma rays, Microwaves

The visible light waves wavelength is between:

- ○ 400 nm - 700 nm
- ○ 1 nm - 1 mm
- ○ 30 m - 70 m
- ○ 1 nm - 100 nm

The speed of a radio wave is:

- ◯ 100 km/s
- ◯ Speed of light
- ◯ Speed of sound
- ◯ 100 000 m/s

Knowing that a wifi router transmits and receives signals at 800 MHz to 1900 MHz (about 10 to 100 m wavelength), what type of wave would the wifi signal be?

- ◯ Microwave
- ◯ Radiowave
- ◯ Infrared
- ◯ Ultraviolet

What medium does an electromagnetic wave need for propagation?

- ◯ Air
- ◯ Plasma
- ◯ They don't need a physical medium
- ◯ Electric field

All electromagnetic waves can be easily blocked by a solid object

- ◯ True
- ◯ False

Appendix 8: Arduino Code

```
/***************************************************************************
  This is a library for the Adafruit AS7262 6-Channel Visible Light Sensor

  This sketch reads the sensor

  Designed specifically to work with the Adafruit AS7262 breakout
  ----> http://www.adafruit.com/products/3779

  These sensors use I2C to communicate. The device's I2C address is 0x49
  Adafruit invests time and resources providing this open source code,
  please support Adafruit andopen-source hardware by purchasing products
  from Adafruit!

  Written by Dean Miller for Adafruit Industries.
  BSD license, all text above must be included in any redistribution
 ***************************************************************************/



//  DON'T FORGET TO REWRITE THE CODE WITH THE NEW PIN VALUES!!!!



#include <Wire.h>
#include "Adafruit_AS726x.h"
#include "Adafruit_SI1145.h"


//create the object
Adafruit_AS726x ams;
Adafruit_SI1145 uv = Adafruit_SI1145();

//buffer to hold raw values
uint16_t sensorValues[AS726x_NUM_CHANNELS];

//buffer to hold calibrated values (not used by default in this example)
//float calibratedValues[AS726x_NUM_CHANNELS];


// Generally, you should use "unsigned long" for variables that hold time
// The value will quickly become too large for an int to store
unsigned long previousMillis_inf = 0;        // will store last time LED was updated
```

```
unsigned long previousMillis_r = 0;
unsigned long previousMillis_o = 0;
unsigned long previousMillis_y = 0;
unsigned long previousMillis_g = 0;
unsigned long previousMillis_b = 0;
unsigned long previousMillis_p = 0;
unsigned long previousMillis_uv = 0;

// Defining different intervals for each LED to blink
int interval_inf, interval_r, interval_o, interval_y, interval_g, interval_b, interval_p, interval_uv;

// Variable that will help set the LED state for each LED
int ledState_inf = LOW;          // ledState used to set the LED
int ledState_r = LOW;
int ledState_o = LOW;
int ledState_y = LOW;
int ledState_g = LOW;
int ledState_b = LOW;
int ledState_p = LOW;
int ledState_uv = LOW;

void setup() {
  Serial.begin(9600);

  // initialize digital pin LED_BUILTIN as an output.
  pinMode(LED_BUILTIN, OUTPUT);

  // initialize digital pin 2,... as an output.
  pinMode(2, OUTPUT);
  pinMode(3, OUTPUT);
  pinMode(4, OUTPUT);
  pinMode(5, OUTPUT);
  pinMode(6, OUTPUT);
  pinMode(7, OUTPUT);
  pinMode(8, OUTPUT);
  pinMode(9, OUTPUT);

  //begin and make sure we can talk to the sensor
  if(!ams.begin()){
    Serial.println("could not connect to sensor! Please check your wiring.");
    while(1);
  }

  // This part is for the UV sensor
```

```
  Serial.println("Adafruit SI1145 test");

  if (! uv.begin()) {
    Serial.println("Didn't find Si1145");
    while (1);
  }
  // Up to here is for the UV sensor

}

void loop() {

  //read the device temperature
  uint8_t temp = ams.readTemperature();
  ams.startMeasurement(); //begin a measurement

  // This is for the UV sensor + IR
  Serial.println("===================");
  Serial.print("Vis: "); Serial.println(uv.readVisible());
  Serial.print("IR: "); Serial.println(uv.readIR());

  float UVindex = uv.readUV();
  float IRvalue = uv.readIR();
  // the index is multiplied by 100 so to get the
  // integer index, divide by 100!
//  UVindex /= 100.0;
//  Serial.print("UV: ");  Serial.println(UVindex);

  //wait till data is available
  bool rdy = false;
  while(!rdy){
    delay(5);
    rdy = ams.dataReady();
  }
  //ams.drvOff(); //uncomment this if you want to use the driver LED for readings

  //read the values!
  ams.readRawValues(sensorValues);
  //ams.readCalibratedValues(calibratedValues);

  Serial.print("Temp: "); Serial.print(temp);
  Serial.print(" Violet: "); Serial.print(sensorValues[AS726x_VIOLET]);
```

```
// update the interval of blinking for each LED
interval_inf = 10000/IRvalue;
interval_r = 10000/sensorValues[AS726x_RED];
interval_o = 10000/sensorValues[AS726x_ORANGE];
interval_y = 10000/sensorValues[AS726x_YELLOW];
interval_g = 10000/sensorValues[AS726x_GREEN];
interval_b = 10000/sensorValues[AS726x_BLUE];
interval_p = 10000/sensorValues[AS726x_VIOLET];
interval_uv = 10000/UVindex;

// Calculating when each LED should be turning on or off

// check to see if it's time to blink the LED; that is, if the difference
// between the current time and last time you blinked the LED is bigger than
// the interval at which you want to blink the LED.
// the interval should be based on the intensity of the light:
// interval = 1000/intensity
unsigned long currentMillis = millis();

Serial.print(" currentMillis: "); Serial.println(currentMillis);
Serial.print("UVindex: "); Serial.println(UVindex);

if (currentMillis - previousMillis_inf >= interval_inf*10) {
    previousMillis_inf = currentMillis;

    if (ledState_inf == LOW) {
      ledState_inf = HIGH;
    } else {
      ledState_inf = LOW;
    }
  }
digitalWrite(9, ledState_inf);

if (currentMillis - previousMillis_r >= interval_r*10) {
  previousMillis_r = currentMillis;

  if (ledState_r == LOW) {
    ledState_r = HIGH;
  } else {
    ledState_r = LOW;
  }
}
Serial.print("interval_r:  "); Serial.println(interval_r);
digitalWrite(2, ledState_r);
```

```
if (currentMillis - previousMillis_o >= interval_o*10) {
  previousMillis_o = currentMillis;

  if (ledState_o == LOW) {
    ledState_o = HIGH;
  } else {
    ledState_o = LOW;
  }
}
digitalWrite(3, ledState_o);

if (currentMillis - previousMillis_y >= interval_y*10) {
  previousMillis_y = currentMillis;

  if (ledState_y == LOW) {
    ledState_y = HIGH;
  } else {
    ledState_y = LOW;
  }

}
digitalWrite(4, ledState_y);

if (currentMillis - previousMillis_g >= interval_g*10) {
  previousMillis_g = currentMillis;

  if (ledState_g == LOW) {
    ledState_g = HIGH;
  } else {
    ledState_g = LOW;
  }

}
digitalWrite(5, ledState_g);

if (currentMillis - previousMillis_b >= interval_b*10) {
  previousMillis_b = currentMillis;

  if (ledState_b == LOW) {
    ledState_b = HIGH;
  } else {
    ledState_b = LOW;
  }
```

```
    digitalWrite(6, ledState_b);
  }

  if (currentMillis - previousMillis_p >= interval_p*10) {
    previousMillis_p = currentMillis;

    if (ledState_p == LOW) {
      ledState_p = HIGH;
    } else {
      ledState_p = LOW;
    }
    digitalWrite(7, ledState_p);
  }

  if (currentMillis - previousMillis_uv >= UVindex*300) {
    previousMillis_uv = currentMillis;
    if (UVindex <= 2)
      ledState_uv = LOW;
      else
      {
        if (ledState_uv == LOW) {
          ledState_uv = HIGH;
        } else {
          ledState_uv = LOW;
        }
      }
    digitalWrite(8, ledState_uv);
    Serial.print("UVindex:  ");  Serial.println(UVindex);
  }

  Serial.println();
  Serial.println();
}

void blinking(int pin_number, unsigned long current_milli, unsigned long previous_milli, int
interval)
{
    digitalWrite(pin_number, HIGH);
    if(current_milli - previous_milli >= 1000){
      digitalWrite(pin_number, LOW);
      Serial.print("c-p: "); Serial.println("Turn it off");
    }
}
```