Technische Universität München

Professorship of Learning Sciences and Educational Design Technologies

Master of Education Research on Teaching and Learning

TUM School of Social Sciences and Technology

Master's Thesis

Sound Making with Tangible Personal Artifacts and Electronic Construction Kits to Foster Engineering Practices

Author: Santiago Hurtado
Supervisor: Prof. Dr. Anna Keune
Advisor: Prof. Dr. Anna Keune
Submission date: 27.12.22

Declaration of Authorship

I, Carlos Santiago Hurtado Melo, confirm that this Master's thesis is my own work and I have documented all sources and material used.

This thesis was not previously presented to another examination board and has not been published.

Munich, December 27, 2022

Place and date   Signature

Abstract

The STEM field faces dropout issues across the globe, leading to a smaller proportion of STEM graduates compared to graduates in other majors. Providing early engineering education to young people can give them exposure and experience that can help prevent dropout issues. One way to engage youth in early engineering education is through personally meaningful projects, with sound making as one promising context. Sound is personally meaningful because it can connect to a person's experiences and represent them. Building on constructionist perspectives, this qualitative study investigated engineering practices in a sound making activity using conductive and non-conductive materials for the representation of tangible personal artifacts. The study explored three electronic sound-making kits: littleBits Synth Kit, Playtronica Playtron, and Squishy Circuits. Open-ended construction kits allowed for more tinkering with materials and projects, and provided better support for engineering design practices throughout the activity compared to more closed kits. This study shows that sound making with tangible personal artifacts is a productive context for engineering explorations. Furthermore, this study suggests that the concept of the personally meaningful in constructionism could be expanded to include materializing personal histories through sound making, which could support learners in their personal projects.

Keywords: Engineering learning, constructionism, sound, construction kits

Table of Contents

Table of Figures

Table Of Tables

1. Introduction

The STEM field faces dropout issues internationally (e.g., Heublein & Schmelzer, 2018; Chen et al., 2018; Fatouru et al, 2019; Bacovic et al., 2022). Alternative approaches to STEM (Science, Technology, Engineering, and Mathematics) education are needed to counteract this trend. I focused on engineering education, which can be a pathway to STEM education (Simmaro & Couso, 2021). Engineering education in K-12 is still not widely implemented, but early exposure could provide youth with positive experiences to inform their decisions to choose to stick with STEM. A promising approach toward adopting early engineering education is through the design of personally meaningful projects (Papert, 1980). Personal projects provide meaning beyond intended use; they evoke experiences that tie domain learning and interests (Turkle, 2007).

One meaningful context in this area is sound making. Sound has personally meaningful properties because we experience sound in everyday life and attribute meaning to sound through memories and emotions (Cambrón, 2005). Sound as a design material can be a quasi-object (i.e., a material we cannot touch but we can create and hear; Wargo, 2018) and therefore, an object-to-think-with that provides a link between abstract and sensory knowledge at the intersection of cultural presence, embedded knowledge, and the potential for personal identification (Papert, 1980, p. 11). Investigating materials and designs that will make it possible for youth to tie their projects to personal histories is still needed. Despite these promises, we know little about the utility of sound making for engineering learning.

This qualitative study investigated the engineering design practices as youth engaged in sound making with electronic construction kits combined with conductive and non-conductive materials for the design of personally meaningful projects. I found that sound making can evoke engineering design practices, particularly when it is possible to combine conductive materials to create nuanced sounds and integrate tangible personal artifacts. I close with implications for designing for engineering learning through sound making.

Research Question

1. ***What conductive and non-conductive materials support personal projects and engineering practices in sound making activities?***
2. ***What sound making kits and materials support a sound making activity, and how do tangible personal artifacts help the design to foster engineering practices?***
3. ***How does sound making with electronic construction kits support personally meaningful engineering practices for middle school students?***

2. Background

2.1 The importance of engineering education

The STEM field faces dropout issues internationally (e.g., Chen et al., 2018; Bacovic et al., 2022). Caprile et al. (2015) mentions that the European Union (EU) is on a downward trend in STEM graduates, despite an overall increase in enrollment and graduation rates in non-STEM disciplines (Fatourou et al., 2019). One example of this are dropout rates in Germany in Engineering, that report a dropout rate of about 50% in majors like electrical engineering (Heublein & Schmelzer, 2018). Alternative approaches to STEM education are needed to counteract this trend (Ata-Aktürk & Demircan, 2021).

STEM education is a key focus of educational efforts, as demonstrated by the creation of standards like the Next Generation Science Standards (NGSS) and the K-12 Computer Science Framework (K12CS) for K-12 education (National Research Council, 2013). These standards provide guidance for designing curricula and activities, and also encourage interdisciplinary connections across STEM domains. For example, developments in computer science can also have implications for engineering principles. The importance of STEM education lies in the potential impact that STEM graduates can have on the development and innovation of their countries, as well as the role they play in advancing new technologies such as renewable energy and sustainability (Kennedy & Odell, 2014).

I focused on engineering education, which can be a path toward STEM education and improves mathematics, science achievement, and engineering knowledge (Simarro & Couso, 2021). Engineers need to be prepared for the challenges of today's world, where pedagogical strategies across curriculums need to evolve (Hernandez-De-Menendez et al., 2020). While engineering education is not widely implemented in K-12 education, early exposure could provide youth with positive experiences to inform their decisions to choose to continue with STEM. One approach to early engineering education is through constructionism, which involves using materials to allow learners to develop their own projects and engage in personally meaningful learning (Papert, 1980).

2.2 Constructionism as an approach to early engineering education

Constructionism is an approach to learning that stems from the educational philosophy established by Jean Piaget, called constructivism. Constructivism states that knowledge is constructed actively in the mind of the learner through the construction of artifacts, positioning the learner as an active agent (Piaget, 1968). Papert (1980) built on this idea and argued that learning is most effective when the learner is able to work on design projects to build meaningful outcomes. In constructionism, learning involves developing connections between old and new knowledge through interaction with others and creating artifacts (Kafai, 2006). This approach emphasizes the importance of learners appropriating knowledge and the role of materials in making this possible.

Papert (1980) also argues that the materials used for the construction of the projects allow learners to explore complex systems and concepts using objects-to-think-with (OTTW). OTTW are objects that enable learners to connect personal creations and theoretical knowledge. Specifically, Pappert (1980) states that OTTW should meet the three criteria of “an intersection of cultural presence, embedded knowledge, and the possibility for personal identification” (p. 11). Therefore, materials that enable learners to explore and create are essential for developing personally meaningful projects and therefore learning experiences. Materials that only allow for binary right or wrong outcomes may not be suitable for constructionist designs, as they leave little room for personal design. OTTW have been studied extensively, with research showing the potential learning experiences that can occur with various materials as OTTW, such as videogames as OTTW (Holbert & Wilensky, 2019), e-books as OTTW (Chronis, 2015), construction kits to create OTTW for physical education (Dittert, 2014), robotics construction kits as OTTW (D’Amico & Guastella, 2018), among others. In makerspace contexts, OTTW have also been explored as materials-to-develop-with, which encompass materials and co-development over longer periods of time and across spaces (Keune & Peppler, 2019).

The personal projects facilitated by OTTW focus on objects that have meaning that goes beyond their intended use and provide learners with experiences that are tied to their interests and learning experiences (Turkle, 2007). OTTW enable learners to connect their learning processes with significant experiences. Within the educational process, the instructors and the activities provide personally meaningful learning. Learners are encouraged to use the materials to create their own projects, establishing design ownership. The open-ended design of constructionism allows learners to dive deep into their own projects. Design principles for OTTW point to analyzing the affordances and constraints of construction kits, including the materials they bring or are made of to support learners in being active agents in their learning processes by enabling them to tinker and design (Resnick & Rosenbaum, 2013).

In this study, I looked at materials and design that can be personally meaningful for learners. The definition of what is personally meaningful will vary from person to person, as it involves subjective experiences of each individual and what they consider meaningful for themselves and others. Following a constructionist approach, learners design personally meaningful projects, which can range from sandcastles and poems, to programs (Resnick, 1996). I used tangible personal artifacts of the participants in this study to guide their personal project. These artifacts are objects that they bring from their personal lives, and represent stories and connections to their histories. Pahl & Roswell (2019) argue that these artifacts can connect personal histories to the learning experience of learners by incorporating them into their learning process. In this study, I used tangible personal artifacts to create personally meaningful projects and foster engineering design practices.

This study focuses specifically on engineering learning. Hernandez-De-Menendez et al. (2020) states that engineers need to be prepared for the challenges of today’s world, where pedagogical strategies across curriculums need to evolve to implement approaches that include active learning, research-based learning, and experiment-based learning to name a few. Constructionist approaches to engineering education may help young learners to understand engineering concepts through personally meaningful projects and materials that allow them to construct their learning experiences. These approaches have been explored, for example, through makerspaces, where learners can create and interact with technology in a hands-on approach (e.g., Peppler, 2016). Makerspace approaches explore how working with or next to peers, and making with objects that matter to the learners, provides an engaging and impactful environment. For instance, Tan (2019) describes the implementation of constructionist approaches in a makerspace, where the implemented design used debugging and reverse engineering of problems as an approach. Within this framework, different materials have been studied towards engaging all students. One of the contexts where constructionist approaches to engineering education could be used is using sound as a material in sound making activities.

2.3 Sound as a context for engineering education

Sound is one context for engineering education. In the context of this study, I used sound as a material in sound making activities. For this, sound needs to be understood as a material, although not completely. Sound can be created by tapping your fingernails on your table, by talking, by singing, or playing an instrument. But at the same time, we cannot touch sounds like we would touch other "more physical" objects. For this reason, Wargo (2018) describes sound as a quasi-object, an object that carries meaning. Sound and auditory sensing is then a material that is familiar to most. It is everything around us for the hearing abled. Sounds can tell and narrate a story, just like artifacts. The alarm clock, shuffling of the sheets, birds chirping, the coffee brewing, the shower running, a cat meowing. For me, that tells the story of a morning routine back when I lived with my family. It brings back memories, smells, touch, and emotions. Some sounds can connect us with deep rooted memories and experiences, and, therefore, be deeply personally meaningful.

Beyond these personal impressions, researchers have also considered sounds as a design element. For example, Cambrón (2005) explored the methodology of sound postcards, in which a written letter is replaced by a sound message and the postcard creator must think about what sounds to include that represent a place. Rodríguez-Sánchez et al. (2018) implemented this methodology with victims of armed conflict in Colombia and concluded that sound can be a powerful tool for recalling and telling a life story because we can connect these sounds to meaningful moments of our life. In the medical field, patients with Alzheimer's Disease have been treated with Music Therapy to regulate emotions and enhance cognitive capacity (Matthews, 2015), because they are able to preserve songs connected to memories and emotions (Woods, 2018). This suggests the potential of sound as a personally meaningful material that we can use in education.

Sound has a wide array of implementations in educational settings, ranging from simple pneumonic devices to understanding the deconstruction of classical pieces with mathematical models (Agustín-Aquino & Mazzola, 2019), and the explanation of mathematical concepts through musical representations of a pangolin's armor (Mannone, 2019). Efforts are now being made to implement music, not only as a learning tool for STEM disciplines, but to combine both to encourage learning in music, STEM and have creative outcomes. Projects such as EarSketch, developed by researchers at Georgia Tech, allows users to create songs through programming, teaching basic Python skills and engaging participants to create songs with samples from known artists and their own samples (Im et al., 2017). Another example is the Algorave movement, which uses programming software that aims to have live performances, with code projected on a screen, to show how the music is being made in real time (Collins & McLean, 2014). The Cinderella software has also been used to teach mathematics using programming for MIDI and algorithms as music outputs (Richter-Gebert & Kortenkamp, 2012).

In this study, I understood sound as an OTTW, a material that connects learners to personally meaningful experiences through representations of their own tangible personal artifacts. Here, representation is defined in its most literal sense, only used to portray interpretations of artifacts into sounds.

3. Methods

The aim of this qualitative study is to identify and test a design for youth to practice engineering design through sound making by designing with electronic construction kits. Sound making is an activity that involves creating sounds inspired by tangible personal artifacts with conductive materials such as conductive paint, copper tape, conductive thread, high graphite density pencils (10B), playdough, and kits that make it possible to produce electronic sounds, such as Squishy Circuits, the Playtronica Playtron, and the littleBits KORG Synth Kit. To develop the design, I followed three phases of iterative workshop design: (1) Material and artifact explorations to identify the affordances and constraints of different sounds making materials that could inform the design of a sound making workshop, (2) a pilot workshop with adults that engaged with kits and materials identified in phase 1, and (3) a workshop in a school with two groups of 10 and 11 ten-year-old students. These three phases addressed the research question by looking into affordances and constraints of materials and sound kits for sound making activities using tangible personal artifacts.

This study used a qualitative research design, which gave a more in-depth look into how sound making materials connect to engineering design principles. In phase 1, the material explorations were analyzed through reflection reports on the materials and sound making kits used. In phases 2 and 3, the workshops, video data was analyzed using narrative summaries that looked into the experience of the participants through the workshop and their behavior. In phase 3, the workshop with youths, I asked the participants about their prior experiences with making and crafting through a semi-structured interview protocol, which allowed them to externalize their creation process. In the third phase, artifact analysis focused on the creations of the participants, detailing their creations and how they connect to both their tangible personal artifacts and their engineering practices during the session. Table 1 shows an overview of my methodological approach.

Table 1
Methodological overview of the master thesis

Phases	Research questions	Data sources	Analytical Techniques	Expected outcomes
Material Explorations	What conductive and non-conductive materials support personal projects and engineering practices in sound making activities?	Reflection Journal (5 pages) Pictures (16 photographs)	Affordances and constraints analysis of materials and sound making kits (Greeno, 1994)	Identifying materials and kits that could be implemented in workshops.
Adult Workshop	What sound making kits and materials support a sound making activity, and how do tangible personal artifacts help the design to foster engineering practices?	Video Recording (100 minutes) of workshop session.	Affordances and constraints analysis of sound making kits, materials, and activity design with a focus on using tangible personal artifacts (Greeno, 1994).	Selecting kits and materials most appropriate for a workshop with youths. Confirm the usefulness of tangible personal artifacts for personal projects
Youth Workshop	How does sound making with electronic construction kits support personally meaningful	Video recordings of two sessions with each group (280 minutes total): Narrative transcriptions	Iterative and thematic analysis of sound making kits (Morgan & Nica, 2020).	The kits will provide a varying degree of tinkerability, and therefore engineering

	engineering practices for middle school students?	and coding of engineering practices of each case. Video recordings of semi structured interviews of each participant (123 minutes): Verbatim transcriptions of the interviews.	Coding of engineering design practices (Creswell & Creswell, 2017).	practices through sound making. The tangible personal artifacts will play a key role in guiding the activity.

For this study, I used a range of conductive materials, including those typically used in combination with the selected off-the-shelf construction kits as well as materials that are supportive of sound making that were included in the kits. Materials for sound making varied in complexity, including buzzers that produced high pitched sound and Musical Instrument Digital Interface (MIDI) controllers that could be programmed to play several tones and songs. In section 3.1.1, I will provide an overview of these kits and how they have been used in the past. This is important to understand the reason for particular design decisions for the conducted intervention (e.g., combining the conductive and input/output sensors of different kits). I also chose to use a range of conductive materials from different kits, detailed in the following section, to provide different resistance levels for participants to interact with and produce different sounds, as well as supporting creative approaches to personal design.

3.1 Research settings and participants

3.1.1 Research settings and participants: Material explorations

Part of the material and kit explorations took place in my kitchen and in the Computational Crafting Lab (CCL) at the TUM Makerspace in Garching. The CCL is a Makerspace that was designed as a space that supports research and design to advance gender equitable approaches in materials for STEM learning as well as the development of teaching materials. The lab was built during the first quarter of 2022 by the research group under the Learning Sciences and Educational Design Technologies professorship of Prof. Dr. Anna Keune, of which I am part of. The lab intends to provide a user-friendly design for its participants, as we intended youth to be the target audience for it. Figure 1 shows an overview of the lab in a panoramic picture.

Figure 1

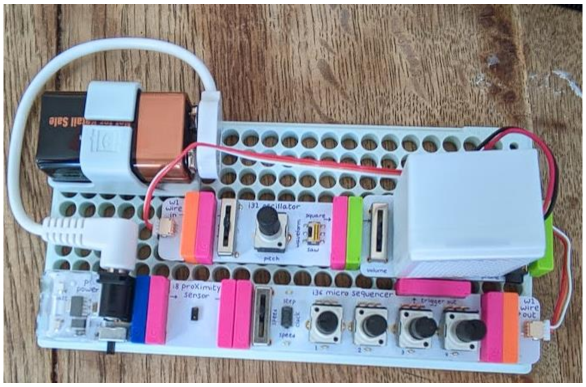
Computational Crafting Lab in the TUM Makerspace in Garching

Some of the proposed conductive materials for the kits involved fruits, therefore a kitchen space provided a good exploration space. I used my home kitchen to do these fruit explorations. The rest of the material explorations involved creating mixtures with glue and paint, as well as implementing different creation kits that the CCL provided. During this phase, I was the sole participant engaging with the materials. Nevertheless, I was able to reflect on and discuss my ideas with my supervisor and the members of the research lab as well.

I explored different kits and materials that could possibly be implemented in a workshop environment. The **littleBits KORG Synth kit** was the first consideration to implement into the workshop. The littleBits KORG Synth Kit is an electronic construction kit made from both the companies littleBits and KORG. The kit uses littleBits modules that have the capability to connect with one another through magnets on their sides, allowing for easy interaction when connecting its pieces (Bdeir, 2009). The kit's modules recreate the different parts of a synthesizer through color coding of Input (Pink), Output (Green), Wire (Orange), and Power (Blue). The Output module is a speaker with volume control, and the Power module is a switch that connects to a battery. The Wire module allows for connecting three inputs, providing more creative opportunities. The Input modules are where the sound inputs play with and modify the sounds. Keyboard, oscillator, and sequencer modules make for most of the building opportunities explained in the user manual, but more complex connections of six or more input modules are possible. This kit allows its users to quickly create sounds, beats, distortions and other features of synthesizers. Figure 2 shows how this kit looks when built.

Figure 2

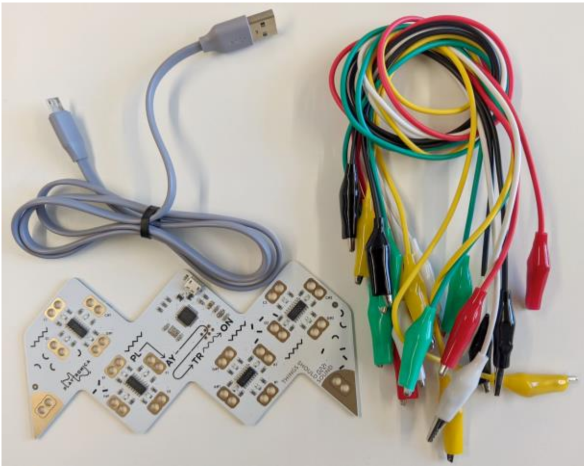
littleBits KORG Synth Kit sequencer, oscillator and proximity sensor



Next, I investigated the **Playtronica Playtron**, which is a MIDI controller that can be connected to a computer or smartphone in order to play an instrument, often a piano. The kit features 16 different outputs that represent 16 different keys from C major to D# major in the next octave. Each of the 16 outputs can be connected to conductive materials that send a binary signal of a key being pressed or not. A common example set up is to connect the 16 points through alligator clips to vegetables and/or fruits to play them as instruments after grounding oneself (*Playtronica*, 2022). This kit works with conductive materials, and, thus, provides an interesting option to experiment with sound creation and the three selected conductive materials (i.e., conductive thread, copper tape, and conductive paint). Figure 3 shows the Playtron, the alligator clips and the USB cable it comes with.

Figure 3

Playtronica Playtron



I investigated different conductive materials that could interact with the Playtrons and the other kits in order to expand supporting engineering practices:

(1) **Conductive Thread** is a material used in a construction kit for sewing circuits and programmable computational components into fabric. Using sewing as a main technique, it leverages familiar materials such as a sewing needle, thread, and fabrics, while combining it with electronic components such as microcontrollers, LEDs, sensors, and batteries. The main connector in this kit is the conductive thread, a silverized thread with a resistance of approximately 50 Ω/m. The conductive thread connects power sources (coin cell batteries) and electronic outputs (LED lights, buzzers, light sensors and others) through sewing (Buechley, 2008). In education, it is connected with learning outcomes such as polarity, connections, and current flow (Peppler & Glosson, 2013), has had impact on who engages with such circuitry concepts (Buchholz et al., 2014) and is argued to broaden interest in computer science (Kafai et al., 2019). Its wearable possibilities enable learners to creatively implement personalized and personally meaningful designs (Kafai et al., 2014). I decided to use conductive thread for the activity design with sound to increase the interaction possibilities, including sewing, knotting, and weaving sound-making

projects. This material was not offered alone, I also included needles that the participants could use to sew into their projects.

(2) **Copper tape**, normally used in Chibitronics, provides sticker-based electronics components (e.g., LED lights) with which one can create circuits on paper whether flat or folded in 3-dimensions. Similarly, this toolkit connects LEDs, sensors, and microcontrollers, and batteries using conductive tape, such as copper tape or conductive fabric tape (Qi et al., 2015). In education, Chibitronics has been used to teach literature and/or social reciprocity through interactive storytelling (e.g., Dinc et al., 2021; Li & Kang, 2021), and moving crafting communities forward towards better gender equity in STEM (Qi et al., 2018). Compared to the conductive thread, the copper tape allows for full conductivity because it is a solid metal spread across a surface (*Chibitronics*, 2022). I decided to use the copper tape as another conductive material that could support creative explorations in personal designs in my workshop that provided low resistance connections in the projects.

(3) **Graphite based paint and pencils** were used as additional conductive materials that would support personal explorations for design. Both use graphite as the base conductive material. The pencil can easily draw any design, but needs various layers to reinforce for conductivity. The paint is generally very conductive, but it is harder to design with it as it is liquid, and it needs time to dry afterwards. Initially, I used Bare Conductive paint, as seen in Figure 4, testing to connect a circuit using a coin cell battery and a Chibitronics LED sticker.

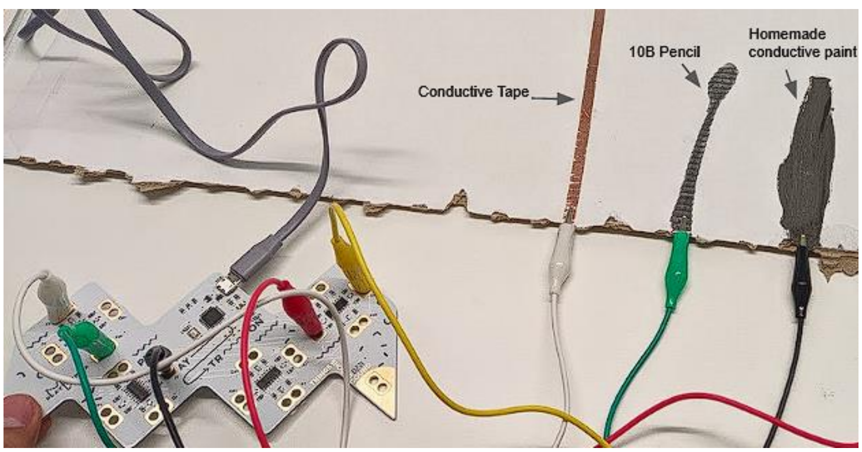
Figure 4

Circuit using Bare Conductive paint to turn on a LED light in a name tag

Further explorations were made with a “do it yourself” (DIY) solution to replace the Bare Conductive paint by mixing graphite powder and school glue for more affordable solutions. This was tested together with the copper tape and 10B graphite pencil with the Playtron. Figure 5 shows the test where the materials are compared side by side.

Figure 5

Homemade conductive paint, copper tape, and 10B pencil with Playtron



Lastly, I explored the **Squishy Circuits kit**, which uses a conductive molding compound (i.e., playdough) to create circuits (Johnson & Thomas, 2010). The kit includes buzzers, motors with attachable propellers, battery packs, and on/off switches which allows for a creative approach to circuitry building activities in early childhood education due to its open-ended creations and parts that are large enough to support the dexterity of younger children (Thomas et al., 2020).

Peppler et al. (2019) show how Squishy Circuits can afford transparency into understanding circuitry concepts in early childhood education. This kit uses a battery pack with positive and negative ends with colored red and black cables. These connect through conductive materials to a buzzer, motor, and on/off switch to work. The Squishy Circuits buzzer creates a loud beeping sound. In my own material explorations, I was able to identify that the buzzer in this kit can have different degrees of loudness depending on the resistance of the material being used to activate it, which provided an opportunity to combine with the conductive thread, copper tape and conductive paint to create a variety of sounds. The playdough was a useful material, whereby using more or less of it, or stretching it as a long line could allow for tinkering with the buzzer's volume. I tested how the buzzer's sound could change when used with the other conductive materials. Figure 6 shows the materials included in the kit and additional playdough manipulation tools for personal design.

Figure 6

Squishy Circuits Kit with playdough "baking" materials

3.1.2 Research settings and participants: Adult workshop

This workshop took place at the CCL (see Figure 1). This space provided all the materials and space for the first trial of this workshop with participants. The participants were adults in an age range of 22 to 32 years of age who volunteered to take part in this study. The participants were four women and two men (self-identified). Four of the participants were master's degree students in teaching and learning research, one of the men was working in management and one woman was in biology research. All participants were recruited through my personal network.

The material explorations helped me choose which materials would be suitable for the workshop with youth. Two participants used the Playtron with conductive paint, conductive thread, copper tape, and pencils. One participant used the littleBits KORG Synth Kit alone. And three participants used Squishy Circuits with the same conductive materials as the Playtron. Additional non-conductive materials were used to set up their projects such as scissors, tape, cardboard paper, etc. The participants were instructed to create music, a sound, or an instrument that would represent their tangible personal artifacts they brought. Participants were introduced to basic concepts of circuitry regarding polarity with a Squishy Circuits explanation. For the Playtron and littleBits users, I explained individually how they worked. Then, they had 45 minutes to work on their projects. Finally, they provided feedback on the experience in a discussion format, where I would ask one question and anybody could answer and contribute.

3.1.3 Research settings and participants: Youth workshop

The youth workshop took place in a Junior Maker Space at an international school in Bavaria. This international school is a private school that uses the International Baccalaureate (IB) curriculum, which is an international program for schools that has English as a primary language and allows students to apply to universities all around the world with this high school diploma. The school hosts international students from 65 nationalities who speak a total of 48 different languages. The school has open enrollment based on need; this means that potential applicants can start school at any moment during the year. Unlike the free public education in Germany, tuition fees range from €11,500 for half a day in preschool to €23,000 per year in grade 12. Students unable to pay full tuition may apply for a reduction in fees, as long as they are already admitted or currently enrolled, but this reduction is not guaranteed. Additionally, having English as a primary language also allowed me to conduct the activities, as my German skills are still in development.

The intervention took place in the Junior School Maker Space of the school. The space was equipped for crafting activities where the students could choose to work on the floor or on tables, walk freely around the room and select from a wide variety of items to add or modify their creations (e.g., glue sticks, paint, glue guns etc.). Figure 7 provides a panoramic picture of the space. This school has had a Maker Space for 5 years and has implemented maker methodologies for the students. The space is often accompanied by an Instructional Coach, that emphasizes on his role that transitioned from teaching basic tech skills to a co-teaching and collaboration methodology with the students.

Figure 7

Junior Maker Space panoramic picture

Two groups of ten-year-old students in Grade 4 participated in this intervention in two sessions each over the course of two days. The first group included 10 students and one of the participants did not participate in the second session. The second group included 11 students, and three of the participants did not participate in the second session. The students had varying levels of experience with the materials provided in the Junior Maker Space, as the space is not used as part of a specific subject taught in their curriculum. Rather, teachers can book the space for their students to work in for particular projects. Students may also conduct personal or after school projects at the Junior Maker Space like the "Tech Team", which is a student-run club focused on technology-related projects and teaches other students how to use apps such as video taking, notes, video conferencing and others. Thus, students in this school are familiar with Maker Spaces and crafting, but their degree of familiarity with the space may vary. All students know where to grab tools and materials as well as to put them back and clean up, always accompanied by an adult that can watch over or guide them depending on what material or tool they will use.

The participants engaged in music creation activities using conductive materials and electronic sound makers. The conductive materials included conductive paint, copper tape, alligator clips, conductive thread, 10B pencils, and Playdoh. As for the non-conductive materials, these included paper, tape, cardboard and among others. Participants had the choice on what materials to use. The electronic sound makers include the Playtronica Playtron, which is a MIDI controller that allows conductive materials to be attached to the board controller to play online synthesizers on web browsers or applications. The second sound making device is the buzzer from Squishy Circuits, a device that allows the buzzer to make a beeping sound when connected to its battery source through conductive materials.

For the activity, participants were asked to bring a tangible personal artifact. This instruction was meant to be made open and vague, so participants could interpret the instructions as they saw fit and choose something very meaningful to them. They were instructed to use the conductive and non-conductive materials together with the sound making devices to represent what sound (music or other) could constitute this object. This activity was carried out over two 75-minute sessions. The time was assigned on the availability of the school, as the activities took place on regular school days. Probing questions were asked throughout the activities. These questions obtained information about their previous experiences with crafting and making, and their creation process in the activity. Another section of the questions asked about how they engaged in the activity to identify their engineering design practices throughout the activity. Both sets of questions are found on section 3.2.3. Finally, I asked them individually to share their project with me, explain the meaning of their object and talk about how they represented their object with sound and materials. The youth worked in tables in the space, organized in a “round table” formation where they could see each other’s progress and creations. They were also allowed to talk with each other if they wanted to.

3.2 Data Sources

Each phase of data collection informed the decisions for the following phases. Different approaches were taken in each phase depending on the goal and the participants involved. Reflection protocols, video recordings, and pictures were the main data sources throughout this study across phases.

3.2.1 Data sources: Material explorations

This phase investigated the affordances and constraints of different materials and sound making kits. The material explorations were recorded through photographs and a reflection journal which was structured with questions that would allow me to describe the materials and kits used. It included the following questions:

- *What was your process?*
- *What challenges did you encounter?*
- *What went really well?*
- *What did you learn?*
- *What did the work remind you of / make you feel?*
- *What connections to computing did you experience?*
- *How is what you were doing different from computing?*

I captured five one-page reflections and a total of 16 photographs. Two reflections focused on using the Playtronica Playtron, one with fruits as a material and the second with Play-Doh as material. One was with the littleBits Synth Kit, one with Bare Conductive Paint, and the final reflection was on Squishy Circuits.

3.2.2 Data sources: Adult workshop

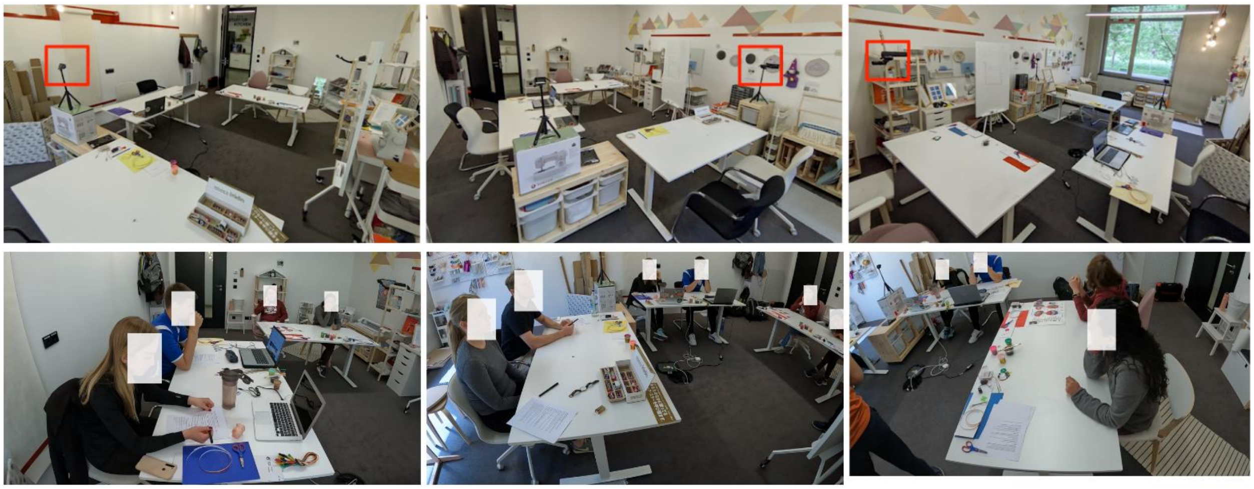
Three GoPro Hero 10 Black cameras (100 minutes) were set up around the CCL. Three tables were set up with one camera per each table that documented the session for two participants per table (Figure 7). The first half of the session documented the workshop activity, showcasing the participants' project creations. The second half of the session documented a feedback discussion where they presented their projects out loud, and then commented on the design of the activity itself by answering the following questions as a group:

- *What was your personally meaningful object?*
- *Why is it meaningful?*
- *Please share your project and how do those two relate?*
- *What worked well?*
- *What could others learn from this?*
- *What would you change?*

The participants joined one table as pairs with one camera focusing on one table and pair. This allowed me to see what the participants did throughout the workshop as well as listen to their commenting and responses throughout. Figure 8 shows the arrangement of the cameras in the lab and the point of view of each one.

Figure 8

Arrangement of cameras in the Computational Crafting Lab (red boxes) and their point of view below



3.2.3 Data sources: Youth Workshop

Three GoPro Hero 10 Black cameras captured a total of 280 minutes of videos and provided different angles to showcase the artifact building process, the conversations between the participants, and any thinking out loud, and non-verbal expressions. Figure 9 shows how the cameras were arranged in the space. Additionally, a phone was used to take pictures of the projects, closely record (123 minutes) the showcasing of their projects and the interview questions asked. Figure 9 also shows what each camera saw. I watched the video recordings multiple times to develop: (1) Narrative summaries of selected cases with a focus on how the youth interacted and developed their projects throughout the two sessions. This allowed me to detail their interactions with materials and progress in their projects. (2) Verbatim transcriptions of the semi-structured interviews and non-verbal communication descriptions were created to closely look at their projects, their showcases of them, and how they shared their learning experience. The semi-structured interview questions included probing questions and sharing questions. The probing questions were the following:

- *Do you have any prior experience with:*
    - *music/sound?*
    - *Engineering?*
    - *Computation?*
    - *Technology*
    - *Crafts?*
- *What sound are you trying to make?*
- *Are there any sounds you are trying to stop? What are they?*
- *How could you make your sounds louder?*

The sharing questions used were the following:

- *Could you tell me about your project?*
- *What are the different parts of what you made? How did you put it all together?*
- *What do these parts do?*
- *What did you do to get here / to where the project is now? How did you make your project?*
- *Why did you choose your personal object? What is your personal object? Why did you bring / select it?*
- *How does your personal object relate to your project?*
- *What worked really well?*
- *Were there any surprises or challenges?*
- *What did you learn?*
- *What do you think people could learn from doing this?*

Figure 9

Arrangement of the point of view of each camera and placement in the space

3.3 Analytical Techniques

The three phases of this study used different analytical techniques to answer the research questions described within Table 1. The material explorations focused on reflections and colleague feedback, while the workshops followed narrative summaries and transcriptions of the sessions. The analytical techniques used in each phase helped build the next one. The first two phases investigated affordances and constraints of materials and kits used in sound making activities to inform the design of the youth workshop. The third phase focused on investigating sound making through personally meaningful design for engineering practices, and how the Playtron and Squishy Circuits kits supported this.

Analytical techniques: Material explorations – The pictures and reflection journals were analyzed and shared with the Computational Crafting Lab team to identify affordances and constraints of the materials and kits used. The kits and materials were tested for their suitability as building materials and their possibility to combine them with the sound making kits. This meant testing for their conductivity and ease of use. These affordances and constraints were discussed in a feedback loop to try different approaches (e.g., using DIY conductive paint and graphite pencils instead of Bare Conductive paint). This guided what materials and kits to use for the adult workshop as a pilot for the youth workshop.

Analytical techniques: Adult workshop – The data source provided a detailed look into the activity design. (1) Summaries of the participants' projects were made and put into slides to look into how they implemented their tangible personal artifacts into their project as well as how they experimented with the materials for their sound making projects. (2) Notes were taken from the feedback part of the activity, where participants commented on how the activity developed and recommendations they could provide, as well as possible affordances and constraints that they experienced with the kits. The results were presented with the research group at the Computational Crafting Lab to analyze and implement the feedback for the youth workshop. This developed a second iteration of the analysis for affordances and constraints in both the materials and the kits.

Analytical techniques: Youth workshop – I conducted iterative thematic analysis of the data through looking at the video sessions at least five times and describing the events with narrative and verbatim summaries. This approach allowed me to review the data and identify common themes. I used NGSS to code engineering practices that were present during the session in each case. Each case was reviewed at least once to identify codes that were present throughout the session. This meant listening to the conversations the participants had with themselves and each other, their interactions with materials and kits, as well as how their projects developed. This presented comparisons between the different cases and the two sound making kits used. Table 2 presents the codes selected for this purpose, which focus on the middle school level of Engineering Design Practices and Core Principles taken from NGSS. I also examined these themes and data with the tangible personal artifacts and their personal projects, if the participants used their tangible personal artifacts, and how they used them throughout the session to guide or not their tinkering.

Table 2

Next Generation Science Standards codes selected to observe Engineering Design Practices

NGSS Standard	Definition
MS-ETS1-1. Engineering Design	Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
ETS1.A Defining and Delimiting Engineering Problems	The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful. Specification of constraints includes consideration of scientific principles and other relevant knowledge that is likely to limit possible solutions.
ETS1.B Developing Possible Solutions	A solution needs to be tested, and then modified on the basis of the test results in order to improve it.
ETS1.C Optimizing the Design Solution	The iterative process of testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution.
MS-ETS 1-1 Asking Questions and Defining Problems	Define a design problem that can be solved through the development of an object, tool, process or system and includes multiple criteria and constraints, including scientific knowledge that may limit possible solutions.
MS-PS3-3 Constructing Explanations and Designing Solutions	Constructing explanations and designing solutions in 6–8 builds on K–5 experiences and progresses to include constructing explanations and designing solutions supported by multiple sources of evidence consistent with scientific ideas, principles, and theories. Apply scientific ideas or principles to design, construct, and test a design of an object, tool, process or system.

MS-PS3-4 Planning and carrying out investigations	Planning and carrying out investigations to answer questions or test solutions to problems in 6–8 builds on K–5 experiences and progresses to include investigations that use multiple variables and provide evidence to support explanations or design solutions. Plan an investigation individually and collaboratively, and in the design: identify independent and dependent variables and controls, what tools are needed to do the gathering, how measurements will be recorded, and how many data are needed to support a claim.
MS-PS3.C Relationship Between Energy and Forces	Models can be used to represent systems and their interactions—such as inputs, processes and outputs—and energy and matter flows within systems.

4. Results

4.1. Material explorations: electronic and physical sound outputs with and without conductive materials

The material explorations included unpacking the kits, exploring the content of the materials they came with, and building projects suggested by the boxes, as well as building projects in creative ways. It also included analyzing how well they connected with each other and how they may support engineering learning through sound making. I tested various materials, both conductive and non-conductive and analyzed their sound making possibilities. Here I looked at the Squishy Circuits kit, the Playtronica Playtron, and the littleBits KORG Synth Kit and how they created sounds and connected to conductive materials (i.e., copper tape, conductive thread, conductive playdough, 10B pencils, and conductive paint). Table 3 summarizes the three kit's engineering design practices possibilities, their possibility to connect with conductive materials, and their sound outputs.

Table 3

Sound construction kits, their connection with materials, their engineering practices possibilities, and sound outputs.

	Engineering design practices possibilities	Connection with materials					Output sounds
		Copper tape	Conductive thread	Conductive playdough	10B pencils	Conductive paint	
littleBits 	Tinkering and troubleshooting through sound making in the kit	No connection	No connection	No connection	No connection	No connection	Electronic sounds created from the device and output from the device
Playtronica 	Tinkering and troubleshooting in the kit and with other materials	Could connect	Could connect	Could connect	Could connect	Could connect	Electronic sounds created from the device and output on another device (e.g., laptop)
Squishy Circuits 	Tinkering and troubleshooting in the kit and with other materials	Could connect	Could connect	Could connect	Could connect	Could connect	Electronic sounds created from the device (i.e., buzzer) and physical sounds from movable objects (e.g., propeller fans hitting a surface)

The three kits worked differently for engineering design practices through sound making. The littleBits kit provided different electronic sounds that would depend on the structures built with its modules, allowing for tinkering and troubleshooting in sound making. The Playtron relied on both additional materials and an output device (e.g., a laptop) to trigger the sounds created. Having to both explore materials and interact with an external device allowed for tinkering and troubleshooting as well. The Squishy Circuits kit provided electronic (i.e., the buzzer) and physical (e.g., propeller hitting other objects) sounds, allowing for tinkering and troubleshooting to create soundscapes. Furthermore, all three kits had varying degrees of interaction possibilities with conductive materials (i.e., copper tape, conductive thread, conductive playdough, 10B pencils, and conductive paint). This was important because it allowed the kits to tinker with materials that could potentially modify their sounds through experimenting with resistance as well as allowing for additional ways to implement conductivity through the kits. The littleBits kit worked with magnetic modules, which restricted its conductive material interactions, where none of the materials could be connected to interact with it or the sounds. The Playtron initially suggested fruits and vegetables as materials (see Figure 11), but I decided to use copper tape, conductive thread, conductive playdough, 10B pencils, and conductive paint as the main materials to output a sound in this kit as it would provide different material explorations and would not incentivize wasting food. The Squishy Circuits kit, despite its initially limited sound-making capabilities compared to the other two kits, allowed for deep exploration and design through its physical connections with conductive materials, resistance experiments, and physical sound making through movable objects.

4.2 Adult workshop: conductive materials and tangible personal artifacts for engineering design practices.

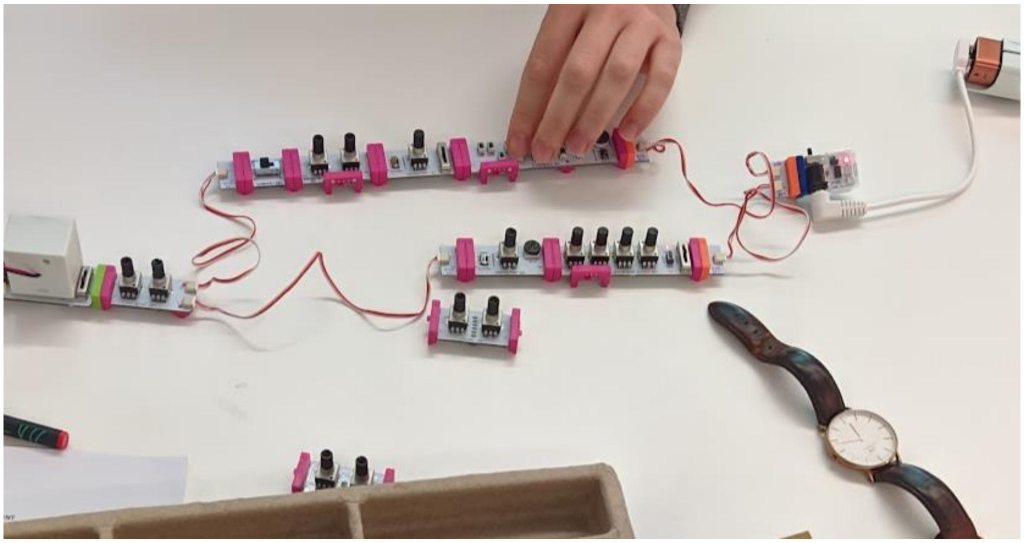
The workshop with adults informed the design of learning activities for youth. I wanted to see whether the possibility of connecting conductive materials makes a difference in terms of engineering, and how participants would use their tangible personal artifact. Thus, I analyzed the adults' engagement with the littleBits KORG Synth Kit, Playtronica Playtron, and Squishy Circuits kit by looking at six adults in a video recorded pilot workshop. Additionally, I asked them to bring a tangible personal artifact that they could use to inspire their sound making projects. I identified two major themes to inform my workshop design with young people. These themes were: (1) the combination of kits through a range of conductive materials more prominently available, which shows the construction possibilities of personal projects when making available a wide array of creation materials (conductive and non-conductive) for sound creation, which in turn increases engineering design practices engagement through material explorations and iterations on their projects, and (2) the introduction of a tangible personal artifact to guide the learning experience, which gave structure and meaning to the participants throughout the activity which deepened their engineering design practices engagement. This resulted in the omission of the littleBits for the youth workshop as it did not support the learning experience like the other kits did in this activity.

The conductive materials offered opportunities to combine, interact with, or represent their object with or through using the kit the participants had. Further, the conductive materials opened creative possibilities and ensured tinkering in the session while the participants worked on designing their personal projects. The littleBits kit allowed for representation of the tangible personal artifact, but its use was constrained when combining with other materials. The Playtron and the Squishy Circuits kits allowed for combination of materials and representation of the tangible personal artifact. Here I describe how the participants used the kits and engaged in the activities:

littleBits – Kara used the littleBits kit throughout the session. She brought a watch as her tangible personal artifact and worked on her kit to recreate it. There were many sound possibilities with this kit, as the synthesizer can create different beats and sounds, using usually no more than four-beat sounds that have limited variability. Kara tinkered with this kit, figuring out how to get it to work during the first part of the session. Once she understood the basics of how to make sound, she considered how to use this device to represent her object. Her object incentivized her to make a plan, and structure her kit exploration to build a sound that could satisfy the representation of her object. She combined different parts of this kit and explored the different, possible sounds. She finally chose the four-beat sound she thought would successfully represent her wristwatch. The timing of the beat was intentionally chosen to mimic continuous beats of a watch. She said that the sound would be very minimalistic due to the four-beat approach. *"So I made like a very minimal beat. [...] The other side is like the more melodic side, in like four-four time, so like the most boring time."* Figure 10 shows Kara's design and her artifact next to it. The lack of combination with other materials seemed to limit an iterative approach to her project, as she found how the kit could make sounds and stopped exploring other possibilities. She stuck to one design, and came up with one approach to represent her tangible personal artifact. This is probably due to the kit not allowing for other materials to be connected, and thus limiting iterations and material explorations for more sound possibilities.

Figure 10

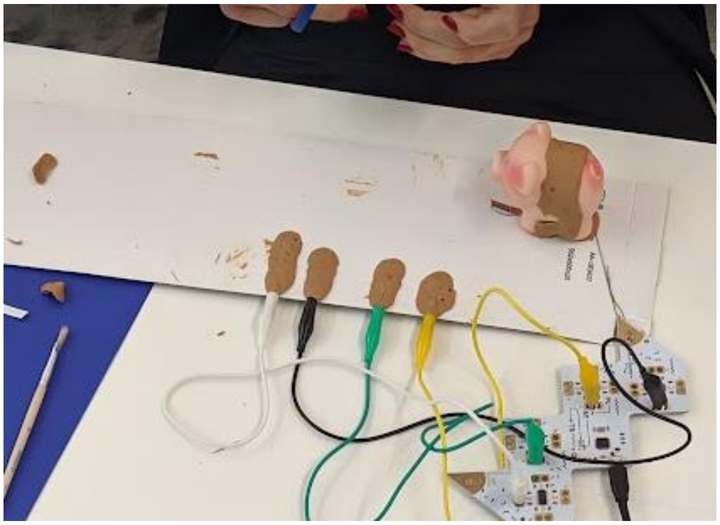
Kara showcasing her project based on her tangible personal object (the wristwatch)



Playtronica Playtron – Tobias and Molly used this kit throughout the session. Molly brought a small toy piggy bank and Tobias brought a pencil case. They interacted with the different materials available for them and integrated them into their projects. Molly used the conductive playdough as her main conductive material, but she did not use it as it is showcased in the Squishy Circuits examples (i.e., through balls that connect circuits), but as a sort of pseudo glue-paint (see Figure 11). She attached her tangible personal artifact to the Playtron with conductive thread as the ground, and then covered it with conductive playdough so she could play the keys she modeled with the playdough when she touched the piggy bank. As seen in this example, the Playtron allows different interactions of materials. In this case I saw conductive (i.e., playdough, thread, and alligator clips) and non-conductive (i.e., cardboard) materials being combined, which fostered engineering design practices through iteration and tinkering of her project.

Figure 11

Molly using playdough in her project



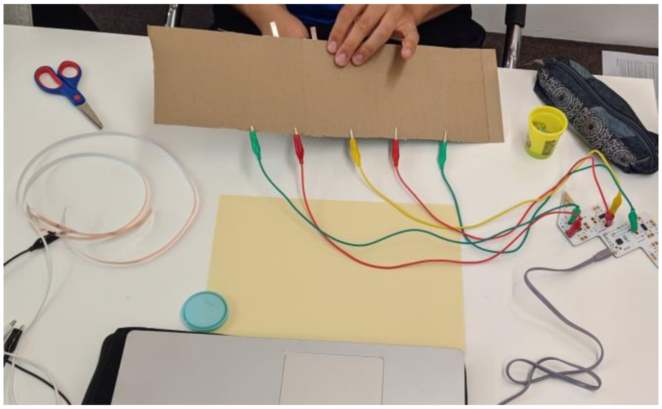
On the other hand, Tobias decided to use the conductive thread and sew through it to ground himself to the Playtron. With this, he was free to use his hands in playing his project. He used the playdough to draw lines that connected the alligator clips to the Playtron, and at the end of the line he used small pieces of copper tape to replicate keys. The keys connected in the kit represented a pentatonic scale, so it would sound pleasant in any way he played it. Tobias said his object was a gift from his friend that he carried around every day, and reminded him of his time as a bachelor student with his friends, saying:

> *"It was about the close bonds that you had. This is why it is [the alligator clips] colors are the favorite colors of my family members. I looked at what notes go into a pentatonic scale because it is the idea that no matter the combination you play them they always sound good. And this is the implicit meaning of, no matter what happens, when you have the right group of people, no matter who of them show up, you are gonna have a good time."*

He explained that the keys, as a pentatonic scale, meant that no matter the situation (combination of keys), being with the right people (pentatonic scale), everything would turn out alright. He focused on representing something the artifact made him think of, which was his friends during his bachelor studies. I observed the presence of engineering design practices while he represented his tangible personal artifact because this activity encouraged him to try using different materials, look for the correct keys on the computer, use different combinations of keys, and iterate on his project (see Figure 12).

Figure 12

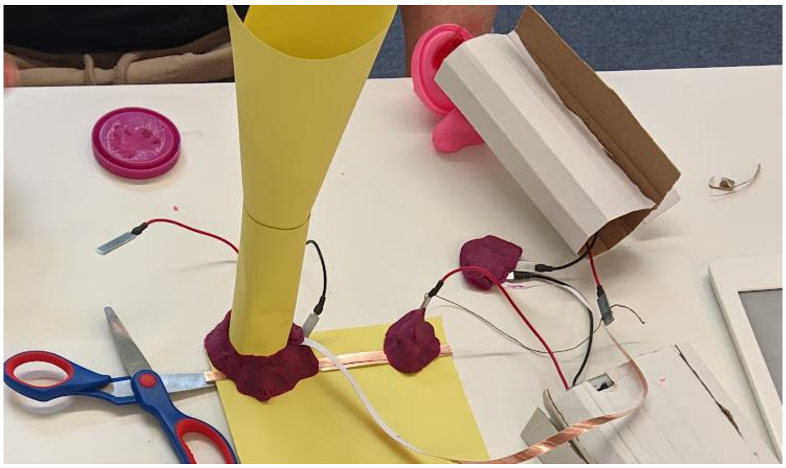
Tobias using the Playtron to represent a pencil case



Squishy Circuits – Todd, Alex, and Dalia used this kit throughout the session. Todd brought his e-reader, Alex a poster showing brain parts, and Dalia a necklace as their tangible personal artifacts. Here I will look at Todd and Dalia's projects. Although the Squishy Circuits only provided one clear sound making opportunity with the buzzer, Todd took two approaches to his sound project. First, he represented an alarm clock with the buzzer where he used some cardboard paper as a loudspeaker to direct the sound. He used conductive playdough, copper tape, and scissors to connect the circuit to replicate the alarm sound. Then he used the propeller, supported by a piece of cardboard and the playdough lid against it, to replicate a soft fan sound that would represent his bedroom fan that is always on when he reads at night. He was able to explore different designs and experiment with various approaches to optimize and advance his project. This meant he was able to engage in engineering design practices through his material explorations, guided by his tangible personal artifact. Figure 13 shows his final creation.

Figure 13

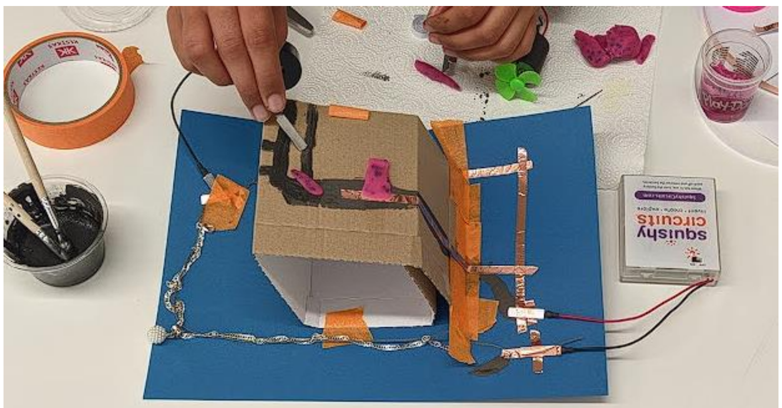
Todd's project using the buzzer and the propeller



Dalia had a similar approach to Todd, where she experimented with most of the materials available to her. She used the conductive thread to sew through her necklace, and raised a small cardboard box that tied her circuit with conductive paint, conductive thread, conductive playdough, and copper tape (see Figure 14). She explained the necklace was a gift from her father that she received before moving abroad, and on that day, she saw her father cry for the first time. She approached her task to create an instrument, and landed on creating a drum with the buzzer. Depending on where she would connect one end of the buzzer, it would make different variations of loudness and pitch, due to the varying degrees of resistance on the materials. She explained that the drums were the beating sound of the heart, and she connected this meaning with her artifact. Dalia was able to tinker with different materials and approaches for her project, engaging in iterations and troubleshooting throughout the session. This meant her project encouraged her to engage in engineering design practices, guided by the representation of her tangible personal artifact, which was similar to Todd.

Figure 14

Necklace combined with Squishy Circuits and conductive materials



Overall, the artifacts that participants brought to the workshop inspired stories that further propelled participants to engage in sound making and to iteratively improve their projects. A wristwatch represented beats and timing, while an e-reader represented the surroundings where the object was commonly used. The objects were different for each participant, and they had a different meaning for all of them. However they still allowed for the participants to stay on their projects and work towards them in a structured but personally meaningful way. They were able to iterate on their designs until the session ended. For example, Tobias mentioned that if the workshop was much longer, he would have kept iterating and making his project better for himself. This workshop also showed the possibility of the kits to connect to multiple conductive materials and how this allowed for iterative approaches to the projects. Both the Playtron and the Squishy Circuits kit allowed the participants to experiment with different conductive materials. This workshop informed what materials and kits to use for the youth workshop. The Playtron and the

Squishy Circuits kits were chosen to be used in the youth workshop due to their higher iterative and representation of the tangible personal artifact possibilities.

4.3 Youth workshop: manipulating sounds through conductive materials to foster engineering design practices.

During the workshop with youths, I investigated engineering practices using the Playtronica Playtron and the Squishy Circuits kit while facilitating the activities with the tangible personal artifacts of the participants. The Playtron, provided many high-tech possibilities with electronic sounds within the output device (i.e., the laptop), but it only had the option to trigger the output between on/off states. The Playtron encouraged most of its participants to use the digital tools it needed to work with, instead of interacting with the materials available (conductive and non-conductive).

Four of the 21 youths used the Playtronica Playtron and 17 used the Squishy Circuits kit. This workshop allowed me to see the affordances and constraints of the two kits, and the materials used to foster engineering design practices in the sound making activity. Table 4 shows a summary of the instances of NGSS Engineering Design Practices and Core Principles present in the two kits used in the workshop. The Playtron did not lead to as many different practices or as frequent as the Squishy Circuits kit. Table 4 shows two cases in Squishy Circuits and two cases in the Playtron as a comparison, but the rest of the Squishy Circuits kits showed similar trends in engineering practices.

Table 3

Next Generation Science Standards instances observed in Squishy Circuits and Playtron cases

NGSS Standard	**Squishy Circuits (two cases)**	**Playtronica Playtron (two cases)**
MS-ETS1-1. Engineering Design	1	0
ETS1.A Defining and Delimiting Engineering Problems	3	0
ETS1.B Developing Possible Solutions	12	4
ETS1.C Optimizing the Design Solution	28	4
MS-ETS 1-1 Asking Questions and Defining Problems	5	1
MS-PS3-3 Constructing Explanations and Designing Solutions	8	1
MS-PS3-4 Planning and carrying out investigations	2	0
MS-PS3.C Relationship Between Energy and Forces	2	0

4.3.1 Squishy Circuits: Physical sound tinkering as conducive of engineering practices

Physical sound tinkering involves using materials not usually involved in creating sound because it did not involve the buzzer in most cases (e.g., using moving objects to hit other objects). Three boys, Barney, Hewett, and Cornelius sat close to each other. Throughout the sessions they helped each other with suggestions and ideas, and figured out how the Squishy Circuits kit worked, by trying the different parts and possible arrangements. The three boys took a physical approach to their sound representations, by using materials other than the buzzer to interact with and create alternative, non-digital sounds. They established early on that the buzzer was too loud of a sound to be usable in their plans, and sought out alternatives. This is similar to the standard *Planning and Carrying Out Investigations (MS-PS3-4),* as they talked about their ideas, approaches, and tinkered with their projects. Although they talked with each other and shared ideas, they worked on their projects individually. Within the next section, I will discuss each of them.

Barney brought a pop fidget spinner toy as his tangible personal artifact, a small toy that has rubber, hollow half-spheres that can be pressed to make a popping sound as they pop to the opposite side (see Figure 15). When asked about why he chose the artifact, he mentioned he forgot to bring a tangible personal artifact, so he used what he had in his bag on the activity: "*Because it was in my bag. Because I forgot it was the day. And I thought it was going to be easier to, like, duplicate it with this stuff. It was proving to be more difficult than I thought."* Nevertheless, this object was meaningful enough to be featured in his project. This object made a popping sound, and he tried to make this sound with the materials throughout the sessions. Barney started out by trying different materials to make his popping sound (e.g., a toy xylophone). But these materials were not quite the sound he was looking for as he brought materials to the table multiple times and tried new ones after not getting the best ones for his design (see Figure 16). He looked through different boxes in the space to test different sounds. He ended up using the sound a metallic container makes when the lid is removed as his sound goal.

Figure 15

Pop fidget spinner

Note. [Pop fidget spinner toy product image] (n.d.) https://a.co/d/4Uu6hyE

Figure 16

Barney's four material explorations for his artifact representation: (1) Squishy Circuits buzzers with playdough, (2) xylophone being hit by the propeller, (3) propeller inside a plastic bottle, and (1) metallic can.

Barney then tried to achieve this popping sound remotely with the circuitry available. This is similar to the standard *Defining and Delimiting Engineering Problems (ETS1.A),* because he tested for a desired goal, and set out to solve it with the available tools. He drilled a hole on the bottom of the container, inserted the propeller, and tried using more than one propeller, more than one battery pack, and different lids to achieve his plan. This shows the standards *Developing Possible Solutions (ETS1.B) and Optimizing the Design Solution (ETS1.C)*, because he talked with his friends and instructor about his plans, strategies, and solutions to the problems that arose, and optimized his design throughout the process. Even though his final design could not complete his objective, as he opted for not using the sound of removing a lid as his design, he explained how he thought at first that the wind from one propeller would be enough:

> "*Well, first of all, I drilled a hole [in the can] with experimenting, putting the fan in. But I thought I was going to make a popping sound with air pressure. But then I realized it was going to be harder with a not very powerful fan inside this [the can]. And then so that I just thought if it was tapping on the side, it would work better than the lid popping."*

When this did not work, he tried alternatives and understood that his design would not allow for his desired result to come through due to not being airtight, the lid being too heavy, and the propellers not having enough force. This is related to the standard *Constructing Explanations and Designing Solutions (MS-PS3-3) and Relationship Between Energy and Forces (MS-PS3.C)*, because he reflected on the reasons his design did not have the outcome he expected, and developed an explanation on the relationship between air pressure and force. Barney finished his project tapping the side of the can with the propeller (Figure 17) and added the possibility of putting an ear inside the can for extra enhancement of the sound.

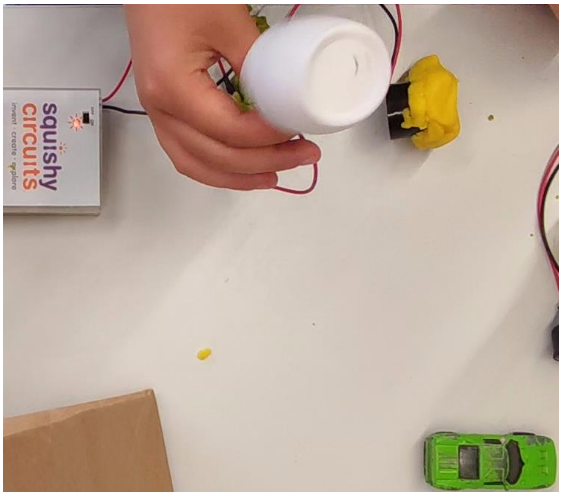
Figure 17

Barney's final project

Hewett mentioned his tangible personal artifact was the first gift he ever received, a small green toy car. He wanted to replicate the soft screeching sound of the toy car being rolled on the table. He started out by connecting various buzzers but, similar to Barney, after saying it was way too loud, he opted to use only one and filtered it to lower the sound, stating: "*This [buzzer], it's really annoying.*" This meant he wanted to use the buzzer but lower its volume for his design. He cut out a small plastic bottle and put it on top of the propeller, attaching it with some playdough. He filtered the sound of his buzzer in various ways with different materials (e.g., playdough, paper on top, playdough inside the buzzer), and tinkered with the plastic bottle design to get his goal sound. This is similar to the *Developing Possible Solutions (ETS1.B) and Optimizing the Design Solution (ETS1.C)* standards, as he quickly found a sound he thought was similar but continued to iterate his design to find the best possible solution. Hewett mentioned his iterations throughout the sessions *"I failed a lot at it. I just kept trying. It was hard, but eventually I did it. Yeah."* And the importance of troubleshooting: *"Well, mistakes worked pretty well because I didn't just give up,* *when it wasn't working. So that's pretty good."* Here he identified the sound he wanted to make from the start, and iterated on his approach to find his sound (Figure 18). This relates to the standard *Defining and Delimiting Engineering Problems (ETS1.A),* because had a goal from the beginning and worked throughout the session to achieve his goal.

Figure 18

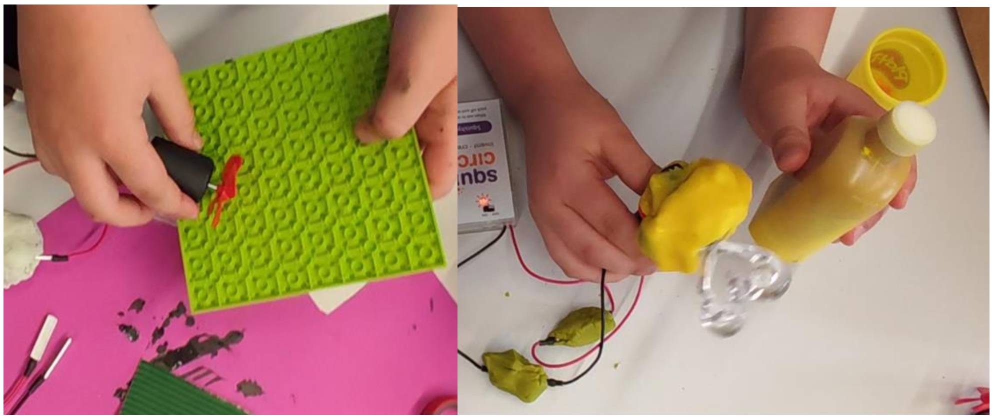
Hewett's final project



Cornelius brought a small glass penguin that his dad had given him from a trip to Hong Kong. He wanted to represent his glass penguin softly walking on the table. After quickly identifying the buzzer would not be accurate for his goal, he played with the propeller as a sound generating device. Initially he used the propeller to hit a piece of plastic (Figure 19) as he mentioned: "*I just thought instead of making a beeping noise like everyone else is doing, maybe use a motor to hit something."* Cornelius said that this design was not making a loud enough sound, he wanted to amplify the sound. This is similar to the standard *Asking Questions and Defining Problems (MS-ETS 1-1),* because he identified that one output was not the appropriate one, and that he needed to amplify the physical output of the propeller hitting plastic.

Figure 19

Cornelius's first (left) and final (right) designs



Cornelius then used a plastic object that resembled the penguin's material, attached it with clay to the propeller, and found a plastic bottle that it would hit. When at first using the bottle, he said the sound was not loud or satisfactory enough with an empty bottle. "[...] *so I thought maybe I fill this with water, and it didn't work. So, then I filled it with a harder fluid. And then I saw I needed weight on this, so I added with a bit of playdough, and then I saw I needed more so I added these [metallic balls] and then it would work."*. This relates to the standards *Developing Possible Solutions (ETS1.B)* and *Optimizing the Design Solution (ETS1.C)*, as he found a possible sound that could work for his goal, and iterated to optimize his result.

With this addition he arrived at his final design to recreate the penguin's walk, making a heavy object hit the filled bottle with a satisfactory final sound (Figure 18). Throughout the activity he mentioned that the materials did not always work, but that trying again and again was important to achieving results. This is similar to the standard *Planning and Carrying Out Investigations (MS-PS3-4)*, because he investigated what materials could help his project and carried them out throughout the sessions. When asked what would others learn from this, he responded:

"*I think they could learn to not give up. Because at first, I really could not get to make all the electric stuff work, and then I figured out how it worked. Then I kept trying and trying and found the right circuit I needed, the right pieces and then eventually I got it to work. So, I think trying again.*"

This shows how the activity allowed him to have an iterative process throughout. He tried different approaches, interacted with his classmates, and arrived at a design that he would find satisfactory. He explains that persistence will get you to a better result, which reinforced a troubleshooting cycle that was brought forward with the activity.

Engineering practices involved the process of defining problems when participants developed their own goals for their projects. They planned and carried out possible solutions, and tinkered with them to optimize the desired outcome. The Squishy Circuits kit brought forward engineering practices by allowing the three boys to take their own approach to the task. The kit did not limit them to using only one possible path, and encouraged them to tinker throughout the sessions.

This group opted to use the buzzer in a non-dominant role (like in Hewett's case), or discard it all together (like with Barney and Cornelius). The design of the sessions and the materials allowed them to tinker with their projects in creative ways. I never suggested discarding the buzzer, and some others in the rest of the group used the buzzers throughout the sessions. The Squishy Circuits kit provided creative alternatives to the task. The lack of modularity in the buzzer pushed this group into trying new approaches in their projects.

Their objects guided their work throughout, and provided guidance to their design and optimization process. Whenever they arrived at a possible solution, they went back to their object, compared, and made decisions to modify. Their object gave them a personal task that was meaningful to them to shape their work. Their object did not necessarily influence the design element of this process, it was however the sound these objects made, or represented, which turned their learning tasks into creative opportunities. They did not interpret only their objects, but also the sound they attached to it individually.

4.3.2 Squishy Circuits - Filtering sounds of buzzers as conducive of engineering practices

Filtering the sounds involved using different materials on top of the buzzers to modify and create new sounds. The three girls, Nina, Greta, and Vivienne, took a similar approach to their task. They were sitting at tables close to each other, but were not working together on their projects. They all shared during their interviews that the buzzers were too loud, and tried implementing different solutions to tinker with the sound it made. It seems that once one of them tried this approach, others decided to start trying to design their own version of it. Essentially, the three girls filtered the buzzers with different materials, and used different amounts of buzzers and methods of filtering. This is similar to *Developing Possible Solutions (ETS1.B)*, because they identified a task that had one outcome of solving it, and they all solved it in different ways.

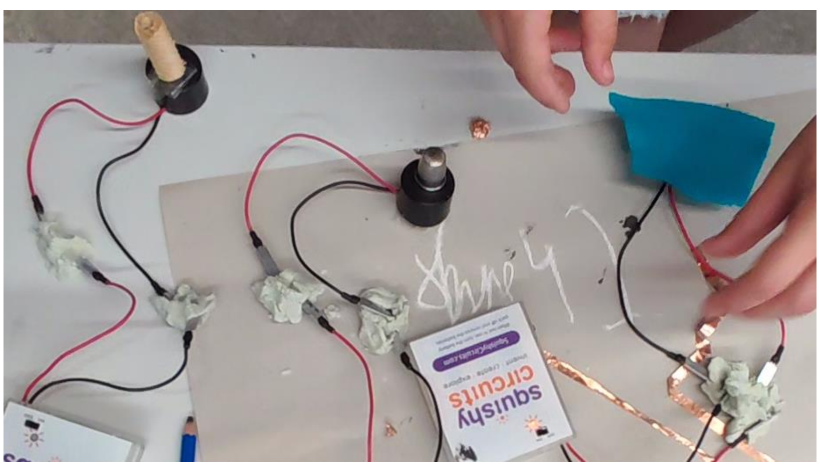
Greta forgot to bring a tangible personal artifact, but used one of the objects in the space as her guide initially. She picked a toy-sized mannequin that allows for joint movement. She did not integrate her object in her experiments, but she tinkered with the Squishy Circuits kit to understand how it works. This relates to the standard *Planning and Carrying Out Investigations (MS-PS3-4)*, because she investigated the materials and tried out how they could best work with her project in mind.

First, she tried with playdough, and once it worked, she experimented with other conductive materials as well. She settled for using the playdough, copper tape, and three buzzers.

Then she focused on using materials to filter the sounds. Greta managed to create three filters that are attached with tape and can be lifted and put back on with the tape: *"So this is high, low, and in the middle. I can take them off and on to make the different sounds. And what I'm looking for right now, is something to make a beat."* This relates to the standard *Developing Possible Solutions (ETS1.B)*, because she developed different ways to modify the sounds. In her case, she did not use an object to guide her design, and focused solely on tinkering with the sound. Greta could not make it to the second session, but seemed to inspire Nina and Vivienne to experiment with filters, as she was the first one to come up with this idea. Greta's design at the end of the first session can be seen in Figure 20.

Figure 20

Greta's final project with its filters

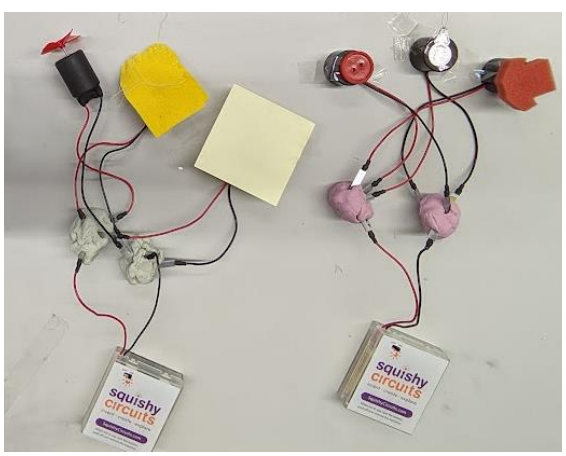


Nina brought a panda squishy toy as her tangible personal artifact. She mentioned she brought it because it encourages her to do things. She started out trying the Squishy Circuits kit with playdough, and used the propeller once she figured out how to implement the different parts of the kit. She set the goal of replicating the sound people make when seeing a cute panda like her object, a loud “Ahh!”. For this, she experimented using as many buzzers at a time as she could, and managed to use five at the same time. Nina was not bothered by using the buzzers, but did want to modify its sound so it would not be too loud. She filtered the sounds of the buzzers to create her own sounds. For this, she used fabric, a button, a piece of metal, a piece of paper, and some foam on top of the buzzers. This is similar to the standard *Planning and Carrying Out Investigations (MS-PS3-4)*, because she was able to carry out different approaches to her desired goal, tinkered with materials and figured out what worked best for her.

Nina mentioned it was challenging connecting everything, but that she eventually figured it out after trying a couple times. She explained that she wanted to see how the different filters modified the sound: “[...]*the sponge and stuff muffled the noises, because it was really really loud but this one [the sponge], it muffled it a bit.”* This is related to the standard *Optimizing the Design Solution (ETS1.C)*, because she experimented with different materials and found out which one worked best for her design. Nina finished her project showcasing the different buzzers with filters, as seen in Figure 21.

Figure 21

Nina’s final project with its filters



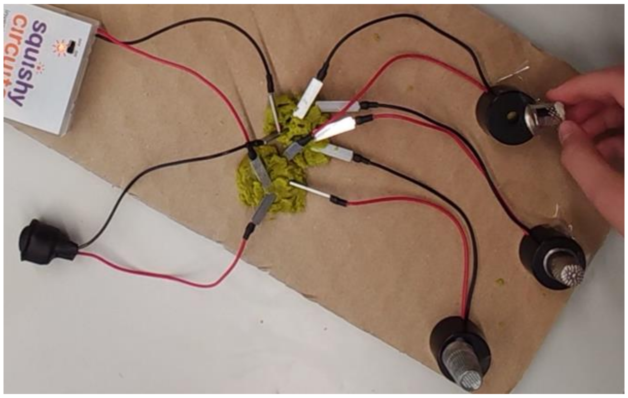
Vivienne did not bring her tangible personal artifact, because it would have been very challenging. She chose the instrument she plays as her object: the keyboard. From the start she wanted to recreate a keyboard with the Squishy Circuits kit. Vivienne experimented with playdough and the buzzers as her guiding sound tools. She opted for using sewing finger guards as her filters, attached with tape to lift them whenever she wanted to change from filtered to not filtered states. This is similar to the standard *Planning and Carrying Out Investigations (MS-PS3-4)*, because she investigated what materials to use to filter the sound and be able to manipulate it when raised. She described her tinkering process when asked about what worked really well:

> "*Well, in the beginning, it didn't work to turn it on and off. Now it's working. And I had a problem with the notes because when there is nothing inside [the sewing finger guards]. Then it don't make any sound. I needed to put something in there, so I needed to find the right thing."*

Vivienne here describes that using the finger guards was not enough of a filter for her design. This prompted her to experiment with different fillings for her finger guards and the tape allowed her to hear the difference between the sounds very easily. This relates to the standard *Optimizing the Design Solution (ETS1.C)*, where she experimented with choosing the best materials for her desired sound. Her design can be seen in Figure 22, where she showcases how the sound can change when lifting the finger guards in the different buzzers.

Figure 22

Vivienne's final project with its finger guard filters



Engineering practices involved tinkering with the materials throughout the session. The three girls took a similar approach to their task, and this prompted them to experiment with many materials available to them. They wanted to modify the very loud sound the buzzer made and represent the objects they brought (except in Greta's case, as she brought no object). They engaged in engineering practices through establishing a goal, developing possible solutions and optimizing through multiple iterations. The kit and the materials available brought forward many troubleshooting opportunities, while seeing their classmates interact creatively opened additional possibilities for them.

4.3.3 Playtronica Playtron - Digital soundscapes constrained engineering practices

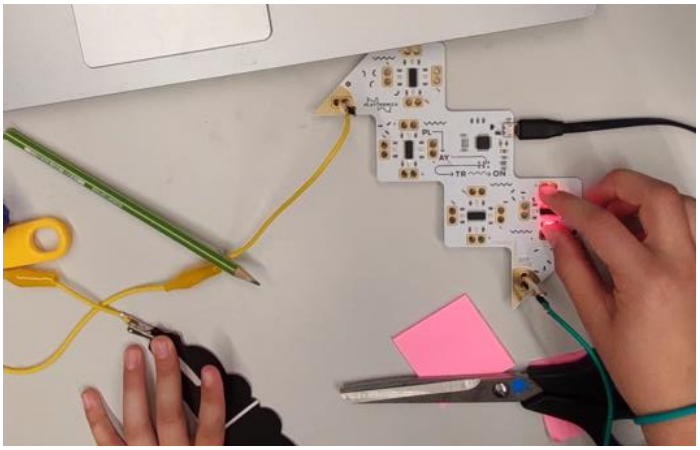
The participants using the Playtron were too involved in creating digital sounds with the laptop instead of tinkering with the materials and the kit, thus constraining their engineering practices explorations. Two girls, Sonia and Emma, sat next to each other and worked with the Playtronica Playtron. They focused mostly on using the computer to interact with the Playtron, and mostly disregarded the other materials made available to them (e.g., conductive playdough, conductive thread, conductive paint, and crafting materials). Although the activity was instructed to be an individual activity, both girls shared ideas to figure out how the Playtron worked and the different interface possibilities with the laptops.

Sonia brought a bookmark as her tangible personal artifact, mentioning she really likes reading. Emma on the other hand, did not bring any artifact in both sessions. They initially used alligator clips to interact with the Playtron after being explained how it worked. They soon figured out that through some combinations of using their fingers instead of the alligator clips. With them they could activate the input parts of the kit. This is similar to the standard *Developing Possible Solutions (ETS1.B),* as they developed one approach to address their task through tinkering with the kit. They mostly interacted with the laptops to look for synthesizers that could reproduce interesting sounds when activated via the Playtron.

Sonia and Emma seemed to be interested in recreating a song. They tried recreating a song by remembering how it sounded, but this proved to be too difficult, so they asked for permission to use a school iPad to search for songs. They browsed different songs, but chose not to recreate one at the end. They seemed to be fully involved in interacting with both the iPad and the laptops instead of the kit and the materials. I prompted them multiple times throughout the sessions with ideas about connecting the Playtron to other conductive materials, or to implement their tangible personal artifacts in their ideas or designs, but they did not engage with any. Their final design included playing a four note "danger" or "warning" sound with their fingers (see Figure 23).

Figure 23

Emma showcasing her project, playing four notes with her fingers



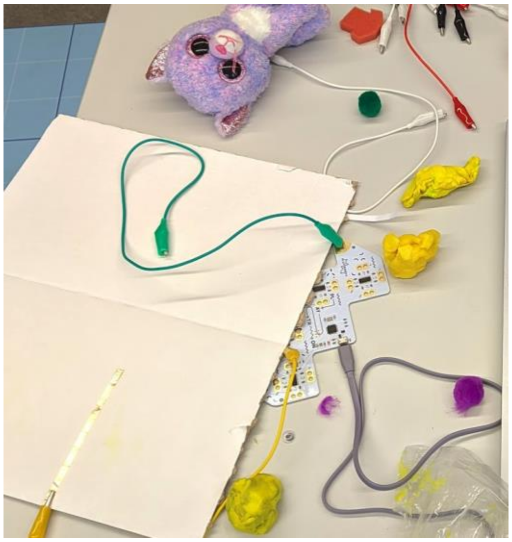
The two girls did not engage with the materials as their other classmates with the Squishy Circuits kit. They Playtron seemed to grab their attention fully, but at the same time made them forget about other material possibilities with the kit. The tangible personal artifact (in Sonia's case), or lack thereof (in Emma's case), did not incentivize them to guide their projects. The interaction with the materials and the connection with representing their tangible personal artifact was almost non-existent when compared with the Squishy Circuits users. This in its turn limited engineering practices possibilities, as the tinkering and problem-solving moments did not happen as they did with their classmates. This is not necessarily representative of all Playtron cases, as the adult workshop showcased more possibilities, as well as the following case with Sara.

4.3.4 Playtron - Binary materiality of sound kit constraining engineering practices

The binary materiality of this kit involved having only on/off states for input/output interactions with the kit, thus limiting further explorations that would allow for more engineering practices to be brought forward. Sara brought a small purple stuffed cat as her tangible personal artifact (see Figure 24). She explained that she really likes cats, and wanted to use the Playtron to make it sound similar to the cat. Sara experimented with materials, conductive and non-conductive, to find the best ways to represent her tangible personal artifact. Overall, she was the only Playtron user that engaged in both material explorations and guided herself with her tangible personal artifact.

Figure 24

Sara's tangible personal artifact and early stage of her project



Sara started out by using alligator clips with the Playtron. She then wanted to integrate playdough as a possible conductive material as the Squishy Circuits users were connecting their circuits mainly through playdough at the start. She soon found out that this specific playdough from the space was not conductive, and quickly moved on to try out other engaging possibilities with the kit. This is similar to the standard *Constructing Explanations and Designing Solutions (MS-PS3-3)*, because she understood that the playdough was not conductive, and moved on to designing alternatives that could work for her.

Sara experimented with using copper tape on a cardboard, attaching the alligator clips to the tape in the cardboard and the Playtron, and touching the tape to activate the Playtron. This relates to the standard *Developing Possible Solutions (ETS1.B)*, because she developed alternatives to use other conductive materials and see how they worked with her design. She wanted to integrate her object in her design, so she used the word ‘cat’ in her circuit using 10B pencils to interact with the Playtron (see Figure 25).

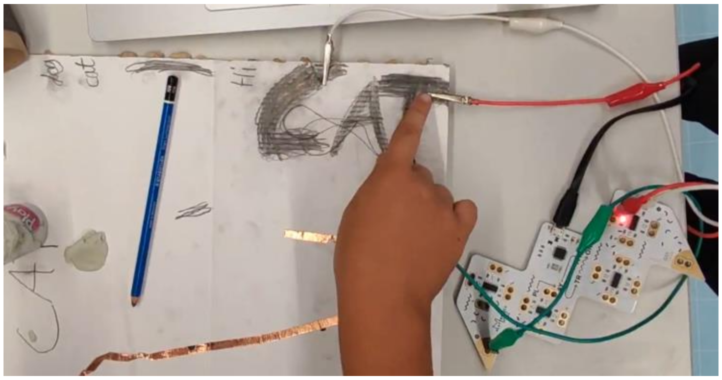
Figure 25

Sara using the word ‘cat’ with 10B pencils

Finally, she wanted to ground herself in an easier way so she did not have to hold on to the ground alligator clip. For this she experimented with the conductive thread attached to the ground alligator clip. She iterated three times to achieve an ideal solution: (1) short piece of thread, (2) thread and copper tape, and (3) longer piece of thread with a couple of loops in the alligator clip. This is similar to the standard *Optimizing the Design Solution (ETS1.C)*, because she iterated on her attempts until she got to a point she could comfortably interact with the material. Her final design implemented conductive thread for the ground output, 10B pencils to draw the word ‘cat’, and alligator clips connected to the Playtron. Figure 26 shows Sara with her final design, but it also shows her material explorations and first iterations with copper tape, writing, and playdough.

Figure 26

Sara showcasing her project



In Sara's case, the Playtron showed possibilities of interaction with conductive materials and representation of the tangible personal artifact. The process involved engineering similar to the Squishy Circuits, which was tinkering with materials and the kit, iterating for troubleshooting and combinations, and optimization of approaches to achieve a desired outcome. Nevertheless, the Playtron presented a big limitation for sound creativity with its binary input/output mechanisms. When a conductive material was connected with the Playtron, it could only send one signal, switching between on/off states. There was no middle ground and no resistance to explore. That meant that even when explored and combined with other conductive materials, the output could not be modulated, which in turn made conductivity and resistance untransparent concepts and not part of the design materiality to be creative with. Sara wanted to replicate a cat meow, but ended up only using one note from the Playtron in her final design.

Sara showed what was seen in the adult workshop, where the tangible personal artifact played a big role in the design of their own projects. Using the tangible personal artifact as a guiding reference did not happen at the same rate it did with the Squishy Circuits users, where most of them structured their projects around their tangible personal artifacts. This shows that the Playtron may need more than just a tangible personal artifact to structure its interaction with conductive materials, and facilitate engineering practices through tinkering.

To conclude, both the Playtron and Squishy Circuits kits showed possibilities to combine with conductive and non-conductive materials. They also supported the representation of tangible personal artifacts through sound making, where the Playtron provided a wide variety of electronic sounds, and Squishy Circuits provided one electronic sound (i.e., the buzzer) and physical sound making through movable objects. The Squishy Circuits kit was the only one that allowed for participants to manipulate the sounds through material explorations of resistance, but also through physical manipulation like filtering and hitting other objects. On the other hand, the Playtron focused its users attention on screens and limited their interactions with other materials.

5. Discussion

Sound making activities provided various interaction opportunities with conductive and non-conductive materials. The findings here show that the designed sound making activity supports engineering design practices. This study pointed to diversifying entry points into engineering and design recommendations for engineering practices through sound making.

First, the activity supported engagement with engineering by creating designs based on tangible personal artifacts. For example, in Barney’s case, he iterated on his sound design by representing the popping sound his artifact made, which encouraged him to engage in iterative designs through material explorations and continuous optimizations to achieve his desired representation. The tangible personal artifact guided the personal projects of the participants, inspired their own ideas, and motivated them to continue working on their projects. This in turn allowed participants to engage in engineering design practices through the sessions while they design their personally meaningful projects.

Second, the activity supported engineering because of the multiple conductive and non-conductive materials that could be connected to the sound making object (i.e., the buzzer and the MIDI controller). For example, in Greta's case, she experimented with different conductive materials that could connect with her buzzers, and decided to use what she found most appropriate to make the buzzers turn on but also to filter the buzzers sound with materials on top of them.

Third, and most interestingly, the activity supported engineering through the kind of sounds that could be created and how the materiality of sound making played into the process. For example, Hewett's case, where he modulated the buzzer's sound by adding materials or turning it upside down, which showed engagement in engineering design practices compared to Emma and Sonia's project, where they created a warning sound, but focused mainly on the laptop screen which engaged less so. Hewett was able to manipulate his sound and therefore was able to tinker and optimize his designs, which resulted in him engaging in engineering design practices. Whereas Emma and Sonia did not engage in these explorations and thus did not engage in engineering design practices at the same rate. The Playtron made a wide array of electronic sounds available, but limited material explorations as the sound output would not change if the material input came from a fruit, conductive paint, or just fingers on the board.

This study highlighted the use of sound as an OTTW to expand the personally meaningful experiences of the learners in their creations. By materializing their tangible personal artifacts, participants were motivated to work and iterate on their personal projects. It also reinforced the constructionist approach for learners, where learning by doing in open-ended design where educators support their experiences can engage them deeply in their own projects.

On the other hand, the study also pointed to limitations in sound making activities, and sound as a material as it may be too abstract for some learners. A common question asked throughout the various sessions was, "*How does* [participant's object] *sound*?" To some, it evoked sounds immediately through sounds the objects themselves could make (such as Hewett and Cornelius's cases), whereas for others it reminded them of sounds around the object (such as Nina's and Todd's cases). However for others, their object was not so clear how sound could be represented (as in Alex's case with her brain parts poster). As Wargo (2018) mentions, sound may exist as a quasi-object, and this can be complex to understand for some, at least as a design element for learning activities.

Further research in sound as a material could bring about engineering practices in K-12 education, where other strategies in sound making activity design could be looked into as well as the use of the plethora of sound making materials and kits. Other differently-purposed kits could support sound making in different ways by expanding conductive (e.g., pressure sensors) and non-conductive material interactions for sound manipulation. Additionally, researching materials like sound, where personally meaningful histories can contribute to the learner's experience, could point us to developing personally meaningful learning. The significance of this approach to learning, can enhance engagement in complex topics like engineering education and promote earlier adoption of this important area for learning.

6. References

Agustín-Aquino, O. A., & Mazzola, G. (2019). Contrapuntal aspects of the mystic chord and Scriabin's piano sonata no. 5. In *Mathematics and Computation in Music* (pp. 3–20). Springer International Publishing.

Ata-Aktürk, A., & Demircan, H. Ö. (2021). Supporting preschool children's STEM learning with parent-involved early engineering education. *Early Childhood Education Journal*, 49(4), 607–621.

Bacovic, M., Andrijasevic, Z., & Pejovic, B. (2022). STEM education and growth in Europe. *Journal of the Knowledge Economy*, 13(3), 2348–2371. https://doi.org/10.1007/s13132-021-00817-7

Bdeir, A. (2009). Electronics as material: LittleBits. *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction - TEI '09*. (pp. 397-400).

Buchholz, B., Shively, K., Peppler, K., & Wohlwend, K.. (2014). Hands On, Hands Off: Gendered Access in Crafting and Electronics Practices. *Mind, Culture, and Activity*, *21*(4), 278–297. https://doi.org/10.1080/10749039.2014.939762

Buechley, L., Eisenberg, M., Catchen, J., & Crockett, A. (2008). The LilyPad Arduino: Using computational textiles to investigate engagement, aesthetics, and diversity in computer science education. *Proceeding of the Twenty-Sixth Annual CHI Conference on Human Factors in Computing Systems - CHI '08*.

Cambrón, M. A. (2005). Sonido y sociabilidad: consistencia bioacústica en espacios públicos. *Quaderns-e de l'Institut Català d'Antropologia*.

Caprile, M., Palmén, R., Sanz, P., & Dente, G. (2015). Encouraging STEM studies labour market situation and comparison of practices targeted at young people in different member states. *Policy Department A*, *12*.

Chen, Y., Johri, A., & Rangwala, H. (2018). Running out of STEM. In *Proceedings of the 8th International Conference on Learning Analytics and Knowledge. LAK '18: International Conference on Learning Analytics and Knowledge*. ACM. https://doi.org/10.1145/3170358.3170410

Chibitronics (2022). Retrieved November from https://chibitronics.com/tapes/

Collins, N., & McLean, A. (2014). Algorave: A survey of the history, aesthetics and technology of live performance of algorithmic electronic dance music. In *Proceedings of the International Conference on New Interfaces for Musical Expression* (No. 14).

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

D'Amico, A., & Guastella, D. (2018). Robotics construction kits: From "objects to think with" to "objects to think and to emote with." *Future Internet*, 10(2), 21. https://doi.org/10.3390/fi10020021

Dinc, B. G., Özkan, B., & Veryeri Alaca, I. (2021). Interactive storytelling through LEDs and paper circuits: Tapping into materials and technology in children's literature education. *Journal of Literary Education*, *4*, 85. https://doi.org/10.7203/jle.4.21021

Dittert, N. (2014). TechSportiv: Constructing objects-to-think-with for physical education. *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*.

Fatourou, P., Papageorgiou, Y., & Petousi, V. (2019). Women are needed in STEM: European policies and incentives. *Communications of the ACM*, *62*(4), 52–52. https://doi.org/10.1145/3312565

Greeno, J. G. (1994). Gibson's affordances. Psychological Review, 101(2), 336–342. https://doi.org/10.1037/0033-295x.101.2.336

Hernandez-de-Menendez, M., Escobar Díaz, C. A., & Morales-Menendez, R. (2020). Engineering education for smart 4.0 technology: a review. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *14*(3), 789–803. https://doi.org/10.1007/s12008-020-00672-x

Heublein, U., & Schmelzer, R. (2018). *Die Entwicklung der Studienabbruchquoten an den deutschen Hochschulen* [The development of drop-out rates at German universities]. Hannover: DZHW.

Holbert, N., & Wilensky, U. (2019). Designing educational video games to be objects-to-think-with. *Journal of the Learning Sciences*, 28(1), 32–72. https://doi.org/10.1080/10508406.2018.1487302

Im, T., Siva, S., Freeman, J., Magerko, B., Hendler, G., Engelman, S., Miller, M., Villa, B., & McKlin, T. (2017). Incorporating music into an introductory college level programming course for non-majors. *2017 IEEE Integrated STEM Education Conference (ISEC)*.

Johnson, S., & Thomas, A. P. (2010). Squishy circuits: A tangible medium for electronics education. *Proceedings of the 28th of the International Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '10*.

Kafai, Y. (2006), "Constructionism", Sawyer, R.K. (Ed.), The Cambridge Handbook of the Learning Sciences, Cambridge University Press, Cambridge, pp. 35-46.

Kafai, Y., Fields, D., & Searle, K. (2014). Electronic textiles as disruptive designs: Supporting and challenging maker activities in schools. *Harvard Educational Review*, *84*(4), 532–556. https://doi.org/10.17763/haer.84.4.46m7372370214783

Kafai, Y. B., Fields, D. A., Lui, D. A., Walker, J. T., Shaw, M. S., Jayathirtha, G., Nakajima, T. M., Goode, J., & Giang, M. T.. (2019). *Stitching the Loop with Electronic Textiles*. https://doi.org/10.1145/3287324.3287426

Kennedy, T. J., & Odell, M. R. (2014). Engaging students in STEM education. Science Education International, 25(3), 246-258.

Keune, A., & Peppler, K. (2019). Materials-to-develop-with: The making of a makerspace: Materials-to-develop-with. *British Journal of Educational Technology: Journal of the Council for Educational Technology*, 50(1), 280–293. https://doi.org/10.1111/bjet.12702

Li, X.-Z., & Kang, X. (2021). Combining computational thinking and chibitronics and makey makey to develop a social story teaching aid system to improve social reciprocity and emotional expression skills for autistic children. *2021 12th International Conference on E-Education, E-Business, E-Management, and E-Learning*.

Mannone, M. (2019). Have fun with math and music! In *Mathematics and Computation in Music* (pp. 379–382). Springer International Publishing.

Matthews, S. (2015). Dementia and the power of music therapy: Dementia and the power of music therapy. *Bioethics*, *29*(8), 573–579. https://doi.org/10.1111/bioe.12148

Morgan, D. L., & Nica, A. (2020). Iterative Thematic Inquiry: A new method for analyzing qualitative data. *International Journal of Qualitative Methods*, *19*, 160940692095511. https://doi.org/10.1177/1609406920955118

National Research Council. (2013). *Next Generation Science Standards: For states, by states*. National Academies Press. https://nap.nationalacademies.org/catalog/18290/next-generation-science-standards-for-states-by-states https://doi.org/10.17226/18290

Pahl, K., & Rowsell, J. (2019). *Artifactual literacies: Every object tells a story*. Teachers College Press.

Piaget, J. (1968). Six psychological studies. Trans. A. Tenzer.

Papert, S. A. (1980). *Mindstorms: Children, Computers, and Powerful Ideas*. Basic Books.

Peppler, K., Sharpe, L., & Glosson, D. (2013). E-Textiles and the new fundamentals of fine arts. *Textile messages: Dispatches from the world of e-textiles and education*, 107-117.

Peppler, K., Halverson, E., & Kafai, Y. B. (Eds.). (2016). *Makeology: Makerspaces as learning environments (Volume 1)* (Vol. 1). Routledge.

Peppler, K., Wohlwend, K., Thompson, N., Tan, V., & Thomas, A. (2019). Squishing circuits: Circuitry learning with electronics and playdough in early childhood. *Journal of Science Education and Technology, 28*(2), 118–132. https://doi.org/10.1007/s10956-018-9752-2

Playtronica. (2022). Retrieved September from https://studio.playtronica.com/

Qi, J., Huang, A. "bunnie," & Paradiso, J. (2015). Crafting technology with circuit stickers. *Proceedings of the 14th International Conference on Interaction Design and Children*.

Qi, J., Buechley, L., Huang, A. "bunnie," Ng, P., Cross, S., & Paradiso, J. A. (2018). Chibitronics in the wild: Engaging new communities in creating technology with paper electronics. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*.

Resnick, M. (1996). Distributed constructionism.

Resnick, M., & Rosenbaum, E. (2013). Designing for tinkerability. In *Design, make, play* (pp. 163-181). Routledge.

Rodríguez-Sánchez, A., Odena, O., & Cabedo-Mas, A. (2018). Using life histories with sound postcards to investigate a music programme for social reconstruction in Colombia. *British*

Journal of Music Education, *35*(2), 177–190. https://doi.org/10.1017/s0265051717000298

Simarro, C., & Couso, D. (2021). Engineering practices as a framework for STEM education: a proposal based on epistemic nuances. *International Journal of STEM Education*, *8*(1). https://doi.org/10.1186/s40594-021-00310-2

Tan, M. (2019). When makerspaces meet school: Negotiating tensions between instruction and construction. *Journal of Science Education and Technology*, 28(2), 75–89. https://doi.org/10.1007/s10956-018-9749-x

Thomas, A., Besser, D., Schmidtbauer, M., Baklund, M., Harjamaki, M., & Verschoor, E. (2020). Squishy circuits (resource exchange). *2019 ASEE Annual Conference & Exposition Proceedings*.

Turkle, S. (2007). *Evocative objects: Things we think with* (S. Turkle, Ed.). Mit Press.

Wargo, J. M. (2018). Writing *with* wearables? Young children's intra-active authoring and the sounds of emplaced invention. *Journal of Literacy Research: JLR*, *50*(4), 502–523. https://doi.org/10.1177/1086296x18802880

Woods, G. (2018). A song to remember: The effects of music therapy on individuals with Alzheimer's disease.