more *Audio Boxes* to collect items during a field trip to re-examine them later on. However, after our first informal tests, we decided that these portable devices could only be part of a more comprehensive educational program. The students should start from the familiar, then slowly expand the known space step by step. Hence, we postponed the refinement of the *Audio Box* and started to focus on the immediate surrounding of the students: the school building. Here the *Audio-Tactile Map* would find its use. Only after learning the basics of cartographic abstraction should the students switch to lesser known areas: the immediate surroundings of the school building at first, followed by the destinations of field trips.

4.2.3 Audio-Tactile Map Prototype 1: Visual Tracking

In contrast to some earlier studies on audio-tactile maps, our device should take the actual local educational processes and needs into account – as well as the individual explorative and expressive interests and abilities of the various stakeholders. From the beginning we were careful not to disrupt existing 'conversational' practices. Supplementing the teacher with a mere information retrieval device was not the goal and considered to be an "anti-pattern". The device should neither hinder proven educational practices, nor collaborative activities. Instead, we aimed at building a tool which would allow teachers and students alike to actively enrich available teaching materials and extend their interaction beyond class sessions.

To address the lack of tactile content, we decided to define an open file format, which combined digital illustrations with links to networked audio recordings. Teachers should be able to share maps and illustrations easily, so that others could reproduce them by downloading and then printing them on swell paper. Storing the linked audio recordings on the Web would also allow the creator to remotely add and update the audible information layer at a later stage. This turned the audio layer from a static collection of recordings into something that could potentially grow with its user base. It also shifted the *Audio-Tactile Map* from a static teaching supplement towards a *communication medium*. While our focus remained on the direct teacher-student relationship, this opened a wide range of new potential use cases.

To download and play back the recorded sounds, we used an embedded computer (BeagleBone) based on open-hardware. Open hardware, to our understanding, would increase the maintainability and adaptability of the system as a whole.

To identify the tactile maps, we connected an RFID (radio-frequency identification) reader. RFID tags, attached to the back side of the swell paper, allowed the computer to recognize the map, download the map file, and prepare the audio files for instant playback. A student would place and fixate the tactile map on the device. The device would download the necessary data. Then the student would trigger the playback by simply touching an area of interest.

For our first tests, we used a visual tracking mechanism relying on a top-mounted camera and optical markers – an approach that had already been explored by an earlier feasibility study [54]. However, this system was only able to track the *position* of outstretched fingers, and not the act of *touching* certain areas. This limited the possibilities of interaction considerably. Hence, we decided to investigate the possibilities of pen-based interaction as an alternative.

4.2.4 Audio-Tactile Map Prototype 2: Pen-Based Interaction

We based our second prototype on a commercially available pen-based input device (see Fig. 1.4). In a first test, a visually impaired teacher lifted the paper with the left hand to “scan” the map with his right hand, which was placed flat on the surface. After putting the map back on the tracking surface, he used the fingertips of the left hand to explore the tactile map in more detail, while using the right hand to hold the pen. Using the pen as a pointing device allowed him to select very small areas (down to 1×1 mm). But holding the pen hindered two-handed exploratory procedures. Moreover, the system was not able to support the user in the search for audible information. The only way to set audible-enhanced areas apart from the rest were the tactile properties of the map itself. This influenced the design of the tactile surface and reduced the flexibility of the whole setup considerably.

For a second test, we invited visually impaired students to actively engage in the creation of their own augmented map. Guided by a visually impaired teacher, the students explored the school building and collected audio recordings – field recordings or short interviews with people working in their offices. These recordings

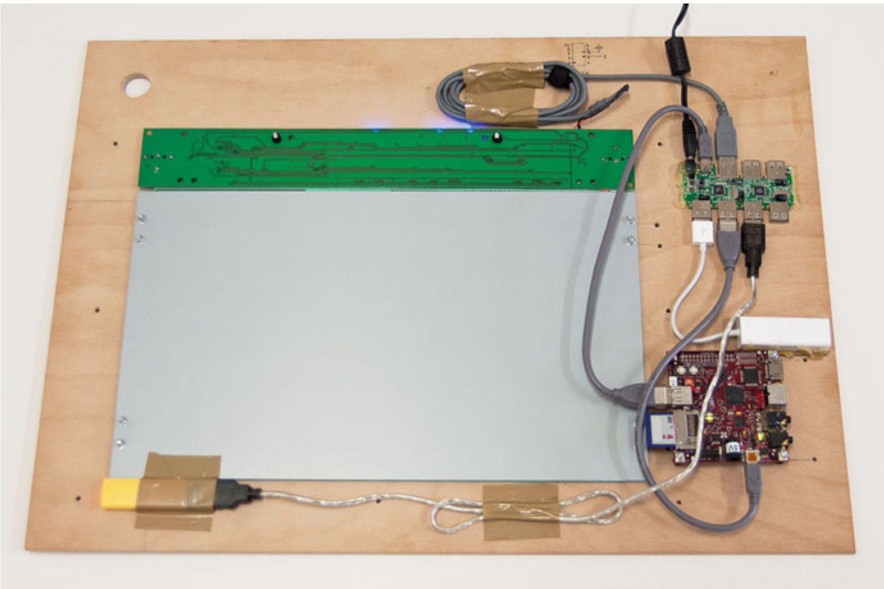

Fig. 1.4 The backside of prototype 2, featuring an open-hardware embedded computer, connected to an off-the-shelf graphic tablet and an RFID reader

were then positioned on a tactile map consisting of several A4-sized sheets of swell paper. The rooms represented on this map were delimited by raised lines resembling walls. The test subject used both hands to explore the map, often using one hand to continuously "walk" from one room to the next, while using the other hand to find the exits. The pen was put aside during these exploratory movements.

We concluded that a preferable tracking mechanism should be able to continuously track both hands when in contact with the tactile surface. This would not only provide uninterrupted exploration, but also allow the system to give audible feedback when an area of interest was within reach. We started to investigate available technical options.

4.2.5 Audio-Tactile Map Prototype 3: Open Projected Capacitive Touch Tracking

Tests with commercially available tablets that supported multi-touch input seemed promising at first. However, as the tablets were based on closed hardware and software, we weren't able to fully customize their behavior and properties; in particular, the limited surface size did not match the format of the maps used in school. Moreover, we weren't able to solve tracking problems that appeared on seemingly random occasions, as the highly specialized fingertip tracking technology wasn't always reacting in a predictable way when multiple parts of the hands rested on the swell paper. Furthermore, as already explained in Sect. 4.2.1, relying on off-the-shelf products as integral parts of the system would influence the longevity of the system as a whole.

We therefore decided to build our own tracking device based on carefully selected widely-available and basic electronics components (see Fig. 1.5). Although this would take up considerable project resources, we hoped for beneficial long-term effects, as we designed for repairability and adaptability. The tracking device should be able to be used with a wide variety of tactile maps placed on top of the sensor panel, including maps based on swell paper. At the same time it should be able to track two-handed explorative movements. The technological approach which seemed most adequate to us was *projected capacitance touch tracking*. By implementing our own solution, we were able to fine-tune all relevant parameters in correspondence with the material in use at the school.

By releasing our tracking system under a free license,[5] and by building it in a modular and highly customizable way, we also hoped for synergy effects. Researchers and hobbyists, not necessarily interested in Assistive Technology but working on touch-based interaction, should be able to use as well as contribute to the design of the tracking device.

To expand the explorable areas on the Audio-Tactile Map and to address the challenge of **content creation**, we decided to pursue two approaches in parallel.

[5] A detailed description of the prototype can be found in a separate publication [62].

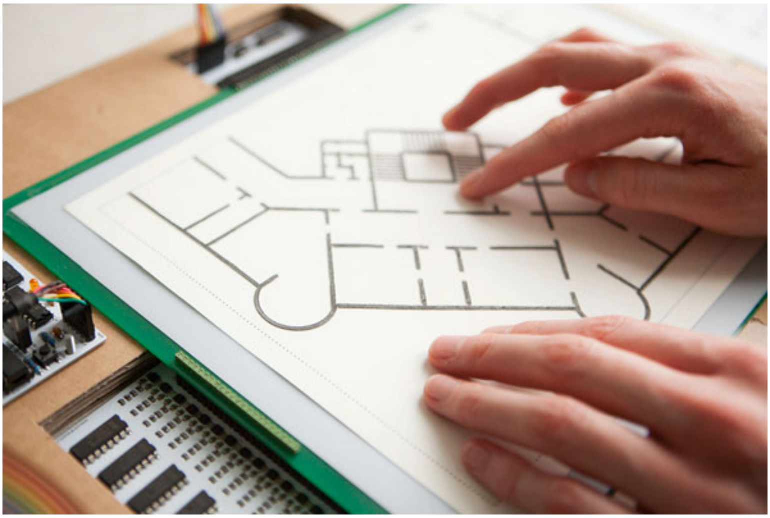

Fig. 1.5 The third prototype of the *Audio-Tactile Map* featured multi-touch and multi-hand tracking based on open-sourced projected capacitance touch technology. A tactile map was placed on the sensor panel. Audio recordings were triggered when the users double tapped locations with their fingertips

On the one hand, we initiated the design and prototypical implementation of a sophisticated map making tool based on OpenStreetMap. On the other hand, we built an accessible web interface that allowed rapid creation of black and white renderings of Google Maps images. While the first approach aimed at a long-term solution, the second one was geared at a "quick win". Completely dependent on an external proprietary service, it served as an intermediary solution providing immediate value. We also helped the school to acquire and install a special printer, which facilitated the process of transforming the created images directly into embossed graphics on normal paper sheets, thereby reducing production costs. To add sounds to geographical maps, we recorded exemplary audio files ourselves. We also tested the integration of web-based field recording platforms in order to benefit from already existing crowd-sourced services. Students should be able to explore the city using several audio information layers, one of them providing "city sounds".

After our first tests, we decided to implement a rudimentary sonification service, providing subtle stereophonic sounds which informed the user about the relative position of the touched area to nearby areas of interest. The sounds changed in volume, pitch and balance during exploratory movements. To trigger the playback of a recording, once the selectable area was found, the user could double tap it.

After we successfully built a *usable* user interface, we concluded that the designed system and resulting *user experience* spearhead a promising direction, but would benefit considerably from research and further design iterations. We were not able to reach a level of product quality that fully corresponded to the requirements of teaching tools used at the school, but we were able to design a toolkit hopefully *resilient* enough to serve as a platform for further research and refinement (see also future work Sect. 5.4).

5 Discussion

As outlined above, there are many ways of conducting research in HCI. We took a practice-based approach (e.g., [35]) to exploring the potential of haptics and related modalities in the education of visually impaired children. Here we discuss some of the consequences of this decision.

5.1 Reflections on the Design Process

In our project, we combined fieldwork with a practice-based Research through Design approach (see, e.g., [32] for an overview of the design research discipline). In retrospect, we think this choice was appropriate, since throughout the process, there were many design choices to be made which could not be inferred from a static requirements specification or "desktop research" [63] (cf. Dorst's work for a comparison of different approaches to *designing* [13]). That is, while the project certainly featured conventional engineering problems that could be tackled by *algorithmic* thinking and procedures (e.g., arranging all components within a shell and manufacturing this shell in a reasonable as well as economical way), it also demanded choices made through the experience of design (both as an artifact and as a reflective process [53]).

For example, we used samples of different translucent materials and shapes to decide the final appearance of the *The Cuebe*. Both look and feel had to be experienced, and the components could not be investigated in isolation. The same argument applies to the push mechanism: one needed to grip the device and pick a color by pushing it against a surface to actually experience this kind of interaction. The designer should experience this with their own senses as the design is eventually intended to address the children's senses, and their therapeutic experience (or outcome, even) relies on that feel. At this point, we would like to emphasize that we regarded all people involved in the project – the children, teachers, therapists, and authors of this article – as designers or *co-designers*, because each one of these groups brought in their own particular expertise, which the others did not have, that were necessary for the project to come into being.

In our estimation, it was also necessary to successively work towards the final design using interactive prototypes. Due to the nature of the project, we could not expect the participants to anticipate interacting with therapeutic toys or educational tools based on simple mock-ups. This required us, relatively early in the process, to use platforms like *Arduino* for 'sketching in hardware', as opposed to sketching on paper or creating mock-ups. Especially in the beginning, we carefully sketched the interactive behavior, while at the same time not paying too much attention to the "polish" or physical appearance of the prototypes.

5.2 Open-Endedness and Customizability of the Design Artifacts

Throughout the co-design process, *open-endedness* and *customizability* emerged as important themes in the design of *The Cuebe* as well as *Audio-Tactile Map*. Both the Early Intervention specialists and the educators working at the Federal Institute for the Blind stressed that the technological artifacts should allow appropriations according to local practices and the incorporation of custom content, for example, by making up their own games with *The Cuebe* or creating their own maps with *Audio-Tactile Map*. Hence, the resulting technology is not attempting to "fix" disabilities by prescribing specific actions or therapeutic plans. Rather, our prototypes offer technological opportunities that can be taken and appropriated to facilitate developmental growth.

5.3 Dissemination of Knowledge

As mentioned in the methods section, practice-based design research is different to conventional science with regard to knowledge dissemination. The research goal is not to describe, explain or predict phenomena, but to understand how artifacts can be constructed. Design exemplars are recognized as important carriers of knowledge as they embody the findings and design decisions the designers made during the process [36].

On these grounds, we described our prototypes *The Cuebe* and *Audio-Tactile Map* in detail, including the underlying design processes, design decisions, and illustrative use scenarios.

Admittedly, scientific contributions in the shape of such design archetypes [63] are problematic in that the embodied knowledge can only fully unfold or be experienced when the user interacts with them directly. Hence, to make this knowledge accessible on an additional level, we decided to publish essential parts of the design of our artifacts under an open-source license. Build instructions for *The Cuebe* can be found online (www.guelden.info/cuebe.php). The blueprints for the tracking device of the *Audio-Tactile Map* have been published on an Open Science platform [62]. Through this strategy, we also hope to increase some of the sustainable effects of our research and to respond to some of its inherent challenges, as elaborated in the next section.

5.4 Reflections on the Sustainability of Our Design Process

As described in Sect. 4, much of our thinking during the design process centered around respecting the participants and their local needs, sustainability, product resilience, and the problem of device abandonment.

These issues have also been investigated by at least two research communities. Academic literature on Assistive Technology defines an abandoned assistive device as a product that gets purchased and put aside before the expected lifetime of usage has been reached, and that is not replaced with a related updated device [46] – a fate that befalls, according to Riemer-Reiss and Wacker [37], at least one third of all assistive products. This not only poses a problem in terms of time and money being wasted in acquisition and training, but can also lead, as Martin and McCormack [40] have noted, to disillusionment about specific categories of Assistive Technologies or Assistive Technologies in general. This dynamic can have far-reaching consequences, not only on the Assistive Technology market in the long term, but also on the intended user, who misses out on the untapped potential of emerging technologies.

To involve all relevant stakeholders, foremost the users themselves, in the acquisition process – to let them decide what assistive product should be purchased or not – is believed to reduce the chance of rejection. Similarly, Kane and colleagues [33] recently highlighted the importance of integrating affected individuals closely into the design process to increase the user acceptance and product success – a proposition which aligns well with the principles of user-centered design.

Such an approach was also favourably noted by our participants. However, although they expressed their general enthusiasm for cooperative design, they also put forward their concerns towards the frequently underwhelming direct impact of academic research on their actual daily practice (see also Sect. 3). These concerns are reflected by a re-occurring debate within the field of design research, in particular within the participatory design movement: It is generally agreed upon that giving the intended users a voice in the design process increases the chance that the designed tool fits into the environment of the co-designers. However, it does not guarantee that the end result is actually able to fulfill the set expectations. The quality of a functional prototype depends on the resources available, and maintenance and long-term support typically exceed the scope of a single research project. Simply facilitating discourse and reflecting on it is clearly insufficient when direct local impact is part of the desired project outcome. As Asaro emphasizes [3], participation should be *realized*; that is, the participants' voices should be echoed by actual implementations in order to make a difference in daily practices.

5.5 Future Work

As next steps, we intend to conduct additional user studies in order to understand how people integrate our technologies into therapeutic/educational settings and ultimately into their life. This will support us in generating intermediate design knowledge [28] about designing technologies for and with visually impaired children and students. Moreover, we want to improve our prototypes and iterate on their technical implementations.

From a broader perspective and connecting to Sect. 5.4, we would also like to spark a discussion about the opportunities and challenges of academic practice-based design with regards to effective local change. We consciously addressed mid- and long-term goals in our design-decisions. At the same time, we attempted to achieve "quick wins" with direct and immediate value for the participants, whenever possible. However, it is not clear how long these quick improvements will last and by which mechanisms long-term goals can be reached after a project comes to an end. It remains to be seen how well our approach fits into the current academic milieu, what structural inhibitors can be identified, and what can be done about them – in order to support future long-term design research where actual local impact is not an afterthought.

5.6 Limitations

The present work collated our experiences from two practice-based research projects in the context of the education of visually impaired children. The resulting prototypes (*The Cuebe* and *Audio-Tactile Map*) were driven by field-work and co-design activities with professional therapists and affected children. In this article, we do not aim at providing generalizable findings or discovering some sort of "truth" in the design of such tools for visually impaired children. Rather, the purpose of our work is to describe the design process, to explain design decisions, and to illustrate how the prototypes can be used. Further research is needed to evaluate possible positive effects of *The Cuebe* and *Audio-Tactile Map* on the education and well-being of children with visual disabilities.

6 Conclusion

Our objective in this research was to design interactive technology for enabling stimulating and educational experiences for visually impaired children of two different age groups. For the preschool children, we wanted to create a therapeutic toy that could be used by Early Intervention Specialists to motivate children with different manifestations of CVI to engage them in exercising. As a response to this