LJUDSKRAPAN/THE SOUNDSCRAPER: SOUND EXPLORATION FOR CHILDREN WITH COMPLEX NEEDS, ACCOMMODATING HEARING AIDS AND COCHLEAR IMPLANTS

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ABSTRACT

This paper describes a system for accommodating active listening for persons with hearing aids or cochlear implants, with a special focus on children with complex needs, for instance at an early stage of cognitive development and with additional physical disabilities. The system is called *Ljudskrapan* (or *the Soundscraper* in English) and consists of a software part in Pure data and a hardware part using an Arduino microcontroller with a combination of sensors. For both the software and hardware development, one of the most important aspects was to always ensure that the system was flexible enough to cater for the very different conditions that are characteristic of the intended user group.

The Soundscraper has been tested with 25 children with good results. An increased attention span was reported, as well as surprising and positive reactions from children where the caregivers were unsure whether they could hear at all. The sound generating models, the sensors and the parameter mapping were simple, but provided a controllable and complex enough sound environment even with limited interaction.

1. INTRODUCTION

This paper describes a system for promoting listening and exploration of sounds based on playful audio interaction. The system is devised for children at an early stage of cognitive development with a focus on children with hearing impairment and complex needs.

The aim is to reduce limitations of activity due to functional disability and to encourage curiosity toward active listening by providing good conditions for exploring, investigating and playing with a collection of synthesized and recorded sounds. The system, called "Ljudskrapan" in Swedish and "the Soundscraper" in English, consists of a software and a hardware part. The software is programmed in Pure data [1], and various sensors are used for interacting. A typical setup includes an Arduino [2] with gesture tracking sensors attached, but other input devices like game controllers, cameras and pointing devices can be connected.

In the typical envisaged use scenario, the child interacts with the Soundscraper through gestures in a school or a clinic, supervised by a special needs teacher or a speech therapist, and with the software operated by a second person. In a simpler use case, a user interacts with and operates the software without supervision. In both cases, the Soundscraper can be classified as a sound exploration tool, a sound toy and musical instrument.

The Soundscraper has ambitions to empower children with hearing impairment and complex needs in the following ways:

- make exploration of sound and music accessible,
- stimulate active listening in a playful and rewarding way,
- be inclusive by using easily adaptable sensor data for control,
- provide means for expanding orientation by listening and promoting audition as a means of orientation and communication.

The aim is also to offer novel possibilities for assessing hearing capabilities in children at an early stage of development. An important function is to improve the possibilities for the child to provide clear and unambiguous feedback to caregivers.

These are by no means modest goals, but we believe that the method may offer many possibilities to support the development of listening capabilities for children with complex needs and hearing impairment. The advantage with the proposed system is that the child can influence listening and choose which sounds are interesting, thus promoting active participation and supporting independence.

Pilot interventions and the first tests have been promising, and the potential future users have expressed a wish for further development of the Soundscraper. As will be discussed in the following section, the situation for many of the children we target is such that measuring the success of our intervention is impracticable or impossible in a short time perspective. The focus in this paper is on the conceptual framework and technical description, illustrated with a few examples from the first two years of small-scale testing.

1.1 Background

Young children with impaired hearing are often provided with hearing aids at an early age. The most common form of hearing impairment, sensorineural hearing loss, is caused by lack of sensory cells in the inner ear. If there is sufficient function in the inner ear an acoustic (traditional) hearing aid (**HA**) can be fitted so the remaining sensory cells are stimulated in an optimal way. With profound hearing loss it is not possible to enhance the acoustic input to create a hearing experience. In these cases a cochlear implant (**CI**) can be used to make hearing possible.

1.1.1 Cochlear implants and hearing development

A CI consists of an electrode array that is surgically inserted into the inner ear (cochlea). The electrode array is fed with an electrical stimulus pattern generated by an externally worn sound processor. The sound processor is programmed to convert the acoustic signals into an electrical pattern that is continuously forwarded by the electrode array to the hearing nerve, and then further on into the central auditory system. The auditory processes in the brain convert the synthetically produced signal pattern into a meaningful listening experience.

CI was initially designed for persons who had become deaf after acquiring spoken language, but the technology has later been successfully introduced to deaf born children as well. The surgical procedure by which the electrode array is inserted into the inner ear is often performed when the child is between six and nine months of age. The challenges are, however, quite different in the pediatric population as hearing development depends on physiological maturation as well as exposure to stimulation.

In a typically developing child, hearing is a gradually emerging skill underlying the development of spoken language. By the age 9–12 months, the majority understands several spoken words and expressions. This means that a child awaiting CI surgery is delayed several months in comparison to their hearing peers. In many cases, implantees go on developing hearing and spoken language with little or only minor difficulty. This do, however, not hold true for all individuals: A specially vulnerable group consists of children with complex needs.

1.1.2 Complex needs

Children with complex needs at an early stage of development is a small group in society. Within this group, many have limitation in vision and hearing as well as limitations in motor control. Children with complex needs are also considered for CI surgery, but the intervention required following the implantation may be different from that of typically developing children [3]. It has been suggested that the benefit of CI use for children with complex needs should be seen in a broader perspective than speech outcome [4].

Objective methods can be applied for adjusting and evaluating the HA/CI, but they are problematic in assessing the performance for young children. Subjective methods target both qualitative and quantitative aspects of hearing. Primarily these are speech recognition and pitch perception [5, 6], but also melody perception [7] and music enjoyment [8]. However, children with hearing impairment and complex needs often show minimal response to auditory stimulation through HA/CIs.

In many cases the responses are unspecific and provide little information on the sound appreciation. In a wider perspective the lack of clear-cut feedback constitutes a serious problem. The capacity to hear is established by auditory stimulation enabling physiological maturation as well as higher level learning. Due to the lack of reactions from the child the caregivers may give up the endeavor to ensure that the HA/CI is used continuously. This may result in suboptimal stimulation and lead to further suppressing of auditory processes.

Studies by Kraus et al [9] have shown that active listening has a positive and lasting effect on perception after surgery, and therefore the child must be systematically exposed to sound in order to develop auditory capacity. Wiley et al [10] concluded that caregivers reported a variety of benefits for children using CI, such as more awareness to environmental sounds, higher degree of attention and clearer communication of needs. Studies also show that children unable to communicate with their environment in a meaningful way may have a disrupted emotional and cognitive development and experience their surroundings as being chaotic [11].

1.1.3 Special needs interfaces for sound manipulation

Within the expanding field of new musical instruments that are based on a software/hardware hybrid solution, work with special needs users has always been a prominent direction. Many of the products and prototypes that have been described (see for instance [12, 13, 14, 15, 16]) address classical music therapy needs and problems, and few look at sound perception specifically. Very little research has been done on the combination of severe hearing impairment and the other complex needs as described above, and in particular with the aim to assess hearing and stimulate active listening [17].

2. SOFTWARE AND HARDWARE

One characteristic of the target user group is that every individual has particularly demanding needs, and there is seldom much in common between the users. Additionally, a set-up that works in one session might not be possible to use at all in the next. It is therefore necessary to be able to radically change the software behavior and hardware configuration within moments. For example, a child that is still and hardly able to move an object in one session may in another session display strong or involuntary movements. The software and hardware must correspond to such diverse states, and the technician must be ready to adapt to the situation quickly to ensure a working system and safe environments for the involved persons.

In particular for the software side, sudden changes in amplitude or sound characteristics must happen in a controlled fashion. The sound should not under any circumstance exceed planned level restrictions. On the hardware side, safety must be ensured with regards to for instance sharp edges, loose parts, and wires that can strangle or unexpectedly return thrown sensors. As the user testing has shown, the hardware will often be vigorously handled.

To accommodate quick and considerable changes, the software was written in Pure data which is an excellent environment for prototyping (and is open source software). The hardware has for the most part consisted of sensors on detachable units that are easy to place on clothing or objects, connected to an Arduino digital–analog board. This low-cost solution promotes both easy distribution to schools and individuals, and easy extensions of the system.

2.1 Design method

Unlike typical situations where the software/hardware developer engages the user in a participatory design process, or feed back responses from test sessions [18], here the decisions were mainly based on solid prior background knowledge about the users. Most importantly, the aforementioned need for quickly altering any part of the setup had to be attended.

After the first trials, which took place in real settings, relatively little has been reprogrammed or redesigned. In future revisions, we expect that the main modifications concern the software interface (which is not operated by the child) and the sensor hardware (which will need to become more durable).

Models for generating the sound output, described below, can easily be added. This was indeed done during the first sessions and is also foreseen to be a continuous process. New and replacement sensors are also expected to be added when needed. These processes possibly advocate a participatory design methodology.

2.2 Software and sound models

The sound interaction was initially inspired by the way scratch DJs treat records: how they drag the sound fast or slow over a certain spot and isolate small fragments of a sound recording [19] (hence also the name *sound scraper*). Another inspiration from scratching, though more pragmatic, was that the audio signal of this instrument typically has a lot of broadband energy that swiftly sweeps the audible frequency range [20]. This, we argued, could seem effective for listening with cochlear implants when we are not sure if a child can perceive sound in a certain frequency region or not.

In the current implementation, the software interface includes around five sound models for choosing, of around ten different ones (see Figure 1). New models can be added to the interface easily, and they are typically based on existing Pure data abstractions, for instance from Pd's patch example library or previous works by the authors. A few examples are given below.

The Looper model loops a segment of a recorded sound and was derived from the Skipproof application [21] and the Pd example `B12.sampler.transpose`. Loop segments can be varied from the whole file down to a few milliseconds, but the typical loop lengths are at least 2-300 ms. Other parameters are starting point, and playback speed ("pitch").

The Vocoder model was added to be able to 'freeze' and move around in the sound file, and it was based on the patch `I07.phase.vocoder`. Available parameters are playback speed, pitch change ("tuning"), and playback position.

The Theremin was included to allow sweeping both pure tone and harmonic sounds across a broad frequency range to assess pitch perception. To introduce variations in tones when they are kept at a stable pitch level, frequency modulation was added. The main parameters are pitch, harmonics, and frequency modulation speed and range.

Pulse trains of bandpass-filtered white noise bursts offer possibilities to manipulate parameters in a rhythmic sequence of tones. The model was added to explore the temporal resolution which can be problematic with CI. Adjustable parameters include tone attack steepness, tempo, tone duration, noise filter, and filter central frequency.

The music player, based on the `oggread~` object, plays compressed audio files. A compressed format was chosen as this model uses whole songs. Only two parameters can be changed: track selection and track position. The music player was not included from start, but when we devised the session program, we decided to include a mode with less interaction.

In addition to the parameters mentioned above, it is possible in all models to control the amplitude, to add echo for making sounds more complex, to add filtering for amplifying or attenuating frequency ranges.

2.3 Hardware and motion sensors

All interaction with the software from the user was projected to be achieved through capturing body movement and gestures with sensors. Such sensor data include inertia measurements, proximity, bending and pressure. In addition to these we have used game controllers. Naturally, even analysing audio or video input would work well (for recognizing speech, facial expressions and body movements see e.g. [22]), but this has not been tested in respect of personal integrity, and also since the included sensors already present a sufficiently rich environment for interaction.

In the last versions, the hardware consisted of up to four sensor "bundles" that could be placed on or near the child. Each bundle was connected to the Arduino board with a 2–3m flat-cable or twinned wire to provide the child with a surrounding space. The bundles were enclosed in protective material and could easily be fastened with tape, rubber bands or velcro. Choosing sensors is still an ongoing process, but typically one of the bundles had an inertia sensor with up to six degrees-of-freedom (accelerometer, gyroscope), one bundle had analog sensors (pressure, light intensity, bending), and one bundle had one or more momentary buttons.

Momentary buttons were used with some sophistication and not as simple triggers. For many of the children, buttons are interfaces which they are familiar with. We extract several control parameters from the pushed buttons, and they are associated with a sort of increasing and decaying energy measure. First, a parameter value has an increase corresponding to the push duration. Second, a parameter

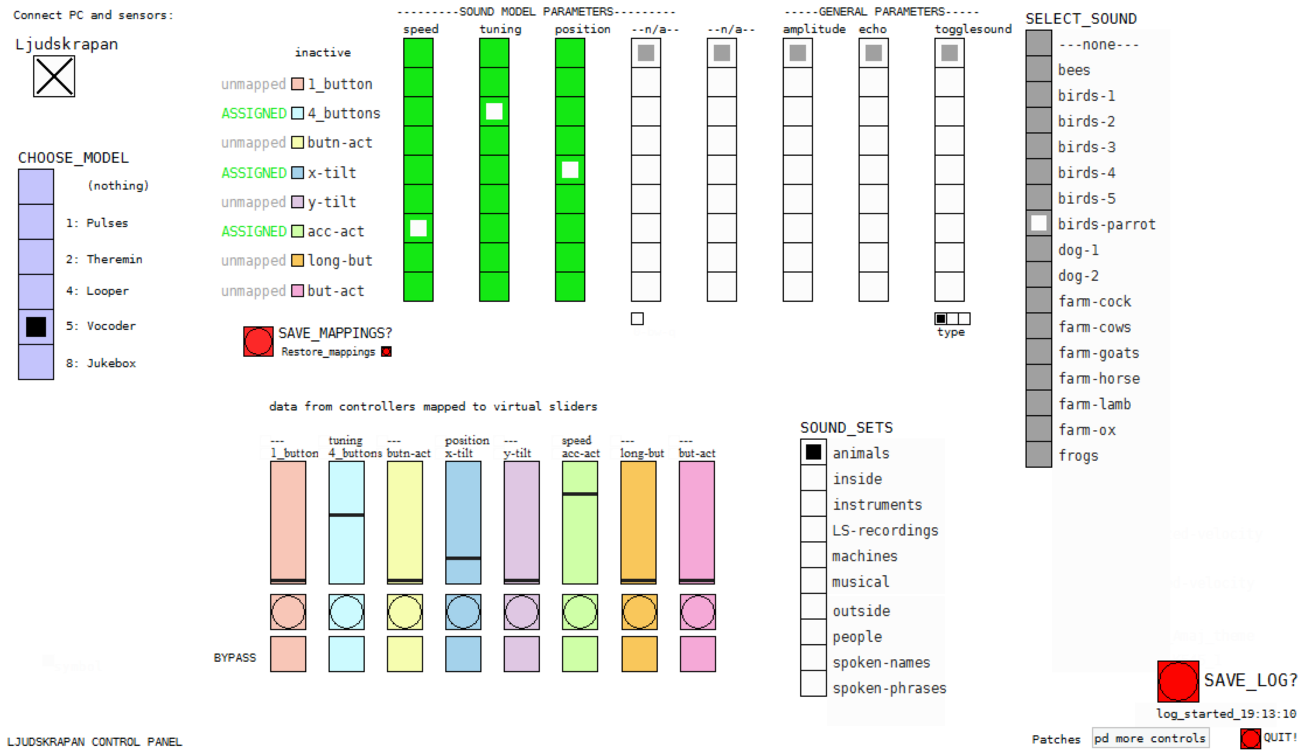

Figure 1. The software interface for the Soundscraper. The person operating the software chooses sound models to the left, mapping of parameters in the middle part, and sound files to the right. Incoming sensor data are mapped to the sliders in the lower part of the screen. The interface shows only the choices available for each sound model and sensor setup.

value has an increase corresponding to the push frequency. These can be used for each separate button or accumulated. Third, a parameter value has an increase related to the number of pushed buttons when there are more than one.

The sensor bundles, including the buttons, were integrated in toys or familiar objects, or they were placed on or around the body. To place sensors on the moving limbs, we used armbands, headbands and similar. For placement on toys or objects, the combination of expected movement, sensor type and fastening possibility had to be explored; two illustrating examples were an enticing rubber bathing duck with a light intensity sensor inside and a steering wheel with an accelerometer inside permitting “steering” in any direction.

Unlike in a typical music interface application, with special needs children we can have a conflict of interest where a movement pattern generates good sensor readings, but there is an incentive to suppress that activity. Likewise, a limited output from a sensor may have to be tolerated, as a more pressing concern is to encourage a certain behavior.

A consequence of having to settle with tracking movement patterns that are very limited, is to be able to scale the input data from the movement range. In the mapping between input sensor data and output sound parameters, we aim at always dealing with full-range signal (0..1). Due to the nature of the movements, it is necessary to rescale the sensor output during use. A problem with the rescaling is that there are not so many typical movements, such as repeating gestures, among the user group. One of the common characteristics is that the individual might be motionless for a while, then only momentarily move before returning to a calm state.

2.4 Parameter mapping strategies

One of the cornerstones in making the software and hardware flexible and adaptable is to allow for changing the parameter mapping between input and output easily. The importance of parameter mapping has been thoroughly studied [23], and we can use experience from previous projects. In a typical new instrument-situation a skilled musician performs practiced music for an informed audience [24].

Here instead, we face a situation where a child interacts with a system and there might not even be visible signs of any audio perception taking place, and similarly the motor control can often appear to be so erratic that it is not feasible to find proof of any interplay with the produced sounds. In these situations, guidelines for parameter mapping could be followed to ensure possibilities for rich and expressive interaction [14], for instance by defining “activity thresholds”, but the main challenge is to ensure that the control input is used effectively.

3. USER TESTING

For each session with a child, the caregivers and experimenters made careful predictions and plans based on the child’s physical and intellectual condition, personality and known preferences. Still in most cases, the expected or intended interaction was in at least some respects compromised by unforeseen behavior. Causes for the unforeseen behavior could be several and hard to explain: some factors include unfamiliar environment for the child, sensed expectations from the people in the room, unusual exposure to sound, excitement or anxiety, insecurity towards new persons, or even factors unrelated to the experiment.

We have so far been conducting tests with a small population of children with severe multiple physical and cognitive impairments. The project has ethical approval, but most of the details and data from the tests are not available for inclusion in analyses. Future experiments are scheduled where more data can be included. Presumably, even results from these experiments will be challenging to use in a comprehensive analysis because of the extremely diverse nature of each session. A few of the aspects we will continue to look at are related to quantitative measures. Qualitative measures require a great deal of objective interpretations and observations that in turn necessitate personnel that are closely acquainted with the child (these qualitative measures are naturally essential in the bigger perspective).

The first quantitative measure we look at is time spent during a task which can be adapted to the situation. Typical time-measured tasks are

- preference of a frequency region over others,
- preference of a (musical) sound over others,
- preference of a motor activity over others,
- sound level preference,
- (...)

These measurements require little interaction, but it is necessary to set the conditions right so that data from a sensor do not coincide with a comfortable resting position. From the experiments, we have noted and been informed that the children in general show a considerably higher amount of attention to the task than they normally would do. It is likely needed to gather much data before making conclusions from a time-measure method.

A second quantitative measure requires a more developed motor control and intellectual capacity. By restricting the range where a sensor produces the aspired result (for instance, making an appreciated sound louder) we can evaluate the determination to achieve the wanted sound both from assessing the difficulty of using the sensor over a restricted range as well as the time spent. Extensions of this method include to evaluate if a sound parameter is preferred over others in spite that it is harder to attain it.

3.1 Evaluation

The Soundscraper concept has been tested with the aim to identify strengths and weaknesses in the design and the method. Twenty five children with complex needs were included for the evaluation.

Before the test session, details and information on the children were collected including general level of functioning, motor skills, personal interest and special fears (if any), and auditory functions. For each child a plan was outlined including adaption of sensor equipment and selection of auditory stimulation (see Figure 2). The children were seen together with a parent, caregiver or teacher. A video recording of each session was made. The testing included reactions to and handling of sensors, answer to sound and sound manipulation, attention span, and mood following the session. All accompanying persons were asked to evaluate the child's reactions.

3.1.1 Reactions to and handling of sensors

The children reacted differently to the sensors, both those attached to the body and to the objects holding sensors. Generally, the impression was that they could be described as having a toy-like function. All children were able to either handle or move the sensor sufficiently for the purpose. One child rejected all types of sensors due to hypersensitivity in all extremities.

Sensors attached to arms or hands were generally less well tolerated than sensors manipulated purposely by the child (i.e. attached to an object or placed within reach). This was also true for children with very limited range of movement. Sensors attached to the head were well tolerated and used for especially demanding situations. When the movements were voluntary, such as for one child who could control turning and tilting of the head, the child immediately grasped the link between movement and sound. However, when the movements were mainly involuntary, it became a challenge to make relevant mappings between movement and sound. Two children with autism and autism-like symptoms devoted all attention to the cords attached to the sensors. One child moved arms and hands freely but stopped moving the extremity when a sensor was placed in the hand or attached to the arm.

3.1.2 Answer to sound and sound manipulation

All but five children showed clear reactions, and generally appreciation, to sound and sound manipulation. This group included the four children mentioned above and a child with profound hearing loss who had HA but not yet received a CI. Three children were intrigued by sound change but did not seem to make the connection between movement and sound.

3.1.3 Attention span

Five children showed limited span of interest. Characteristic of this group was that they all clearly understood the task and made the coupling between their actions and the sounding result. However, they more quickly became bored and started to act without purport and would need a more complex mapping between gestures and the sound output. For the other children, an increased attention span was registered. It should be noted that these observations were based on the children's first encounter both with us and the Soundscraper, and long-term effects on attention span were not investigated.

3.1.4 Evaluation of the children's reaction

Two children showed mild negative reactions during the session. This was the child with hypersensitivity and one child who did not make the connection between movement

Figure 2. The images show how the sensors can be adapted to different situations. In the left picture is a blind girl who disliked holding onto objects, and the sensor was thus placed on the head. In the middle is a girl with good grip and movement in her left hand. The right picture shows a boy who had a plastic rod used in gymnastics class that he enjoyed waving with, and the sensor was placed there. For all three, the sensor is the same inertia unit that measures movement. (Video stills are printed with permission, but moments where the face was covered were chosen deliberately.)

and sound. The negative mood did not persist for any extended period. A few children fell asleep directly following the session, but this was reportedly due to reasons outside the test situation. Fourteen out of twenty five caregivers were surprised by the interest in sound and the persistence showed by the child. One mother said that she did not believe that her son reacted to sound but rather to the sensor as such. However, this impression was not shared by the audiologist and the other caregivers present.

One unexpected observation was that a girl with spastic tetraplegia and involuntary reflex movements was able to relax when listening to a particular sound. During this relaxed state she was able to move one hand voluntarily. This suggests that active manipulation and listening to preferred sounds may strongly influence the overall motor pattern, which will be explored further in forthcoming tests.

4. CONCLUSIONS

The Soundscraper was successfully applied in user tests involving 25 children with hearing aids or cochlear implants, in addition to other physical or cognitive impairments. Both the software and hardware parts could be adjusted to the conditions of each individual session. The results of the preliminary testing were encouraging, and the caregivers indicated that the concept is promising and could possibly be introduced in their school activities.

The concept was judged to be stimulating and rewarding to children with listening capabilities at an early level of auditory development. On the contrary, children who already mastered conscious listening appeared to need higher degree of interaction freedom, especially when they were not able to produce sufficient or controlled movement.

Sensors that require active handling by pushing, pulling or moving an object were more likely to be accepted than sensors that were directly attached to the body of the child. Children with autism-spectrum diagnosis possibly need specially designed sensors to overcome problems not directly related to movement constraints.

The sound models were quite simple, but they provided a complex sound environment even through limited interaction. When the sensor readings were poor, creative mappings and data scaling were successfully used to compensate the scarce input. Having a small but versatile arrangement of sensors that could be placed freely was a great advantage over sensors fixated to objects.

During a session with a boy having a hearing loss combined with blindness, it was noted that he was eager to explore objects with his hands. This behavior was seldom observed for this boy, who for most of the time was reluctant to use his hands. This suggests that the Soundscraper could even be useful for normal-hearing children with blindness and complex needs.

4.1 Future work

User testing will continue with a group of children included in the present study. The Soundscraper will be included in the daily activities at school. Three different functions will be explored: listening for joy and amusement; active listening and training; and using sound for communication and as a means for raising contex awareness.

Future analyses of the logged data will hopefully reveal characteristics of sound perception and listening preferences. Such efforts need to be carried out in collaboration with audiologists and caregivers who know the child well. Finally, the software and hardware components need to be developed further to provide an effective and stable environment for the involved caregivers.

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