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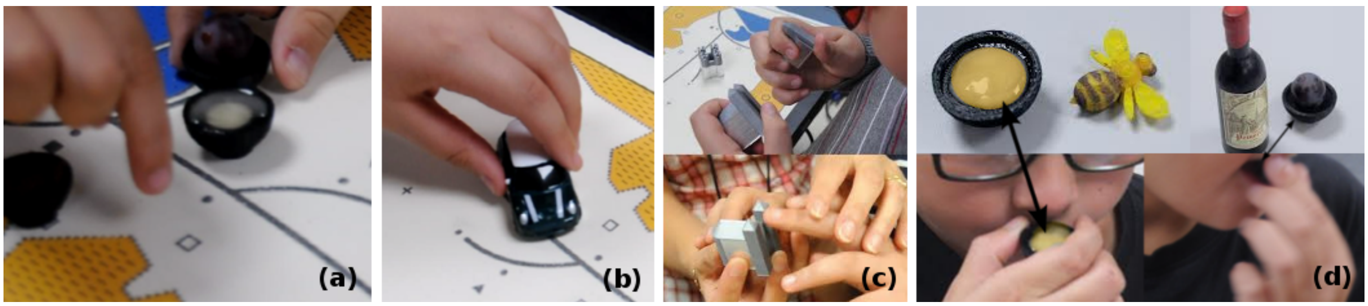

Figure 1: (a) Children collaborating using multi-sensory tangibles, (b) child exploring the map using a figurative tangible, (c) Children during tactile discovery of figurative tangibles, (d) examples of multi-sensory tangibles, which can be tasted or scented.

ABSTRACT
We report on the design process leading to the creation of *MapSense*, a multi-sensory interactive map for visually impaired children. We conducted a formative study in a specialized institute to understand children's educational needs, their context of care and their preferences regarding interactive technologies. The findings (1) outline the needs for tools and methods to help children to acquire spatial skills and (2) provide four design guidelines for educational assistive technologies. Based on these findings and an iterative process, we designed and deployed *MapSense* in the institute during two days. It enables collaborations between children with a broad range of impairments, proposes reflective and ludic scenarios and allows caretakers to customize it as they wish. A field experiment reveals that both children and caretakers considered the system successful and empowering.

Author Keywords
Visual impairment; field-study; children; accessibility; tangible interaction; interactive map; DIY; 3D printing.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; K.4.2 Social Issues: Handicapped persons/special needs

INTRODUCTION
The WHO estimates that 285 million people live with visual impairments worldwide [38]. As visual impairments often have important consequences on people's social inclusion [46], numerous assistive technologies (e.g. [40, 31, 36]) have been proposed for visually impaired *adults*. However, very few have been proposed for visually impaired *children* while (1) they are 19 million worldwide [38] and (2) early specialized care plays a crucial role in their development [12].

Designing assistive technologies for children is challenging. We lack insights on the way children experience disability and technologies [4, 7]. Moreover, it is difficult to access this population which is not prevalent in occidental countries and may lack time, given the fact that they have to attend quite a number of therapy sessions. Finally, it raises ethical issues such as obtaining children's and parents's informed consent, protecting their privacy, or proposing research processes beneficial for children's development.

In this paper, we report on the design process leading to the creation of a multi-sensory interactive map. We first conduct a 5-week field study in a specialized institute in order to get insights on the way children experience disability and technologies. From interviews with both caretakers and children as well as our observations of their activity and usages of probes [13, 20], we identified three major needs: the need

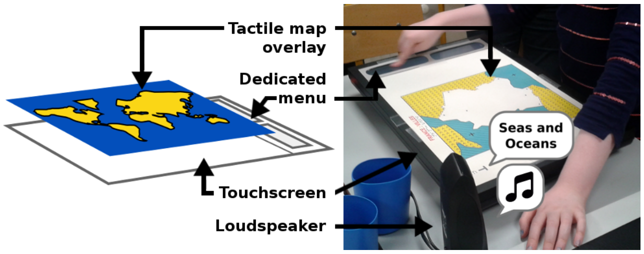

Figure 2: Mappie consists of a touchscreen, a colored tactile map overlay and a loudspeaker. Double tapping on a element of the map provides audio cues. A sliding gesture in the dedicated menu filters geographical informations (e.g. cities, seas etc.).

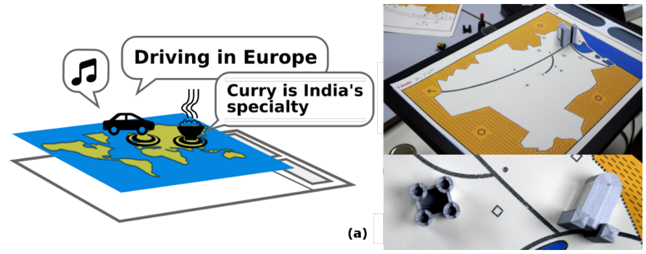

Figure 3: (a) MapSense augments the audio-tactile Mappie prototype with Do-It-Yourself conductive tangibles. Some tangibles are enhanced with food and / or scents. (b) On double tap, an audio cue is triggered. (c) Tangibles are also used to follow an itinerary.

for tools to help children access symbolic representations (including maps) in their own empowering way, the need to enable caretakers to easily design and produce highly specific educational material, the need for more collaboration between children (sighted or not) as well as between children and caretakers.

Building on the field study and our prototypes, we produced four design guidelines: (1) visual, audio and tactile aesthetic quality is beneficial for social and cultural inclusion; (2) multi-sensory interactions, which accommodate different cognitive and perceptive needs, are beneficial for collaboration and inclusion; (3) scenarios should be ludic and reflective (i.e. engage students to examine what they are learning, and to relate it to other experiences), to stimulate engagement and access to symbolic representations; (4) Do-It-Yourself methods enable a high-level personalization by children and caretakers, which reinforces the satisfaction of the former and eases the work of the latter.

Based on our findings and previous studies [34, 53, 5], we implemented a first interactive map called *Mappie* (Figure 2). Mappie is made of a raised-line map overlay, on a touch-sensitive surface. It uses colors and ludic audio cues, for children with low vision or with residual color perceptions, in order to enable a better collaboration in the classroom. Mappie was successfully used by a class of seven students during two months.

Our observations of children using a kinesthetic approach for learning and feedback from the teachers led to a second version called *MapSense* (Figure 3). MapSense augments Mappie with multi-sensory tangible artefacts to increase the number of possible use cases and improve inclusivity.

We observed 5 children and 2 caretakers using *MapSense* during two geography classes. We evaluated its adequacy to children's and caretakers's needs. Results show that the system (1) fostered collaboration while enabling personal cognitive strategies; (2) had a beneficial impact on children's memorization; (3) triggered creative and unexpected uses by children and caretakers; (4) suited the needs of children with different and multiple disabilities.

RELATED WORK

Assistive Technology for the Visually Impaired

Several prototypes have been proposed for blind people. They rely on tactile or haptic [40]), audio [36] or a combination of these modalities [45]. They are mostly dedicated to pedagogy (e.g. exploring mathematical formulas [36] or maps [15]), mobility and orientation (e.g. Electronic Travel Aids [48], object finder [10] or maps [45]), the access to graphic information [41] or games [32]. We review two sub-areas of assistive technologies: interactive maps and multi-sensory interfaces.

Interactive Maps. Accessible interactive maps can be divided in four categories [55]: 1) virtual acoustic maps are entirely based on verbal and non-verbal audio output; 2) virtual tactile maps make use of haptic (e.g., force-feedback) devices; 3) braille tactile maps are based on the use of dedicated raised-pin displays; finally, 4) augmented paper-based tactile maps use a raised-line map as overlay over a touch-display combined with audio output.

Mappie and MapSense, as well as previous works [34, 53, 39] belong to this last category, because tactile maps are easily produced by caretakers. When augmented with audio feedback, the maps are more usable than traditional ones with braille legend [5]. For instance, Miele et al. [34] proposed a system using informative audio cues and sounds for guidance, as well as a software to assist individuals in producing their own maps. Their system has been distributed, but we do not have data about its adoption. Our MapSense prototype differs from these systems because it exploits the olfactory and gustatory modalities as well as tangible interactions. Moreover, it has been evaluated in the field for a long period.

Multi-sensory Interfaces While, audio and tactile modalities have long been used in assistive technologies, it is not the case for smell and taste. However, these modalities have several potential advantages [26]. For instance, it has been shown that olfactory interfaces [22] can reinforce experience's credibility, pleasurability [27] and provides directional properties in virtual reality [23]. Gustatory interfaces are rare, but have been investigated for their ludic properties [35]. Moreover, several studies [47] point out that smell and taste may be used in education to facilitate elaborative encoding, or the process to acquire new knowledge by relating it to previous experiences, as they trigger souvenirs and convey emotions.

Figure 4: Top left: Probe 1, TactiGlobe, a tactile 3D printed globe. Bottom left: Probe 2, WoodMap, an interactive map with a laser-cutted overlayer, using ludic audio cues. Right: Probe 3, SoundRec, an audio-recorder Android app.

MapSense is inspired by these studies and provides multi-sensory experience through gustatory, olfactory, audio and tangible interaction. Only few assistive technologies rely on tangible interaction (e.g. the use of physical objects to interact with digital information [52]). For instance, McGookin et al. [33] used tangible interaction for the construction of graphical diagrams: non-figurative tangibles were tracked to construct graphs on a grid, using audio cues. Manshad et al. [31] proposed audio and haptic tangibles for the creation of line graphs. Pielot et al. [43] used a toy duck to explore an auditory map. However, we are not aware of assistive technologies combining gustatory, olfactory and audio modalities.

Design process

While numerous assisitive technologies have been proposed, several studies [42, 25] point out that they are often abandoned for various factors such as stigmatization, cost, maintenance or because they are not adapted to the caretakers practices [18]. For instance, two children with the same biological impairment may have different abilities depending on their familial and social context, the age of onset of blindness, the moment they started therapy, etc [1, 37]. Even the term "blind" covers a broad range of visual abilities: some people may have residual light perceptions, while others may see bright and contrasted colors. It is thus necessary to take into account the environment, in particular the relationships with the care-takers during the design process.

Involving Children in the Design process. Involving children in the design process and considering long-term needs (both are linked) can increase the adoption rate [42, 2]. For instance, participatory design methods have successfully involved children living with various impairments such as autism [30] or hearing [44] in design processes. Children can play several roles in the design process [11]: users, testers, informators or collaborators. Methods include observations, interviews, journals, collaborative prototyping sessions or probes [13, 20]. In our study, children were considered as design informators, even if we involved them as much as possible in design decisions. We conducted interviews and observations to share their activities and to get feedback on precise points such as probes.

Do-It-Yourself and 3D Printing. To improve the design process of assistive technologies, Hurst and Tobias [19] have proposed to promote "Do-It-Yourself" (DIY) approaches. DIY is useful in the design process because it allows anyone, user or caretaker, to build, create, iterate or personalize devices. DIY approaches may be enabled by digital fabrication techniques, such as 3D printing.

There is a growing body of work investigating the use of 3D printing for/by the visually impaired. Gual et al. [16] have studied the usability of several forms of 3D printed tangibles. Gotzelmann and Pavkovic [14] have proposed to semi-automate production of personalized maps, using open source data. Kim and Tom [24] have investigated the use of crowd-sourced 3D models to the design of personalized tactile books and the role of caretakers's community.

FORMATIVE STUDY: USES, PREFERENCES & NEEDS OF VISUALLY IMPAIRED CHILDREN & CARETAKERS

We conducted a 5-week formative study in a French specialized institute to identify visually impaired children's and caretakers's needs for the design of interactive maps. The institute provides therapy (e.g. psychomotrician, locomotion, speech, low vision and occupational therapists), pedagogical assistance for children attending inclusive schools, and specialized curriculum for children with particular learning needs. Moreover, it provides rehabilitation or professional training for young adults (such as YA1-YA3), some having recently experienced sight loss, while others seek professional retraining. The study consisted in two stages:

Phase 1. We conducted *observations* or participant observations (e.g. observing a situation while staying an outsider, or we were one of the actors of the situation observed and participating in activities as described by [21]). Those observations covered: functional therapy sessions; various classrooms; and transcribing processes (i.e. adaptations of educational material for visually impaired children). During those observations we met 40 young people living with visual impairments. We also met several of their inclusive school's classmates, most of them sighted, and some of them living with other kind of impairments.

We also conducted 13 interviews (Table 1) with children (aged 7-10), teenagers (aged 14-16) and young adults (aged 16-19) living with visual impairments. The interviews focused on their use of technologies, daily experiences and interests; We also conducted 12 interviews with caretakers (Table 2), about their roles and practices, professional history and the ways they defined children's educational projects.

Phase 2. During the second phase, we continued our observations and interviews. We also introduced three design probes (Figure 4) to get children's and caretakers's feedback on design properties such as ludic audio cues and colors,

Id	Gender	Age	Description
C1	M	8	Blind from birth with light perceptions, motor and psychological impairment
C2	M	10	Blind from birth with light perceptions
C3	F	9	Severe visual impairment from birth and dyslexia
C4	M	9	Low vision from birth
C5	M	10	Low vision from birth
C6	M	8	Deaf with remaining audio perceptions, severe visual impairment from birth and learning disabilities
C7	M	10	Blind with light perceptions and learning disabilities
T1	M	15	Blind from birth
T2	M	14	Blind from birth, autism
T3	F	16	Deaf with remaining audio perceptions from birth, blind from age 5
YA1	F	17	Low visual field from birth
YA2	F	18	Undergoing sight loss
YA3	F	19	Blind from birth

Table 1: Interviews: 7 children (C), 3 teenagers (T), 3 young adults (YA)

and to elicit new insights on the uses of digital fabrication techniques. The probes were *TactiGlobe*, a 3D printed tactile globe; *SoundRec*, a microphone android app; *WoodMap*, an interactive map of the oceans with a lasercut wood layer and three levels of interactivity: 1) ocean's names; 2) ocean's name with ludic audio cues; and 3) story describing ocean's fauna or surroundings, with ludic audio cues.

To analyze this data, we followed the Grounded Theory [6] method. We open-coded interviews transcriptions and observations. We then grouped them in four categories: uses of interactive technologies, preferences concerning technology aesthetics, needs in the classroom and caretaker's practices.

Findings

Children's uses of interactive technologies

All children, teenagers and young adults reported using interactive technologies in their daily lives: computers, braille note-takers, mp3 readers, tablets or smartphones. Computers and braille note-takers are available for all at the Institute, while tablets are confined to therapeutic sessions or to the family home. Smartphones (N=4) are personal, mostly used by teenagers and young adults, but they are customized by caretakers (either parents or CT9) and their use is taught in the Institute. Children and teens are also equipped with mp3 readers (N=6). Some reported playing video games using audio cues or remaining visual perceptions (N=7), all reported using Youtube (N=13). This is actually a concern in the Institute as caretakers do not perceive this website as serious enough. Children display a high enthusiast regarding the learning of new technologies, although they may refuse when they consider it as useless (T1: "I want to learn alone! Do you think I'm an idiot? (...) reading newspaper is not fun.").

This high adoption level may be partly explained by the fact that therapists and teachers have been early adopters of new media in the educational context (especially CT9 who has sensitized her colleagues), but it may also be linked to better accessibility features in recent phones (CT3 and CT9 underlined it was much easier to adapt and use iPhones).

We observed that technologies may favor social interactions and inclusion: communicating with friends and family (YA3: "sometimes it's just easier to talk by texts"), accessing mainstream media for social inclusion (T2: "because they were all talking about it, and I don't want to be weird") or sharing documents. Similarly, several children reported using internet to be able to help others (C2: "I feel good when I'm explaining things"). Interestingly, several children have underlined that the use of adapted technologies, that sighted peers or caretakers do not know well, are empowering for them and shift the roles of the "able" and the "disabled." (i.e. C1: "my smartphone makes me more-able and cooler than my (sighted) friends, because I can use it with a dark screen as if I was doing magic." C2, about his braille note-taker: "I am not the disabled, but the teacher is! He can't know what I'm doing, and I can play tricks. And I am not punished because, you know, I'm blind, so they're nice.") Here, their use of technologies enable them to redefine disability not as a limitation, but as "special abilities." It seems to enable them to develop a positive self-image and to help them manage their relationships with others.

Design implications: It follows that there is a high adoption rate of technologies among the young people living with visual impairments we have met. The technologies they use may be different (with variations depending on age and impairments), but the will to get access to mainstream media is common. In each example, technologies are self-gratifying. They ease social inclusion, dialogue, collaboration access to culture or propose interactions visually impaired children are actually better at than their sighted peers. Designers should provide ways of supporting children expressing themselves positively in social interactions (i.e. helping them, on their own terms, when interacting with others) and enabling them to tell their own stories using objects.

Children's preferences concerning technology aesthetics

When asked to describe the technologies they used, or while observing their interactions, all youngsters commented on their aesthetic experience with devices. The first properties they highlighted were tactile ones and were either expressed verbally (T1: "That [smartphone] is so soft, it makes me feel good;" C7 "Wood! I like touching wood. It's noble;" C2 "This kills my fingers;" YA3 "Do you feel these scratches? They say a story;" T2 "I don't like to touch that part, it's too hard;"), or using body language (i.e. T2 and C6 would "stroke" an object, and C6 would either smile and laugh or discard the object).

Most children also highlighted the role of the olfactory experience. For instance, when discovering *TactiGlobe*, C6 first raised it towards its nose. Or when asked to show its smartphone, T1 encouraged to smell the leather case ("it reminds me of grandpa"). When discovering *WoodMap*, C5 exclaimed: "Burnt wood! Like summer's camp!"

Same goes for auditory cues: C1, C2, C5, T1 and T3 gave special care to the ocean's sounds of Probe 2, even commenting it did not sound like "their" ocean (e.g. the Atlantic). T2 and YA3 explained that they would not listen to audio books if they were not read by humans (YA3: "people's voice make me feel what they feel") although they would use the most common and rapid synthetic voice for practical informations.

ID	Gender	Role	Expertise
CT1	F	Parent	White collar worker
CT2	M	Locomotion Instructor	Mostly working with adults in professional retraining, used to work with researchers, expert in sensitization
CT3	F	Locomotion Instructor	Deafblind and accessibility specialist, used to work with researchers in a foreign lab
CT4	F	Psychomotrician	Theorician and practician
CT5	F	Speech therapist	Specialist in logic-mathematics and mental management
CT6	F	Low vision therapist	Experience with all age groups for 30 years
CT7	F	Specialized teacher	Ex-lawyer, used to work with researchers, mostly working with children living with multiple disabilities
CT8	F	Specialized teacher	Blind, teaching braille for 30 years
CT9	F	Occupational therapist	New media and tactile devices specialist
CT10	F	Transcriber	Low vision, maps and books in fabric specialist, working in fablabs
CT11	F	Transcriber	Thermo-inflated documents specialist
CT12	F	Art teacher	Contemporary art specialist, expert in sensitization
CT13	F	Psychiatrist	Identifying each child needed care (psychological, social, medical etc.)

Table 2: Description of the 13 caretakers interviewed

Surprisingly, visually impaired children seem to be sensitive to colors as well, asking whether or not objects had colors, and to describe them. This was confirmed by CT12 who uses colors in art classes for their ”symbolic importance” (e.g. Blue is mom’s color, rose is love). She also underlined that there were quite a number of legally blind children who could actually perceive bright and contrasted colors. Assistive technologies without colors may be perceived as stigmatizing (YA3 about TactiGlobe: ”all white? (...) It screams *this is for blind people*”). Moreover, several children expressed the fact they would like to customize our probes (T3 about TactiGlobe: ”I want that, but bigger. And to be able to turn it on an axis”), which may be connected to overcoming material activity limitations (T3: ”I’ve always wanted a tactile globe. But [the cheap ones] not sold anymore!”).

Design implications: Tactile, olfactory and auditory experiences of technologies seem to trigger rich memory association, satisfaction and pleasure, and to serve as connections between life experience and technologies. Colors should not be forgotten, as they keep a symbolic meaning even for children without sight. Designing Assistive Technology with this concern in mind could lead to richer and more meaningful experiences, and ease the ”psychological distress most of our children feel” (CT13). Furthermore, multi-sensory learning is a promising pedagogical approach [50].

Children’s needs in the classroom

When presented with Probe 3, SoundRec, all children (N=7) used it to record their own voice, before listening to it and recording it again (louder, further from their mouth etc.) if they were not satisfied. C5 played with it to answer our questions (as if ”I was a journalist”). C4 used it to explain his lesson to himself. C7 used it to narrate a story his ”own way.” These reactions point to the importance of objects in reflective practices (i.e. reflecting upon action for continuous learning [49]). Moreover, caretakers use objects to symbolise children’s personal experiences of the world through ludic scenarios (CT7 to C1 ”Imagine you are this figurine and you are buying those flowers (...)”), or objects may hold special meanings or experience (when T3 discovered Probe 1, TactiGlobe, she exclaimed ”earth is so much greater than I imagined! And I am so small in comparison!”).

Earlier, we saw that children had various sensory experiences of the technologies they used. It is to be noted that gustatory perception is also exploited by teachers and therapists in their activities (CT3, CT4, CT7, CT12). CT7 described it as a ”cognitive approach,” that can help to link various informations to an object and facilitate the memorization and the development of mental representations, including spatial ones. For example, she uses regional foods in her geography classes, in connection with a map and stories from around the world. Children express whether they like it or not, and often connect it to their own history. For example, C3 explained where she had tasted this food before, or C6 mimicked how to make a cake. Similarly, locomotion trainers may use gustatory perception to help children remember a point of interest while exploring the city: if they tasted something during the outdoor session, they would eat it again when working on maps to develop a mental image, or symbolic representation of their journey.

The need for more collaboration was highlighted by both children and caretakers: collaboration with sighted peers (C7: ”Often I can’t work with the other children in my class;” T3: ”I don’t want to be ”the disabled. I want to do like others—only differently.”), collaborations between children in adapted classes (CT2 ”I often work with several children at the same time, and they all have different mental models.”) and collaboration between caretakers and children (CT7: ”even if I only have five to seven children in my class, I can’t help them individually at all time. My goal is to make them as autonomous as possible. For that, they must want to learn, know how to do so, and when to ask for my help.”). This is in line with enabling reflective learning practices.

When asked about their objectives in the classroom, caretakers outlined the fact they were juggling between official national education programs and three global objectives. The first is ensuring the best social inclusion for children, the second is to develop their autonomy, and the third is to foster their well-being. To reach these goals, caretakers often insisted on the need to help children access symbolic representations, so they can efficiently communicate and understand what surrounds them.

Design implications: Traditionally, when assistive technology for visually impaired people proposes multi-sensory outputs, it consists of audio-tactile cues. It would be interesting to consider olfaction and taste when designing multi-sensory experiences. It could reinforce children's satisfaction, engagement and cognitive development [50]. It should also have a positive impact on the development of a reflective approach to learning [49], as it allows children to relate the symbolic representation to their everyday experience. Designers should also meet this need for reflection by proposing artifacts and technologies supporting storytelling, ludic approaches to learning and providing meaningful symbolic representations of life experience. To overcome the activity limitations linked to disability, designs should focus on enabling collaborations as it allows children to overcome activity or participation limitations.

Caretakers' Do-It-Yourself practices

Most of the adapted material is realised within the Institute (e.g. braille or enlarged schoolbooks, maps etc.). Caretakers underlined the lack of fundings, and thus the lack of available educational resources (CT1, CT2, CT5, CT7, CT8, CT10). Adaptations are time consuming, leading some caretakers to feel overworked (CT10, CT11, CT7, CT3, CT4), not entitled to ask adapted material for their activities (CT2, CT3), or to skip lunch to work more (CT7, CT3, CT4). Adapting technologies for children is also part of the Institutes's missions, but several caretakers (CT9, CT3) feel like it's difficult to stay up with new technologies, as accessibility features are not precisely described and may be very different between one device and the other (CT9). Furthermore, caretakers feel they do not know yet how to use well and efficiently some tools at their disposal (e.g. Inkscape or Microsoft Word) but are willing to continuously learn (CT7, CT10).

Caretakers reported having always made Do-It-Yourself adaptations, and being interested and pleased when doing so (CT10). Since the beginning of our study, some caretakers have spent quite some time in fablabs to find out what electronics, 3D printing and lasercutting could bring to their practices (CT7, CT12, CT9). They underlined it eases the adaptation process and broadens their possibilities. Which also has a downside: the institute dedicated carpenter was not replaced, for example. Caretakers also have a strong engagement in communities. For example, CT7, CT5 and CT9 teaches other caretakers their methods, CT12 and CT10 are often solicited by artistic venues to develop adapted materials, CT2 and CT3 do a lot of sensitization or CT3 attends public meetings to expose her views on accessibility.

To summarize, this illustrates the financial and practical barriers to full accessibility—which are also felt by children (C2: "the law says everything should be accessible, so I don't feel disabled." T3: "I've always wanted a tactile globe. But [the cheap ones] are not sold anymore, [it is] so expensive!").

Design implications: Studying the broad range of caretakers's practices may provide numerous design guidelines. They are quite expert concerning colors or textures that can be used, how to simplify objects for tactile understanding, which kind of sounds are representative, which kind of gestures are meaningful etc. Also, designers could provide tools to share experiences or models, facilitating or enabling Do-It-Yourself adaptations to ease caretakers workload.

Analysis

Our findings are consistent with the literature: A DIY approach to Assistive Technology is empowering for children and caretakers [19], technologies perceived as stigmatizing are more often abandoned [42, 3], children may not feel disabled once the material barriers are overcome [9] and technologies allow them to develop strategies to reduce negative reactions from other people. Children's use of assistive technology and their educational context influence which activities they can engage in, as well as their experience of disability [17]. It also underlines the need to assist caretakers in the realisation of adaptations, used to help children access symbolic representations and develop accurate mental representations—including spatial ones. Nevertheless, it should be noted that those results should be completed by further investigations on the roles of parents and family relationships in children's education. As parents are not often present in the Institute, we could only interview one of them.

To summarize our design recommendations, designers should propose assistive technologies soliciting several sensory modalities to enable different cognitive approaches. Classrooms' technologies should enable collaborations between children living with or without various impairments [54], therefore also accommodating visual learning. They should support ludic pedagogical scenarios, encourage storytelling and children's reflectivity on what they are learning, which may be achieved by allowing a high level of customization using Do-It-Yourself techniques, as well as by taking great care of aesthetic properties (textures, colours etc.).

MAPPIE: FIRST INTERACTIVE MAP PROTOTYPE

Motivations. We built Mappie (Figure 2), an interactive map prototype to explore how to help children access symbolic representations. This prototype aimed (1) at involving several caretakers in a participatory design process (especially CT3, CT7 and CT10) on a long term basis, to investigate if and how this would raise technology adoption; (2) at getting insights on the impact of colors and ludic audio cues on children's collaboration in the classroom as well as on their memorization of the map. Indeed our formative study showed that colors not only had symbolic importance, but can also enable better collaboration between children with remaining color perceptions. As for ludic audio cues, we saw that it could be used to help children relate the symbolic representation to their everyday experience.

Setup. Mappie is an extension of a previous existing prototype [5]: a tactile map overlay on a touchscreen triggering verbal audio cues when clicking on a point of interest. These maps can be produced autonomously by caretakers using swell paper. Mappie consists of a 22" capacitive projected touch screen 3M 2256PW and a computer running a java program managing the sounds using the MT4J library [28]. It may be connected to speakers or to a hearing aid when necessary. The overlay is a colored tactile map. At the right of the map, a first menu allows user to define the type of geographical informations to access (e.g countries, cities, rivers). In return, the system delivers audio feedback to confirm the selection. A double tap executes it. A second menu, contextual

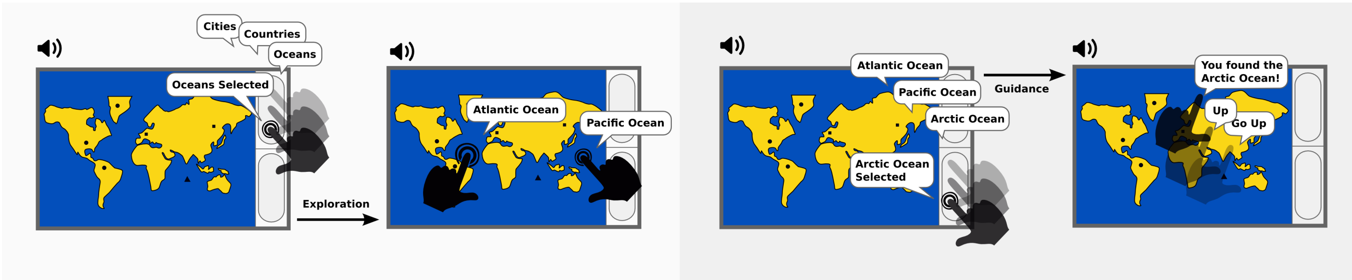

Figure 5: At the right of the map, a first menu allows user to define the type of geographical informations to access (e.g countries, cities, rivers). In return, the system delivers audio feedback to confirm the current selection. A double tap executes it. A second menu allows to choose a specific point of interest and be guided towards it.

to the first one, allows to choose a specific point of interest and be guided towards it (Figure 5). Once an element is selected by double tap, the system provides audio directions. Once the user has found its targeted point of interest, the system provides a verbal confirmation. On doubletaps on a point of interest, we added ludic audio cues, such as songs.

Evaluation

Deployment. Mappie was used by seven children and CT7 in their weekly class during three months at the end of our formative study.

Findings. The reactions to the use Mappie are consistent with the literature on the same kind of devices [5]. It enhanced children's satisfaction (C3: "fun to use", C2: "very much more practical", C6: "I liked it better"), compared to non-interactive maps. CT3 reported that Mappie required maximum half an hour of use for children to learn how to use it, even for children with motor impairments. Specifically, children reacted positively to the use of colors (C2: "I prefer to touch that one, because it has colors"). According to CT7, the use of colors enabled closer collaboration in the classroom: children with all kind of visual impairments were able to work on the same map.

Mappie also had a positive impact on the cognition of children (CT7: "usually, they recite their lesson without understanding. But [with Mappie] they told me stories about the map, which is perfect because I can evaluate what they understood and how"). CT7 underlined it was beneficial for children's short term and long term memorization, over a week, and over two months (CT7: "usually, I have to remind them everything we've done the week before. [With Mappie] it's faster to remind them what we worked on. Also, they remembered it after the summer holidays! That's huge!") and to keep them focused on an activity (CT7: "Sure, there's a part of *wow, that's new and cool*, but overall, it helps them not to get frustrated, to concentrate and to work together").

MAPSENSE: SECOND INTERACTIVE MAP PROTOTYPE

Motivations. Mappie successfully involved caretakers in the design process and had a positive impact on children's collaboration and cognition. However, CT7 and CT3 underlined it was not covering all needs: it had a limited impact for children with specific cognitive needs. For example C6 uses a kinesthetic approach to learn and discover concepts through movement. Furthermore, several spatial concepts, such as altitude or being on top/under something (like a bridge for example), are difficult to translate on a 2D map.

We thus designed a novel version of Mappie, called *MapSense*. MapSense's design was guided by some findings of our formative study such as using unconventional modalities—olfactory and gustatory—to foster reflective learning, and use objects to support storytelling. Moreover, MapSense relies on tangibles, as it was proposed in brainstorming sessions with CT10 and CT7. Indeed, tangibles can allow a larger variety of cognitive approaches and can be carried during the class trip, serving as "narrative vessels" (CT7) between the map and the lived experience [8]. They should also enable collaboration as they can be exchanged or played with. We kept a participatory design approach, as it was used successfully with Mappie. To sum up, our goals were (1) to explore olfactory and gustatory modalities as a way to foster reflective learning and memorization; (2) to explore figurative tangibles, as supports of storytelling, in the acquisition of spatial skills; (3) to get insights on the impact of this multisensory approach on children's collaboration; and (4) to investigate whether this approach would empower children and caretakers.

Setup. MapSense uses Mappie's hardware (i.e. an overlaying tactile map on a 22" capacitive projected touch screen). In addition, it also uses tangibles. These ones are detected by the screen as touch events. MapSense uses the same interaction principles: the menu allows to select the type of informations to access. Users could navigate between "points of interest," "general directions," and "cities" (Figure 5). Once one of this type of informations is selected (e.g. cities for example), MapSense gives the city name through text-to-speech when it detects a double tap on a point of interest. Children could also choose "audio discovery" which triggered ludic sounds (e.g. the sound of a sword battles in the castle, of flowing waters where they were going to take a boat, of religious songs for the abbey etc.). Finally, when users activate the guiding function, vocal indications ("left/right/top/bottom") help the users move the tangibles to their target (Figure 5).

Maps. We designed two colored tactile maps illustrating the class trip (Figure 6): one with all the points of interest the

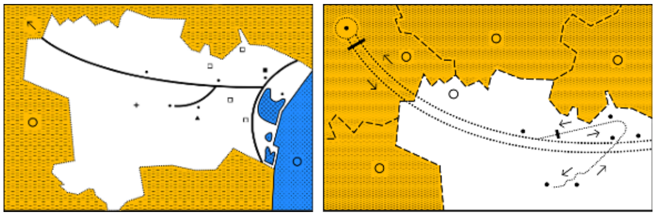

Figure 6: Left: Map of a french region, with cultural points of interests. Right: Map with the itinerary of the class trip.

Figure 7: MapSense's Do-It-Yourself tangibles were 3D printed. Some were added sticky aluminium to be conductive. The flags were printed using conductive PLA. The bee is used with the versatile conductive supports, that can be used with any toys or objects. The bowls can be filled with scented oils or food.

children were going to visit, the other illustrating more precisely the itinerary. These maps were produced by CT10 on swell paper, and can therefore be produced autonomously by the caretakers. A smaller non-interactive version of the map, was printed for each child to take home.

Tangibles

Design. MapSense provides fourteen "Do-It-Yourself" conductive tangibles. They were designed in collaboration with CT7 and CT10, on the CAD tool Tinkercad. CT7 and CT10 described or drew the objects while the researcher was building the 3D models with instant feedback. The choice of objects was guided by CT7's pedagogical needs as well as by requests formulated by the children (e.g. C7 wanted to know what a bee is like).

Fabrication. We 3D-printed the eleven tangibles illustrated in figure 7. We also used three commercial toys (a duck, a car and a bottle of wine) augmented with 3D printed supports. We used "protopasta" PLA filament as material. We added aluminium around 6 tangibles, as it is conductive and could be detected. We used those two approaches mainly for aesthetic and practical reasons. It is easier for children to manipulate objects without any additional support, but the aluminium must be discreet and in line with the object design. Even if it does not take much time to add aluminium, using conductive supports is more convenient for caretakers. Moreover, using aluminium requires that the object have a flat part, and it was not adapted to several tangibles.

Smell and Taste. Some tangibles (Figure 1) could be filled with "scents:" olive puree, smashed raisins, honey...

Guidelines. We established a few guidelines in collaboration with CT9 and CT13: artifacts should (1) be larger than three centimeters to be recognisable because small volumes may be difficult to understand; (2) have bright and contrasted realistic colors, to be consistent with residual visions and not be considered as stigmatizing; (3) artifacts should not have sharp relief, as it is uncomfortable or frightening during exploration (i.e. children would avoid some part of the object in order not to hurt their fingers); (4) surfaces should be at least "two fingers large" (CT7) so children can feel the differences between the volumes; and (5) objects that could be compared during the class (i.e. historic sites like the abbey, the cathedral and the castle) should respect the differences of scale, to provide a correct mental image.

Evaluation

Deployment: Those two maps were explored during two classes of 3 hours separated by a week. They were taught conjointly by a locomotion trainer and a specialized teacher (CT7). They are working in collaboration with other caretakers (educators, CT5 and CT12) to develop children's autonomy in the city, general culture and spatial skills. CT7 outlined the activities she wanted to conduct, but the scenario of use was very flexible and depended on children's inputs. It included: general discovery of the map (title, orientation, surfaces); exploring through sounds; exploring the itinerary and its surrounding points of interest; situating a point of interest in comparison to another using cardinal points. The sessions involved 5 children (C1, C2, C4, C6 and C7).

First, the children explored a non-interactive version of the map. Second, they tried to identify the tangibles. Then, one child used MapSense to trigger ludic cues while the others tried to associate it with one of the tangible. After that, they worked on the concept of directions, one child using the car on the tactile map while the others were following the track on their own paper map. For a second activity, they gathered around the interactive map and answered the teacher's questions about the position of the points of interests (e.g. "The city of Carcassone, is it east or west of Toulouse?"). The children proposed and tried to argument their answers, which were then checked using the interactive map (e.g. one child would "drive" the toy car on MapSense).

We observed children and caretakers, assisting them with manipulations, and regrouped our findings following the same method [6] than our field study.

Findings

Satisfaction and reflective learning: The maps and artefacts seemed to trigger strong positive emotions (C2: "That is... a castle! Castles are great! They're old and impressive!"). The tangibles quickly passed from hand to hand and children played with them (C1 would trigger the bee sounds before trying to surprise his classmates with the 3D printed one). Children used the tangibles to trigger sounds they liked several times in a row, laughed to the sound of a wine bottle opening (to symbolize the wine museum), mimicked knights while listening to the castle... Moreover, they commented that it was fun, that they liked the tastes and odours (C7: "Oh this smells good! Can I eat it?") and were highly focused. They volunteered for each activity, and asked if they were going to use the prototype again. However, at the end of the second class, C2 and C4 expressed boredom by sitting down apart from the others: they had quickly discovered and learned and had to let others use the map and artefacts. They were asked to help C7 and C6 with manipulations, which triggered their interest again.

Learning strategies and collaboration: While interacting with the prototype and with each other, children used different strategies. C2 would take one or several objects to use them with his non-interactive map, if he had already understood the teacher's explanations. C1 would keep an object in particular, especially the tangible with olive puree. C6 always shook the artefact when discovering them—CT7 underlined that he often had displayed kinesthetic learning methods (e.g. learning using movements). C4 would help C6 by repeating the sounds he just heard. C2 helped C1 associating the smashed raisin odour with the bottle replica before placing it on the map to trigger the sound of wine bottle opening. On the other hand, C2 tried to interact with the map while C6 was already fulfilling a task, but the two interactions were conflicting (as the interactive map does not provide multiple interactions at the same time). C2 also suggested it would be interesting to use it with his sighted classmates "so I can work with them better." C6 used the tangible car not just for triggering audio cues but also as a tool for exploring the maps. He listened to C2's guidance to go from one point to the other. When interacting freely with the map, they negociated "where to go" (C7: "Me, I want to go to the place where there are olives! I know that when it is crushed for oil, the olive makes a cool sound" C6: "Can we first take the car to show where my home is?").

Adoption and unexpected uses: We had had numerous discussions with caretakers before the class and identified several scenarios of use, such as placing the tangibles by types of informations (i.e. all the tangibles representing cities, or all the ones representing points of interest), or using the car to follow the road when exploring the journey. But new scenarios emerged during those two sessions. The first observation was that the teacher also used the tangibles to compare data quantity, by comparing the number of cities to the number of visits. It gives a synthetic view of the maps data, which is usually accessed only by fragments (i.e. one data point at a time).

A second observation was that we could not place several tangibles at the same time as planned by the teacher: indeed, they were pushed by the children and fell down. However, C7 used the objects one by one to trigger the informations but placed the others on the side of the screen. C6 placed the scented tangibles, before replaying the journey to get there with the car toy, projecting himself in the scenario ("I am in the car, I'm going to see bees"). C7 used the car to reproduce the journey besides the map, without feedback. This is quite interesting as reproducing maps is "very difficult, if not unavailable, to most blind people" (CT7).

Children's empowerment: Children not only used our prototype in unexpected and personal ways, they also suggested sounds or artefacts to be added and other applications (games, historic battles...). C7 asked to follow another itinerary ("can we also go to the Pyrenees, in the south?"). C1 proposed that all points of interest should be accessible at the same time, and insisted on the fact that he was able to use the map without help. All children wanted to demonstrate they know how to use the maps (C1: "Don't help me, I can do it alone!"), and to show around the 3D printed artefacts.

Impact of MapSense on memorization: At the end of the first session, the locomotion trainer felt that, for some children, it was only a game or a reward for good work. At the end of the second, she asked whether we could use audio records made by the children during outdoors sessions, so they could make highly personalized and subjective maps. Moreover, the caretakers commented they had better results when interrogating the children, after working with this design, than with traditional maps. After the sessions, the teacher was very enthusiastic to see they were perfectly able to orally describe the map a week after having worked on it, which had never happened before. In future work, we will check if this is true on a longer time span.

DISCUSSION

The impact of MapSense on the classroom

MapSense aimed (1) at exploring the use of the olfactory and gustatory modalities, as a way to foster reflective learning and memorization; (2) at exploring the use of tangibles, to support storytelling, in the acquisition of spatial skills; (3) at evaluating the impact of this multisensory approach on children's collaboration; and (4) at evaluating whether this approach would empower children and caretakers.

The observations above show that MapSense was overall perceived as being satisfactory and pleasurable. Each child used the system differently: the use of tangibles, as well as gustatory and olfactory modalities allows for highly personalized learning strategies. This is in line with the literature [27, 47]. It also enabled them to add personal stories during the exploration process and engaged them in proposing design modifications. Children made use of tangibles to reflect on what they were learning as a way to relate it to their past experiences. The maps can be modified on demand, and we wish to enable them to change the sounds on their own. MapSense was used by children with different and multiple disabilities (see Table 1). This suggests that our approach may cover a broad range of children with special needs and foster their inclusion in regular schools.

Our multisensory approach also improved collaboration: the children helped one another by using their preferred modality. This collaboration is not just beneficial for the helped children. It is also empowering and gratifying for the children who help. Furthermore, children complete each other's abilities which could contribute to overcoming the participation barriers of disability as it reinforces their self-esteem.

MapSense improved children's memorization and understanding of spatial data. It shows that our prototype successfully assist children in the construction of their own knowledge and can be used by caretakers to stimulate collaboration. This opens perspectives for new pedagogical approaches for the caretakers. A few months after these experimentations they underlined that they needed more teachers to be involved so they could better reflect on their teaching practices. The set of all possible scenarios is still to be determined. Further inquiries will be made in future work.

MapSense was quickly adopted by the caretakers, and seem to reinforce their engagement with technologies, which is consistent with the literature [19]. For example, after those sessions, CT10 can now design and print her own 3D models, create a map and various tangibles (laser-cut or 3D printed) with CT3, without our assistance. The Do-It-Yourself process also allows caretakers to have full control over the production of educational material, and on the pedagogical goals of their lessons. It eases their workload as they can design exactly what they were searching for, instead of multiplying adaptations. Nevertheless, producing maps and tangibles remain time consuming. We aim at automating part of the maps's production process using custom software, and at fostering a community of caretakers using digital fabrication techniques, as others also advocated [24]. The empiric recommendations proposed by caretakers during MapSense's design are a step towards this latter goal.

Our system has perspectives for other graphics, such as historic or artistic documents because they are predestined for multi-sensory scenarios (i.e. historic auditory documents, tangible artwork etc.). The prototype itself should be enhanced to identify tangibles regardless of their material and to allow for multi users interactions.

Design recommendations

We observed 40 young people living with visual impairments and interviewed 13 of them. We completed these observations with 13 interviews of various caretakers (representing all the therapeutic team and most of the educational specialists). From these observations and interviews, we identified key design features intervening in children's experiences of technologies. We also exposed various practices and factors impacting children's uses of technologies and proposed design recommendations. Using these findings, we designed an interactive map prototype, that we implemented and tested. The goals and success criteria identified with children and caretakers (i.e. fostering children's collaborations and reflectivity to empower them, improving their access to symbolic representations and engaging caretakers with new technologies to open new pedagogical perspectives) were met during these sessions.

The number of participants was small, but represented a wide range of impairments, social situations and age. Moreover, interviewing and observing caretakers allowed us to outline a wide picture of children's educational environments. We adopted a triangulation method [29] (i.e different methods such as field studies, field experiment, etc.) to guarantee reliable and appropriate feedback. Our findings are consistent with the formal theory proposed by the literature on the sociology of childhood and disability studies [9]) and our recommendations complete and extend existing design approaches (e.g. [19, 51]) by taking into account a variety of users.

Our prototype has already raised interest in three other specialized institutions, as well as in the regular schools that the children attend part time. Nevertheless, further studies are necessary to extend our results to other impairments or educational contexts, because the caretaking processes may be quite different (i.e. if children attend regular schools, the teachers may have less time to prepare tangibles and would prefer a pre-defined set and scenario). Our results should serve as a basis for contrastive analysis and be used to "probe" other fields.

Our recommendations can be summarized as follows:

- Taking great care of visual, audio and tactile aesthetic quality, is beneficial for inclusion and for reflective learning, as it evokes past experiences and triggers positive emotions;
- When designing for the classroom, one should be designing for inclusion and collaboration, using multi-sensory interactions as they accommodate different cognitive and perceptive needs. Tangibles seem to be particularly beneficial as they can be used in multiple ways;
- Scenarios of use should be ludic and engage children in storytelling. It stimulates engagement and reflectivity, thus improving access to symbolic representations;
- Do-It-Yourself methods enable a high-level personalization by children and caretakers, which reinforces the satisfaction and engagement of the former, and eases the work of the latter.

CONCLUSION

We conducted a field-study on visually impaired children's uses of technologies and caretakers practices in the context of a specialized institute advocating an inclusive education. These observations allowed us to propose design guidelines for educational technologies, based on multi-sensory interactions to support collaboration, inclusion and reflectivity. We also reported findings from the field for the design of tangibles. Future work will include an extended field-study of a year on the impacts of our design and approaches upon children's ways of learning, experiences, and caretakers's practices; the design of wearable technologies for children encompassing our design insights; as well as a design toolkit for caretakers and other schools.

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