Enabling Collaboration in Learning Computer Programing Inclusive of Children with Vision Impairments

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ABSTRACT
We investigate how technology can support collaborative learning by children with mixed-visual abilities. Responding to a growing need for tools inclusive of children with vision impairments (VI) for the teaching of computer programing to novice learners, we explore *Torino* – a physical programing language for teaching programing constructs and computational thinking to children age 7-11. We draw insights from 12 learning sessions with Torino that involved five pairs of children with vision ranging from blindness to full-sight. Our findings show how sense-making of the technology, collaboration, and learning were enabled through an interplay of system design, programing tasks and social interactions, and how this differed between the pairs. The paper contributes insights on the role of touch, audio and visual representations in designs inclusive of people with VI, and discusses the importance and opportunities provided through the 'social' in negotiations of accessibility, for learning, and for self-perceptions of ability and self-esteem.

Author Keywords
Collaboration; design for children; visual impairment; visual disability; accessibility; education; tangibility; tactility.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
As children grow up in the digital age, more importance is being given to computing education [31, 38, 48]. This has motivated establishment of organizations such as *code club*[i] and *code academy*[ii] , which offer online learning resources, and the development of visual and physical technologies specifically for teaching coding to children [15]. All of these resources require vision to either create code [26, 43], or experience its result [50]. Being reliant on visual imagery, such as drag and drop blocks to create code, or animation to experience the code, these tools are inaccessible to young children with vision impairments (VI) [34, 54, 61]. While accessible programing languages exist for older children, e.g. *Quorum*[iii], there is still a need to identify suitable tools for teaching programing to children as early as ages 7-11 [15].

To address this gap, we created *Torino*, a physical programing language for teaching basic programing constructs and computational thinking to children age 7-11, regardless of level of vision. Torino offers instruction beads (Figure 1) that can be physically connected and manipulated to create code that generates stories or digital music. We describe the design process and implementation of Torino, and first insights into the usability, understanding of the concept of, and engagements with, the technology elsewhere [46]. One aspect that received particular design attention was collaborative learning. With the majority of children with VI in the UK being educated in mainstream schools, or special schools that are not specific to VI [53], we wanted to design a technology that enabled inclusive learning through collaborative use independent of level of vision.

In this paper, we assess in detail how collaborative learning took place with Torino. Specifically, we draw insights from 12 sessions involving five pairs of children with mixed-visual abilities to explore how they collaborated using Torino. To work collaboratively typically presents a major challenge to children with VI. A lack of vision not only complicates the locating or identification of objects that are being attended to or manipulated by others, it also impedes non-verbal behavioral cues intrinsic to social communication and coordinating of tasks. Despite these difficulties, research has demonstrated that collaborative learning (CL) can: result in higher achievement and productivity, foster caring, supportive and committed relationships, aid psychological health, self-esteem, and social competence [37].

Against this backdrop, our research explores: (i) how the design of Torino assisted or hindered the children's sense-making of the technology, (ii) how children with mixed-visual abilities were collaborating using Torino and how this was bound-up with learning important computing concepts, (ii) and how they experienced such collaboration in learning.

Examining differences between the learning pairs, our findings contribute rich insights as to how educational and collaborative designs can sensitively respond to variations in visual ability, account for differences in learning styles, and

DIS 2017, June 10-14, 2017, Edinburgh, United Kingdom
 ISBN 978-1-4503-4922-2/17/06…$15.00
DOI: http://dx.doi.org/10.1145/3064663.3064689

include strategies for recovery from potential breakdowns in understanding. Furthermore, in demonstrating the value of collaborative learning especially for children with VI, we discuss the importance of the 'social' not only for accessibility; but also for the children's self-esteem and perceptions of their abilities as they experience themselves as achieving and as valued contributors to the learning group.

BACKGROUND & RELATED WORK

We first describe HCI research and design for people with VI, and for assisting collaboration and learning of children with mixed-visual abilities. We then present a definition of collaborative learning and describe common mechanisms to assist collaboration – especially in absence of vision.

Design for People with Vision Impairments

The majority of existing assistive technologies (AT) seek to support people with VI in carrying out everyday activities *independently* [i.e. 18, 23, 68, 70]. As a result, explorations into how accessibility is managed socially by people with mixed-visual abilities are more limited. Branham and Shaun [6] present a recent exception. They interviewed pairs of persons with VI and a sighted partner to understand how they created an accessible environment at home by organizing things spatially, using tactile markers and jointly rehearsing certain routines. Other research [2] suggests supporting social communication between persons with VI and sighted peers using computer vision to recognize facial expressions and gestures. There are also interface examples utilizing audio and haptic feedback, often in addition to graphics, to support accessibility and collaboration by blind and sighted users [55, 56, 66, 69]; many of these examples are games.

Accessible, Fun & Collaborative Games

Many of the games designed to be accessible and fun to be played by sighted and blind gamers are built on sounds, rhythm and music [3, 19, 39, 67, 71], and gestures and haptic feedback for interactions. Examples include *AudioOdyssey* [22], a rhythm game in which users' generate music using a keyboard and Wiimote controller, or *Audio Flashlight* [66], a mobile game in which a phone serves as an audio 'radar' to help find a treasure inside a dark room. Other games seek to offer entertainment and support socialization specifically for children with VI. These designs typically combine spatial sound with a graphical interface [14, 42], or are built solely on touch-input and the generation of music to be accessible [36]. Whilst designed to be fun, easy-to-use and inclusive of sighted players, these systems were only ever evaluated for their technical feasibility [14, 56], usability [22, 42], and accessibility [66] rather than for their potential in promoting collaboration between people with mixed-visual abilities.

One exception in this regard is Winberg and Bower's [69] game *Towers of Hanoi*. It offers a visual interface for sighted and an auditory interface for blind users. Being collocated, pairs of a blind and sighted player were instructed to take turns in moving discs in the game. A study with three pairs revealed how users interleaved their movements with verbal explanations of their reasoning and steps taken, and how sonic feedback in response to the sighted person's actions aided the blind player to orient in the game. Thus, the authors found that successful collaboration was not achieved through the accessibility of the interface alone, but the interplay of different senses and skills, a monitoring and listening to the partners' actions, and by remembering the state of play.

Educational Designs for, or Inclusive of, Children with VI

Elements of game design are also employed in educational designs for children with VI [i.e. 47]. Song et al. [62] i.e. designed audio-based mobile games to improve spatial orientation of children age 13-17. The game was played in groups of 3-6, which the children enjoyed particularly for being able to discuss their solutions and share success stories. Others [i.e. 55] describe combining spatial sound with user movements on a haptic carpet for navigating children (age 6-14) through a virtual game. Besides, haptics such as force feedback, vibrations or touch have been explored for teaching how to: draw and recognize geometric shapes [9, 52], improve math literacy [8], handwrite characters [49], or practice Braille [1]. There have further been efforts in HCI for creating tactiles using Lego and 3D printing [35] to assist emergent literacy [64], and to learn abstract concepts [57].

Designs for learning computer programing are limited [41, 54, 61, 65]. The few existing developments in this area include accessible programing languages (i.e. *Quorum*) and speech interfaces (i.e. *Emacspeak*[iv]) that can be effective tools for those who already know how to code, but are often less suitable for novices. To assist computer science majors with VI to learn how to program, Smith et al. [61] introduced *JavaSpeak*, an editor providing additional information about the structure and semantics of written Java code. Sánchez and Aguayo [54] created an *Audio Programing Language* for blind, novice learners (age 17-20) to simplify the program logic and commands, and offered step-by-step instructions. Ludi et al. [41] presented *JBrick*, a technology that simplified the browsing and entry of text commands and code compilation through visual and audio-feedback, helping sighted and blind teenagers in programing Lego robots. Bigham et al. [5] worked with high-school children to create personalized instant messaging chatbots to invite interest in computer science, teach problem solving skills, and the use of screen readers. Finally, Kane and Bigham [34] described teaching students with VI how to write Ruby programs for analysing Twitter data to produce 3D printed visualisations that allowed for a tactile exploration of their program output.

These approaches mostly serve to increase the accessibility of text-based programing by simplifying coding syntax or teaching the use of screen-reader or magnification software. As such, they are targeted at, and more suitable to, older students. In addition, with engagements being primarily bound to a computer screen (except for 3D printed models [i.e. 34]) they rarely support hands-on physical engagements. Thus, they do not capitalise on the possibilities offered by manipulating physical objects for learning complicated or abstract concepts [57], or for supporting collaborative learning [26]. Despite tangible programing languages and tools for sighted children [i.e. 15, 26, 43, 50], this space has not yet been explored for young children with VI.

Furthermore, we found that whilst many existing educational designs emphasize the importance of social interactions for blind learners [i.e. 5, 55], they were mostly studied for their usability [1, 9] and effectiveness in accomplishing certain tasks or skills [8, 45, 47, 49, 55], or their potential for increasing programing self-efficacy [65]. Often following tutor-led or independent learning approaches [i.e. 5, 34] rather than an explicit focus on collaborative work with (sighted) peers; potential implications of using their systems or learning approaches in groups – apart from [62] – are rarely reported. One exception of an educational design for children (age 5-8) with mixed-visual abilities are Milne et al.'s word games [44, 45]; these allow learning of Braille characters whilst playing against a collocated friend. This was found to enable collaborative play with sighted siblings or parents; providing opportunity for relatives to also learn Braille concepts and identify with the blind child [45]. Yet, more research is needed to understand how children with mixed-visual abilities can collaborate in learning, especially in programing, and how this can be supported by design.

Collaborative Learning

With the term collaborative learning, we refer to partners of a group doing a task *together*. This contrasts with the term cooperation that is often associated with partners dividing and solving parts of a task for achieving a combined output, where learning is regarded to take place individually [12, 63]. Instead, we understand collaboration as Roschelle and Teasley [51] define it, as "*coordinated, synchronous activities that is the result of a continued attempt to construct and maintain a shared conception of a problem*" (p.70). Here, learning occurs socially as the collaborative construction of knowledge [63], enabled through a process of partners negotiating and sharing their understandings relevant to the task they seek to address. Through these interactions and the respecting of individual contributions consensus is built [37] and knowledge developed [63].

Mechanisms for Collaboration: Awareness & Grounding

Clark and Brennan [10] describe how all collective actions are built on common ground, which they define as *"mutual knowledge, beliefs and mutual assumptions"* (p.222). In face-to-face conversations, common ground is achieved through an iterative collective process that involves verbal utterances, non-verbal expressions, and indications that the information is understood. In the context of solving tasks collaboratively, Fussel et al. [21] also highlight the value of observing people's behaviors or changes to an object for inferring shared comprehension beyond verbal cues. This highlights the widely recognized importance of *awareness* for grounding and collaboration [i.e. 24, 40, 72], which Dourish and Bellotti [13] define as an *"understanding of the activities of others, which provides a context for your own activity"* (p.1). In collocated settings, awareness often evolves implicitly as part of ongoing interactions [72] and subtle voice inflections of the other. Relevant information can also be made available through explicit explanations of a persons' actions [24], may be generated by the person, or automatically created by a system [13]. For people with VI, for whom visual information may be less accessible, audio or haptic feedback resulting from technology use can present valuable information about the other persons' actions and the state of a shared system [40]. In the context of teaching computer programing, especially to young children, tangible designs may further aid active collaboration [27]. Typically, their physical form allows users with VI to explore them through touch, thereby assisting the identification and interpretation of object characteristics [28, 29], and offering opportunities for direct manipulation to control computation.

Mechanisms for Collaboration: Access & Entry

Recognizing how interactions are embedded in real world spaces, Hornecker and Burr [29] also draw attention to the importance of how the object and place of engagement are configured for collaboration. In designs for users with VI, the provision of well-defined, easy-to-locate and consistent references points are often recommended [60]. Furthermore, Hornecker et al. [30] describe the significance of the provision of entry and access points by a system (*shareability*) for engaging collocated users in interactions. Entry points invite uses of a system by making clear what one can do with it, and why this might be relevant, whereas access points draw attention to where and how something can be manipulated. To aid entry, the *directionality* of a technology – how it is made available – matters. For physical artifacts, this can be for example by means of passing on, or bringing an object into the proximity of others to access [40].

Mechanisms for Collaboration: Roles & Social Practices

Collocated interactions with a system are mediated by how shared access is managed. While multiple access points can enable many people to interact with a system simultaneously, parallel use can make it difficult to follow each person's actions [30] and result in less collaboration if users focus on their own interactions rather than the group [40]. To facilitate collaboration in learning, teachers can utilize specific strategies including the setting of tasks that can only be achieved when working together [4], assigning *roles* to group members for managing areas of responsibility [13], teaching *language* to assist the person to seek and give help, explain their actions, or to reflect about alternative problem solving approaches with their partner [31]. Engagement in collaboration can further be nurtured through motivating features such as *individual accountability* – the belief that each person is responsible for their own performance and learning, *positive interdependence* – the believe that if all team members support the activity the group will succeed, and *group rewards* – the recognition of all group members' when succeeding in the completion of tasks [20, 31, 33].

TORINO

Torino is a physical programing language for teaching basic programing constructs and computational thinking to children age 7-11, inclusive of children with VI [46]. For the design of Torino, we employed *Cooperative Inquiry*, a commonly used method for including children as design partners that enables their in-depth, longer-term involvement throughout the entire technology design process [16]. Over the last 18 month, we therefore partnered with two blind and two partially-sighted children to generate new ideas for, and prototypes of, technology. The design process and implementation of Torino, as well as an extensive review of other existing (modular) coding tools, are detailed in [46]. Next, we explicate some of the key decisions made in the design of Torino to support accessibility and collaboration.

Design Rationale & Technology Implementation

The design of Torino is largely built on audio feedback and physical representations that can be identified through touch; representing senses that are shared independent of level of vision. To create computer programs, children physically connect 'instruction beads' (Figure 1, top) that generate digital music or stories in the language Sonic Pi[v]. There are three types of instruction beads: *play*, *pause* and *loop* (Figure 1, bottom) that each represents a line of code in the program. Adding a play bead instructs the program to play a particular sound that can be altered using a dial that rotates through a number of available sounds. The pause bead adds a temporal suspension to the program. Both beads further have buttons to increase or decrease the length of play or pause. The loop bead allows for those instruction beads that are added, to repeat, and can be set to be 'infinite' or to cycle through a specific number of 'iterations', which further introduces the concept of *variables*. The use of a metaphor of beads that can be strung together and round shaped objects were deliberate choices to invite picking-up and exploration with the hands [29, 59]. To facilitate their *identification*, each bead type is further distinct in size and shape, and their physical controls (buttons and dials) emphasized using high contrasting colors.

Each bead contains a custom circuit board, containing a microcontroller and connectors that provide power and communication to connected beads, allowing them to form a network. When a bead is connected, it becomes powered and transmits data to its neighbors; including details such as the bead type and its current state. Messages propagate until they reach a central hub, which is connected to a Raspberry Pi[vi] device. From these messages it is possible to construct a graph of the network, where a node is a bead and the edges are connections between them. A Python script running on Raspberry Pi translates this to Sonic Pi code.

With the electronics and controls locally embedded in each bead, *real-time audio feedback* is played via a speaker in the hub in response to *direct manipulations*. Further, because it is necessary to connect beads to the hub, the hub acts as a *starting point*, a physical reference to the origin of the program, and *directionality* of the program flow can be inferred by following the networked beads. Furthermore, auditory feedback is provided each time an instruction bead is added or removed from the network, to support awareness and keeping track of both one's own and other people's interactions with the system. The hub provides a start-and-stop button to play back the program, and four different ports to connect beads to. Each port represents a unique set of sounds (i.e. piano, drums, natural sounds) to choose between, or to program simultaneously by creating bead threads that play in parallel. Finally, we defined a work space using a black felt mat and storage box with compartments specifically for each bead type to facilitate spatial orientation and the *locating* of spare beads. This was done in response to observations of the partially-sighted children taking beads away from the blind children assuming these were not in use.

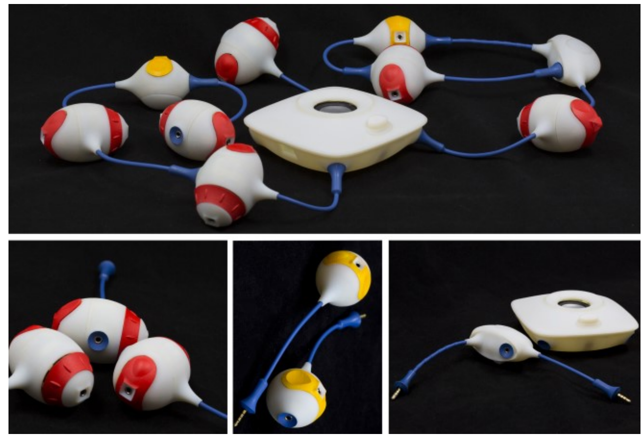

Figure 1. Top: Instruction beads connected to the main hub for the creation of an audio-based computer program. Bottom, left-to-right: play bead, pause bead, loop bead & hub.

Tasks & Challenges for Learning Computer Programing

In addition to the physical, spatial and auditory configuration of the technology, we designed a set of activities to assist the children in the learning of computer programing. These were informed by the KS2 curriculum [11] and other programing exercises[vii] explored in the design workshops. For instance, we used bell instruments to introduce the concept of giving commands (i.e. 'ring bell No. 4') and sequence (i.e. 'create a musical program using Braille commands on paper cards'). From these engagements we learned that concepts such as sequence were difficult for the children to comprehend, and required more time and scaffolding. For using Torino in programing, we thus created lesson plans for three sessions that focus on a step-by-step learning of more complex computing concepts and their regular rehearsal before new concepts are introduced. Our activities aim at teaching: (i) *programing concepts* of sequence, threads, variables and iteration, (ii) an understanding of *abstraction* – i.e. that play beads represent information containers that can hold different sounds, maintain their state, or be manipulated, (iii) *problem solving skills*, such as breaking down problems and debugging, and (iv) domain specific *vocabulary*.

EXPLORATORY EVALUATION

Next, we describe how we explored the potential of the design of Torino in supporting collaborative learning of programing by children with mixed-visual abilities.

Children & Pairing	Age	Gender	Design Partner	Evaluation Sessions	Level of Vision	Additional Detail	Mobility aid
Cat	8	Female	Yes	3	Partially sighted	She can see, but her brain has difficulty processing visual information, impacting her ability to read or write.	No
Grace2455	8	Female	Yes	3	Partially sighted	She is increasingly losing her sight. She can see color and big buttons. She is learning Braille.	Yes
Reuben	8	Male	Yes	3	Blind	Blind from birth, has low color vision. Very good Braillists.	Yes
Penelope	12	female	Yes	3	Blind	Blind from birth, no visual ability. Very good Braillists.	Yes
HTBP	10	Male	No	3	Full vision	/	No
Hairy	10	Male	No	3	Full vision	/	No
Charlotte	7	Female	No	1	Full vision	/	No
David	7	Male	No	2	Blind	Blind from birth, no visual ability. He is learning Braille.	Yes
Ginny	7	Female	No	1	Full vision	/	No
Fin	7	Male	No	1	Blind	Blind from birth, low light perception. He is learning Braille.	Yes

Table 1. Summary of Torino participants. All names are psydoneums, most were chosen by the children themselves.

Participants
Our exploratory evaluation involved 10 children (5 male) age 7-12 years, who had varying degrees of visual ability ranging from blindness from birth to partial- and full-sight. The children came from various socio-economic backgrounds. As illustrated in Table 1, the children were working in pairs: we had one pair of partially-sighted children, one pair of blind, one pair of sighted, and two pairs of mixed blind-sighted children. Five participants were users of a white cane. Two of the blind children, Reuben and Penelope, were 'tactile learners', meaning that they were very good at reading Braille, whereas Grace2455, who was progressively losing her sight, and Fin and David, two of our youngest participants, were only beginning to learn to read Braille. Only two of the children, Hairy and HTBP, had some prior experiences of programing, using Scratch[viii] in school.

Four of the children (Cat & Grace2455, Penelope & Reuben) had previously been involved in the project as design partners in developing the Torino prototype. This meant they had some experience with the shapes of the play and pause instructions. Yet, as this was the first time that the technology was implemented, they still – like the other children – had to learn and make sense of how to assemble and manipulate these instructions into computer programs. We further collaborated with a qualified teacher for the blind, who assisted in and organized meetings with two blind children at their respective schools. Each of these children chose a sighted peer at school to attend the sessions with them. The pair of sighted children was recruited through personal contacts at work. The research was approved by our internal ethics review board. Parents gave informed consent for the sessions to be video recorded and for photographs to be used in publications. While explaining the study to the children, we described the writing of research reports, for which many of them provided their own pseudonyms (see Table 1).

Procedure
Over a two month period, we conducted three consecutive sessions that typically lasted for 1 hour (in minutes: *Median* = 64, *min* = 61, *max* = 97). The first two sessions were attended by the pairs of children, in the third, the children were asked to work separately with one of their parents and to explain Torino to them. This served to gain insights into each child's understanding of Torino and learning progress. With exception of our meetings with those children that we visited at their schools, who were unfortunately unable to complete their three sessions due to scheduling issues, all sessions were held in a meeting room in our research lab.

The sessions were attended by two researchers. One researcher (CM), who is both experienced as a teacher and in working with blind children, led the programing activities. At times, parents or teaching staff present would also oversee and assist in the activities. To teach for instance the concept of sequence, it was explained how the program structure is made of a number of commands that play one after the other, and the children are asked to create specific audio tracks that produce a sequential program, such as a musical scale or a particular jingle (i.e. *twinkle twinkle little star*). To engage the children in problem solving, they were frequently invited to: explain their approach to addressing a challenge, predict what their program would do, identify alternative solutions, work with constraints in resources, or debug a faulty program created by their partner or the researcher. Furthermore, we sought to balance the requirements for explicit, systematic instructions to support learning with the need to keep the children engaged in the process through more open-ended exploratory activities. To this end, we offered the children space for their own input, creativity, and play; inviting them to create own programs, and in the last session, to also bring their own sounds for use with Torino.

Data Capture & Analysis
All sessions with the children were video recorded (17 hours in total). Two of the researchers (AT, CM) immersed themselves in the data and conducted a Thematic Analysis [7] that focused on the children's progress in learning programing, their engagement with Torino, instances of collaboration, and overall usability. The process and findings of this analysis are reported in [46]. Building on the theme of collaboration, our data analysis was guided by the three main research questions: (i) how did the design of, and practices for introducing, Torino assisted the children's sense making of the technology?, (ii) how did the children collaborate using Torino, how did this differ between the pairs, and

impact their learning of important computing concepts?, and (iii) how did they experience their collaboration in learning? Upon review of the entire data set, the findings present descriptions of selected vignettes of collaborative behaviors by the pairs of children that exemplify relevant phenomena. The cases were selected to reflect both common observations of each pair as well as key differences in behaviors between them. They describe in rich detail how the pairs coordinated tasks and assisted each other's learning, and how interactions with Torino supported and, at times, caused breakdowns in understanding of the system state, or the partners' actions.

FINDINGS: COLLABORATION & LEARNING WITH TORINO

Our findings are structured according to the three research questions. For each, our analysis presents key insights that evolved from our observations of the individual pairs.

Understanding Torino & Developing Collaboration

First, we describe observations of how specific practices that were employed in introducing the technology and the scaffolding of programing tasks contributed to the children's understanding of Torino, and the development of important references and practices for collaboration and learning.

Joint Explorations in Developing an Understanding of Torino

To get started with Torino, and working in pairs, one of the researchers (CM) handed each child a play or pause bead and asked them to describe their similarities and differences. With vision being the dominant sense for those children with partial or full sight, they instantly pointed to visual properties such as the color as key identifiers. The blind children in contrast took time investigating the form of each bead, recognizing their connectors, size and shape, or highlighting how parts felt 'bumpy' or were 'moving'. For instance, when Charlotte, who has full sight, explained her pause bead to David, who is blind, she described indentations in its shape. Prompted by the researcher to press on these, Charlotte noticed: *"It's like a button."* Feeling indentations on his play bead, David immediately starts pressing the buttons on his bead too. This example illustrates two important findings:

Firstly, an identification of the bead types and understanding their functionality was not only built up through distinctions in their physical characteristics, but through the combination of tactile clicks and audio feedback in direct response to manipulating the controls. Secondly, the process of *jointly exploring and discovering* the physical and auditory features of each component presented a gentle way into familiarizing the children with the program instructions. This allowed for the learning of a shared vocabulary and physical points of reference that can be crucial for grounding and developing collaboration, especially for children with low or no vision.

Making Sense of Abstraction & Problem Solving Practices

Motivated to assist all children in building up a mental model of their program through its placement in physical space, the researcher frequently taught all children to touch each bead along their program as it was executed. We learned how this practice of tracing and *physically following the program* had a number of additional advantages. It assisted all children in gaining a better understanding of the more abstract mapping between the bead containers and their audio representation. This was important as initially, all children, including Hairy and HTBP who have full vision, experienced difficulty for example in following their program if it included pause beads. While hearing a sound for each play bead was to be expected, the absence of audio when a 'pause' was executed appeared less intuitive. An enforced mapping through touching each bead as it was 'playing' or 'pausing' helped clarify this more abstract relationship. Furthermore, as programing challenges increased in complexity, *physically following the program* became a method that the children started to apply systematically to locate incongruences in their program, and used particularly in the debugging of their programs. Thus, teaching this physical mapping method aided both their sense-making of the program abstraction and their learning of important problem-solving approaches.

Balancing Engagement & Individualized Support

To ensure proposed programing activities were achievable, the researcher (CM) tailored the task complexity at times to the children's individual abilities. This was particularly prevalent in the case of David, who encountered significantly more difficulties – even with very simple tasks – than any of the other children. For most of his first session, he struggled to even connect beads together. Very quickly, he became frustrated when things did not work straightaway, requesting more help from, while simultaneously rejecting the involvement of others; striving to solve the problem himself. Yet, as soon as he had mastered i.e. an instance of the tuning of a bead, he wanted to do it over and over again, and enjoyed his engagements. Responding to his personal struggles however overshadowed and considerably slowed down the group activities. As such, it became more difficult to keep his partner Charlotte equally engaged in the process; resulting in her role often being more passive: patiently watching and assisting David. The need for a more individualized response in this case thus challenged efforts to balance interactions and likely reduced the potential for Charlottes own learning.

Mechanisms for Collaboration & Learning

We now illustrate different mechanisms that the children employed to externalize their thinking, and be aware of the program state, or their partners' actions. We describe how these were enabled through the design, and came to matter differently in collaboration and learning, which depended on the learning partners' visual abilities, and their individual approaches and strengths in achieving the programing tasks.

Visual References & Awareness of Non-Verbal Behavior

In those pairs where one of both partners had full or partial sight, their interactions largely built on visual references and non-verbal behaviors to direct the partner's attention, and localize problems or clarify certain ideas and actions. As can be seen in Figure 2 (left and middle) and Figure 3 (right), this often included pointing gestures and visual cues provided through body-language and eye-contact. The following more detailed example of the two sighted boys and friends, Hairy

Figure 2. ***Left***: **Grace2455 is attentive to Cat setting the bead.** ***Middle***: **Cat indicates an idea for solving the problem.** ***Right***: **Greace2455 and Cat jointly try to identify the right setting.**

and HTBP, illustrates how they made eye-contact at each step in their programing to invite confirmation or request help from their partner, and were frequently pointing at, or touching specific beads as reference in their conversations:

As part of teaching the concept of sequence, the children were asked to build a seven-note piano music scale. First, the children were asked to listen to an audio file of the scale, and to explain how they planned to create the program (as an array of seven play beads). HTBP starts by suggesting they identify the piano port on the Torino hub, and then add and tune beads, with the first one being the lowest note. While describing his plan, he looks at Hairy for confirmation, who then connects the first bead. As Hairy tunes the bead, HTBP explains: "*You want 'do'*", building on their shared knowledge of solfège, a method used to teach pitch in musical education. Both children play the piano, and HTBP also plays trumpet and cello. Once Hairy has the right note, he looks at HTBP, who agrees: "*Yeah, 'do'*", reaching for the next bead to add. Pointing with his finger at the remaining play beads, he names them '*re', 'mi', 'fa', 'so'*, and lays them out in front of Hairy, for him to assemble into the sequence.

One by one they tune the beads – first HTBP, then Hairy. Attending to Hairy's audio tuning, HTBP believes that the desired note should be one setting lower. He reaches out to help retune the bead with Hairy without taking it out of his hand (Figure 3, left). The program playback reveals that Hairy originally parameter setting of the bead however was correct. Both laugh as HTBP apologizes: "*Ah no, higher, sorry. You got it right!"* (Figure 3, middle). As they continue, they keep offering and asking for each other's advice: "*Wait, is this the right sound?,* and share their plans for actions: "*Yah, now we need 'ti'"*. On occasion, the audio playback reveals inconsistencies in the 'duration settings' that Hairy tends to spot, whilst HTBP is particularly attuned to finding the right 'pitch'. As their program finally executes the desired scale, the boys celebrate their success with a hug.

This example highlights how the children built on visual cues for maintaining awareness of their program state and each other's contributions to it, and includes deliberate uses of the physical design in laying out and thereby structuring and externalizing ideas for a proposed program. It further shows the fluidity of both learning partners' turn taking in the program creation; shifting between the roles of *manipulator*– adding or altering instructions – and *monitor* or *advisor* of the partners' actions. What is also apparent in this instance is how the two boys developed an understanding of each other's strengths in programing Torino; building on HTBP's expertise in setting the pitch, and Hairy's sensitivity for durations. Continuously attending to, respecting and actively stepping in to help the other aided learning from each other, and achieving the programing task more effectively together.

Figure 3. ***Left***: **HTBP assists Hairy in setting a bead to the right pitch.** ***Middle***: **Both laugh as Hairy proves HTBP wrong.** ***Right***: **HTBP points at a bead he assumes needs re-setting.**

Touching, Handling & Passing of Program Instructions

Independent of visual cues, we observed how the ability to touch, handle and share the program instructions was a key enabler in the collaboration and learning process of all pairs of children. In the example of HTBP and Hairy above (Figure 3, left), and also in interactions by the two partially sighted girls, Grace2455 and Cat (Figure 2, right), we often saw how both partners would manipulate the instruction bead they needed to attend to, together. Such instances demonstrate a joint awareness of, and focus on, the program creation that was enabled through the 'shareability' of the design. It also reflects a way of working together in which learning partners can step in to assist one another without needing to take over; keeping both involved in this as a joint activity, and learning about the program creation through each other.

For those children with no vision, touching the instruction beads was further key to their locating and identification, and for gaining a sense of the program arrangement. In the case of Reuben and Penelope, who are both blind, Penelope was initially more unsure about bead types. Following the task to create a sequence of play and pause commands that Reuben was reading to her from a Braille sheet, she takes a bead from the storage box, handles it, and then reaches out to Reuben for advice: *"I'm not sure the one I've got is a play?"* (Figure 4, left). Reuben, who has slight color perception is faster at identifying the beads, he touches the bead in her hand: *"No, it is not, it's a pause."*. He then picks up and places a spare closer to her so that she can continue building the program. In creating and executing the program, Reuben and Penelope not only touched each bead added, tuned or executed; they also frequently laid their hands on top of each other through which they can sense each other's movements when stepping through the program, which further assists in keeping track of individual steps or difficulties encountered in the program

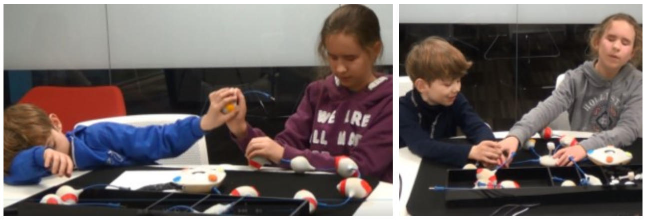

Figure 4. *Left*: Penelope asks Reuben for help in identifying what type of bead she is holding in her hand. *Right*: Reuben guides Penelope's hand to the play bead she is supposed to set.

creation. At times, mostly following a turn in the program creation, Reuben would also guided Penelope's hand to the place where he had added a bead for her to continue with the built or set a bead to the desired tune, or pace (Figure 4, left). This demonstrates the importance of touching hands and the handling and moving of components for directing the partners' attention, for gaining a shared awareness of the program, and for being able to build on each other's contribution to jointly succeed in the programing challenges.

In collaborations by pairs of one sighted and one blind child, we saw the application of hybrid approaches. For example, Figure 5 shows how Ginny uses her finger as a pointer in visually following the program, while Fin touches each bead. Despite their differences in visual ability, the beads act as references – visually or physically – that both can access to make sense of the components and program structure.

System Generated Audio & Explicit Verbal Communication

Besides the visual and physical representation of Torino, audio feedback was crucial for understanding the state of the program, of the manipulators and functionality of each program instructions, and in following the partners' actions.

The blind children especially attended carefully to the specific sound that marked the adding or removing of beads. For example, Penelope always waited for the add-sound to appear, saying *'Oh good'* each time the program provided that auditory confirmation. Yet, this audio configuration was not always as accessible or helpful. Once, when Penelope and Reuben both disassembled a larger sequential program, it remained unnoticed that Reuben had already disconnected a string of beads from the hub, which Penelope was supposed to unplug. Since her string of beads was now already detached from the power supply of the hub, no remove-sounds appeared in response to her disconnecting of beads, causing confusion. In such cases, the researchers would make use of their vision to explain what happened. Invited discussions to clarify such instances further provided a means for explaining how the children could step-by-step analyze what the source of a discovered disruption might be so that they could manage future breakdowns by themselves.

Outside of vision as a shared sense, and with both partners handling components together, it could also be challenging, at times, to keep track and distinguish the audio feedback produced through one's own actions from those of the partner. For example, when both Fin and Ginny were each

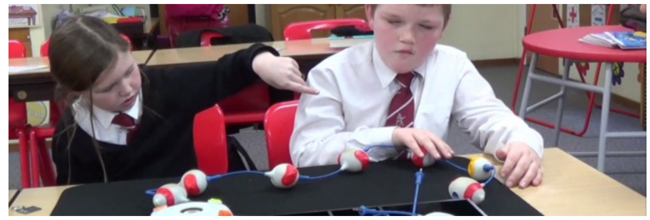

Figure 5. Ginny follows the beads visually, Fin touches each.

simultaneously tuning a bead, the audio of their individual parameter changes became indistinguishable. Fin therefore asked Ginny to: *"stop changing 'cause I want to see if I can [find the explosion sound]…"* to coordinate their actions. This made her pause until Fin was finished before continuing to tune her bead. It was through explicit talk and turn-taking that the audio feedback and individual actions became interpretable, and that working together was productive.

Furthermore, as illustrated in the initial example of Hairy and HTPB, the opportunity to instantly execute the audio program revealed any inconsistencies with it, inviting further analysis about the source of, or alternative approaches to solving a problem – all essential skills to programing. While the audio execution served the two boys, who were very systematic in the planning and breakdown of their program steps, to test their a priori assumptions; Grace2455 and Cats' interactions – in contrast – evolved around experimentation, play, and learning by attending to, and copying, the partner.

For example, asked to build a sequential program of play and pause instructions, both girls start by adding beads to two different hub ports. The audio playback reveals that the resulting two 'threads' played 'in parallel' instead. Prompted to re-think how to get the instructions to play one-after-the-other, Grace2455 proposes: *"We need to join them all together, with a pause"*. With no more pause beads available, Grace2455 picks up two remaining play beads and adds one to each existing thread, commenting towards Cat: *"I'm just experimenting; this is just a guess"*. Once done, she notices: *"No, doesn't work, I can't connect them."* Asked how else they could connect the beads, Grace2455 offers another idea: *"We could all plug it into one [port], we could all plug it in piano."* This worked. To foster the newly learned concept, the girls create more examples of sequential programs, which they built by taking turns. The example illustrates how audio aided the girls' sense-making of the program structure, and a shift from experimenting with Torino to learning and replicating more *abstract concepts of threads and sequences.*

Experiences of Joint Success & Sense of Achievement

Elements of the Torino design and the social dynamics between the children also invited play, creativity, and a sense of progress that contributed to positive learning experiences.

All children expressed their liking of the activities. When asked at the end of their sessions to summarize in one word what they liked most, Cat responded excitedly: "*Programing!",* Grace255: *"I do like coding, with these blocks",* whereas Reuben described his overall experience as

"Funny" and his partner Penelope as *"Funny and Tuneful"*. The children liked the mechanics of connecting beads and often fiddled with their controls even if those beads were not connected to the program. More prominently, the children enjoyed exploring the Torino sounds; especially the more unusual 'natural sounds' (i.e. a 'comedy kiss'), which often caused laughter, and stimulated imagination for creating stories with these. They also enjoyed when they realized that they had created a program they liked the sound of, and when they successfully solved a problem together – as was described above in the case of Hairy and HTBP hugging.

We also saw more playful engagements especially in the case of Cat and Grace2455. In one instance, when the two girls realized they were missing one bead to complete the end of their program story, Grace2455 decided to place her pinky finger on the last connector – personifying the missing bead. Upon Cat triggering the program execution, Grace2455 imitated the desired sound when it was her turn to 'execute'. Further, we frequently observed a sense of pride when the children demonstrated and explained their programs to parents or siblings. This was particular prevalent in the case of David. Motivated to demonstrate his newly acquired expertise, he asked his parents to watch and comment on how well he was doing as he was building programs; pointing out to them: "*I'm making progress with this"* to receive recognition for his achievements; jumping up and down on his chair for excitement when he succeeded in a task.

DISCUSSION: COLLABORATIVE LEARNING & VI

Our findings suggest two contributions, they: (i) confirm and built on previous work discussing the role of touch, audio feedback and visual representation in designs inclusive of children with VI, and (ii) highlight opportunities provided through the 'social' in negotiations of accessibility, and for collaboration and learning especially for children with VI.

Recognizing & Carefully Responding to Multiple Senses

For designs inclusive of mixed-visual abilities, our findings indicate the need to recognize the interplay between, and to support, multiple mechanisms for understanding a system.

Tangibles for Learning: Building on Touch in 3D

With a focus on teaching basic computing concepts, Torino did not require the learning of language syntax that can be frustrating to beginners. Instead, its configuration required for physical components to be connected to each other and the hub. This assisted all children to build up an understanding of the program structure and direction of its 'flow'. For those children with vision, the physical offered additional cues for awareness and collaboration in learning [cf. 29, 72]; who would be deliberately arranging, or pointing to, components to externalize their thinking [25]. The ability to physically explore, hold, or locally manipulate beads was particular important to the blind children, who tend to build a 'picture' of things by actively touching them and listening to the sounds that bounce off objects [cf. 17, 62, 71]. Our findings showed how a handling and sharing of components enabled the blind children to identify program instructions, manipulate their controls, and assemble programs. It was through constantly touching and moving along their built and careful attendance to audio mappings in response to physical representations or actions that they were able to make sense of the technology and also their program. Although there are many examples of haptics in designs for VI (i.e. stylus [49], pressure mat [47, 55], mobiles [9, 36, 66], and others [1, 22, 71]); opportunities for the handling, tactile inspection or direct manipulation of physical 3D objects for sense-making and programing are still under-explored.

Creating Informative Audio Feedback & Strategies for Repair

Understanding Torino was bound-up with its physical-audio mapping and the immediacy of audio feedback that were key for testing a created program or identifying problems with it. This was emphasized for blind children as we saw in the case of Penelope, who was confused when her actions of unplugging beads did not trigger the audio signals she anticipated. Partly, this presents a limitation of our design that did not clearly enough distinguish between unplugging events of a single bead or a sequence of beads, nor did the audio provide any information about its location (i.e. 'bead 4 unplugged'). Besides, our system was unable to differentiate if a bead was unplugged deliberately, or whether a connection became loose accidentally. As discussed in other audio-based designs for VI, this highlights the importance of providing sounds that are clearly distinguishable [14, 42], informative and coherent [62], and – depending on use context – to offer localized information [14], while keeping the complexity of sounds both memorable and manageable.

Furthermore, as technical problems and breakdowns in understanding are likely to occur, it is important to develop strategies for assisting in their recovering. In the example of Penelope, we explained how the researcher, as a sighted helper, extended the children's awareness of what was happening (cf. [6, 9]), and used this as an opportunity for teaching them important problem-solving approaches (i.e. *What may have happened if there is no audio feedback anymore? How can you check?*).

Considering Visual Representations for Sense-Making

Our findings described how children with (some) sight quickly identified and acted upon visual information such as differences in bead color. With sight being a dominant and pervasive sense for someone who has (some) vision [16, 47], it is important for designs inclusive of variations in visual abilities – not just blindness – to create not only distinct tactile or auditory features, but to also carefully consider how visual representations aid sense-making and engagement. This is further emphasizes by previous work showing how an appealing visual interface can help invite collaboration with sighted users [69] and encourage technology use [45].

Supporting Accessibility & Learning through the Social

We now discuss how social interactions, taught programing practices, and fluid shifts between multiple mechanisms for awareness and collaboration that were enabled through the design can contribute to accessibility and learning. Similar to

Winberg and Bower's [69] research of the *Towers of Hanoi,* who concluded that it was through '*concerted manipulation, listening and talk'* with a sighted co-player that their game sonification was effective; our findings show how the children's sense-making of Torino and collaboration were interweaved with, and enabled through, joint explorations, explanations, and a following of each person's actions and thoughts in creating programs. Depending on the abilities of each partner, this built on an interplay of visual cues, audio, touch, communication, or explanations of sighted helpers.

For example, children with (some) vision visually monitored each other's actions, pointed to, or laid out particular beads as references when explaining a problem or plan. In interactions by blind children, audio feedback interleaved with an active handling of components, and making contact with or physically guiding the partner's hand supported their awareness of the program and partner, whilst real-time audio aided in testing and learning about created programs. In addition, our findings showed how the interactions of all pairs were bound up with conversations; describing i.e. how Fin verbalized to Ginny that his bead manipulations were inaudible during parallel interactions, and how this led to the development of a more productive turn-taking approach. Explaining one's idea or actions, and asking the partner for advice also served to introduce alternative problem-solving approaches and highlighted individual strengths; building on which advanced their program and process of learning.

Our examples indicated how the technology design came to matter differently in, and enabled multiple, approaches to collaboration and learning by the pairs. This was facilitated through joint processes of familiarizing the children with the components and teaching practices such as physically following the program. It was through the interplay of these practices with the particular audio-physical configuration of Torino that enabled the development of a *shared vocabulary* and *physical reference points* that served as foundations for conversation and working together. Thus, for accessibility and collaboration by people with mixed visual abilities, this suggests to explicitly develop strategies to help create a language and references that can be shared outside of vision.

Approaches for supporting joint learning independent of visual ability are further important for enabling a more equal response to education that avoids treating children with VI in isolation, or that unnecessarily emphasizes a need for 'specialized' support. We showed how this was complicated in the case of David and Charlotte, where David's personal struggles however meant that he needed more support and time to engage. To enable successful collaboration with Torino thus required for the skills levels of both partners to be fairly balanced; and moderation by a teacher to sustain productive interactions through their expertise in planning and delivering the curriculum [63, 64]. Our findings also illustrated how doing and succeeding in tasks together with a peer was enjoyable; allowing for self-perceptions of being a valued contributor to a group, and to be progressing. These are invaluable experiences especially for children with VI, who are often excluded from learning with peers. This builds on Shinohara and Wobbrock [58] recent call for assistive technologies (AT) to be more considerate of people's social needs and what is conveyed about their *ability* and *social identity* through interactions with ATs in social contexts.

Limitations & Future Work

Our exploration of Torino as part of a longer-term design process provided initial insights about the diverse ways in which children with mixed-visual abilities appropriated it for collaboration and learning. We have to acknowledge however that the context and scaffolding of the activities impacted the children's experience; introducing limitations to the transferability and wider impact of the insights. To address this, we are currently working closely with teaching professionals and charity organisations in the UK to set up a large scale study of Torino within different teaching settings. Further, we want to note that Torino is not envisioned as a standalone tool, but for use under guidance of teachers. Despite a need for formalised support, we regard potential collaborative uses of Torino by children with mixed visual abilities as a particular strength for inviting peer-to-peer learning and social inclusion. As for the technology itself, we are continuing to add functionality that allows for the *code* generated through the beads to be read out (alongside the audio sounds), and are building an app with different accessible representations of that code – thereby exploring ways to assist a transition from the physical language to written code and screen-reader software. Presently not explored are possibilities still for a speech-based interface for children to hear instructions or give voice commands, which promises to be very intuitive.

CONCLUSION

We explored the design of the physical programing language Torino for enabling collaborative learning experiences for children with mixed-visual abilities. Our findings show how sense-making of the technology, collaboration, and learning were enabled through an interplay of system design, programing tasks and social interactions. They illustrate how identified mechanisms for gaining and keeping awareness of the program and partner came to matter differently between the learning pairs. We contributed insights to the role of touch, audio feedback and visual representations in designs inclusive of children with VI, and highlighted the importance and opportunities of the 'social' for progress in learning, for creating shared languages and references outside of vision that can supporting accessibility and inclusion, and for self-perceptions of ability and self-esteem of children with VI.

ACKNOWLEDGEMENTS

Special thanks to all children who participated, their parents and supporters for their help and input to the research. We further thank all our colleagues and collaborators for their contributions to the research project: Zahra Ashktorab, Alan Blackwell, Daniel Cletheroe, Darren Edge, Yuki Machida, Tim Regan, Oscar Salandin, Greg Saul, David Sweeney, Eloise Taysom, Haiyan Zhang, and Tony Wieser.

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