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Research paper

Designing integrated physical–digital systems for children–nature interaction

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ABSTRACT

Studies in the last decades have highlighted how children spend less time outdoors, while they are increasingly attracted by screens and indoor digital activities. Based on the assumption that technology and open-air activities are not necessarily mutually exclusive, this article illustrates the design of integrated physical–digital systems motivating children to connect with nature and learn from it. A key ingredient is providing unobtrusive technology supporting playful, creative, and educational outdoor experiences without distracting children from their experience with nature. Based on the insights gathered through design-based research, the article also outlines design considerations that aim to refine the theory and practice of technology for children–nature interaction.

1. Introduction

Establishing and cultivating a connection with nature, especially at a young age, is considered crucial for developing a healthier way of living and sensibility for environmental issues (Beery & Jørgensen, 2018; Dopko, Capaldi, & Zelenski, 2019; Richardson, Passmore, Lumber, Thomas, & Hunt, 2021). However, studies conducted in the last decades state that children spend less and less time outdoors (Barrera-Hernández, Sotelo-Castillo, Echeverría-Castro, & Tapia-Fonllem, 2020; Clements, 2004). Children's interest in the variety of animal species has steadily declined, linking life in the cities with a growing apathy for the biodiversity they should protect (Beery & Jørgensen, 2018). Indoor habits also increase the onset of medical conditions such as asthma, obesity, and vitamin D deficiency, and affect children's mental well-being. Richard Louv worryingly describes this condition as a "nature-deficit disorder" (Louv, 2005). Although this definition is certainly not scientifically compelling, there are studies emphasizing this concern and proving that spending time in a natural environment has the potential to improve children's mental and physical health (Beery & Jørgensen, 2018; Clayton, 2012; Knapp, 2006; McCurdy, Winterbottom, Mehta, & Roberts, 2010; Richardson et al., 2021). Despite this, different factors such as structured school activities, difficulty in accessing outdoor spaces in urban areas, or safety concerns (Turkle, 2017) prevent children from spending time outdoors. Technology is addressed as being one of the causes of this disconnection (Natural England, 2009; Turkle, 2017): children are easily attracted by screens and increasingly dedicate their free time to indoor activities with digital devices. However, technology and nature are not mutually exclusive: digital tools motivating children to play outdoors can be effective in establishing a connection with nature in a spontaneous and genuine way (Natural England, 2009; Richardson et al., 2021; Turkle, 2017).

1.1. Contributions

This paper discusses the design of integrated physical–digital systems that aim to engage children in playful and creative discovery of nature. The illustrated research investigates how technology can be used as an unobtrusive intermediary to (*i*) motivate children to explore nature and (*ii*) improve their perception and knowledge of nature through interaction with natural materials. In relation to this research question, this article contributes with:

- *A children-centered design process*. Design-based research (Reeves, 2006), with multiple cycles of design and evaluation activities playfully involving children, progressively led to the identification of ingredients for the design of integrated physical–digital systems for nature exploration.

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- *A new system for the interaction with nature sounds*. One design and evaluation cycle resulted in *Ekō*, a new physical–digital system that allows children to capture the sounds of nature and play with them while learning.
- *Design considerations*. Based on the analysis of the literature and the new insights gained through the conducted design-based research, the article outlines design considerations that refine the theory and practice of technologies for connecting children with nature, also leading to the notion of *smart nature ecosystems*.

1.2. Article organization

Section 2 discusses the related works and presents design considerations for pervasive technology for outdoor activities as emerging from the literature. Section 3 introduces the overarching design-based process, summarizes the cycles of design and evaluation of two physical–digital systems, *ABBOT* (Delprino et al., 2018) and *GAIA* (Gennari, Matera, Melonio, Roumelioti, et al., 2019), and outlines their contribution towards refining the design considerations distilled from the literature. Section 4 illustrates the "children-centered" design process that investigated the role of senses in perceiving nature and that led to the design of Ekō, a new integrated physical–digital system centered on the interaction with nature sounds (Section 5). Section 6 presents a user study assessing children's attitudes towards Ekō and its effectiveness in engaging children with the natural environment. Section 7 discusses the results of the study and further design considerations. Section 8 finally draws our conclusions and outlines future work.

2. Background and related work

The research discussed in this article aims to understand how technology, purposely designed to be "unobtrusive" when used outdoors, can motivate children to explore the open-air environment and learn from the natural world. It addresses today's digital context in which children use technology extensively (Alakärppä, Jaakkola, Väyrynen, & Häkkilä, 2017; Vincent & Haddon, 2005), with many new opportunities for learning but also a reduced attitude towards exploring and interacting with the outdoor natural world (Knapp, 2006; Larson, Szczytko, Bowers, Stephens, et al., 2019; Louv, 2005; Tandon, Zhou, & Christakis, 2012). The children–nature connection, however, plays a fundamental role in the development of pro-environmental habits and behaviors in adults (Giusti, Svane, Raymond, & Beery, 2018; Ives, Giusti, Fischer, et al., 2017), and has a positive impact on physical and mental well-being, on the correct development of the individuals and also on their role within the society (Giusti et al., 2018; Howell, Dopko, Passmore, & Buro, 2011; Tam, 2013). Therefore, there is an increasing interest in the development of technologies that leverage the attraction towards technology to encourage children to re-establish a relationship with nature (Cumbo, Jacobs, Leong, & Kanstrup, 2014a; Hitron et al., 2018; Lentini & Decortis, 2010). The main contributions, which we discuss in the following, relate to the design of mobile, pervasive games and unobtrusive smart objects, and to the assessment of the impact that these interactive technologies can have on children's relationship with nature.

2.1. Mobile technology for outdoor experiences

A number of works have been focusing on mobile applications (Chatzidimitris, Gavalas, & Kasapakis, 2014; Häkkilä et al., 2018) mostly proposing mobile phones and tablets as intermediaries for nature exploration. For example, Geotagger (Fails et al., 2015) is a collaborative platform developed to engage children (primarily of age 6–11) and adults as they explore the outdoors, motivating them. to observe the surrounding world document the observation by generating tagged outdoor items, and share them to encourage discussion. Mobile devices are used to locate the tagged items, thus encouraging the observation of the natural world, but also to connect and collaborate with peers. Retrieving tagged items builds a community around crowd-sourced knowledge that can help people ask and collectively answer questions about the world around them.

Other works adopt augmented-reality paradigms: Computer-Vision algorithms, running on mobile phones, recognize nature elements and provide related content through a virtual layering of perspectives, narratives, or otherwise inaccessible information (Alakärppä et al., 2017; Kumar, Belhumeur, Biswas, et al., 2012; Zimmerman, Land, Mohney, et al., 2015). Evaluation studies proved how these systems enable learning processes concerning nature. However, they do not consider how to engage children in nature exploration and observation; also, there are works discussing how using screen-based devices, such as smartphones and tablets, can distract children from their experience with nature (Soute, Markopoulos, & Magielse, 2010; Soute, Vacaretu, de Wit, & Markopoulos, 2017a).

2.2. Unobtrusive smart objects for nature exploration

To overcome the limitations deriving from the adoption of screen-based devices, some works discussed the need for non-invasive and screen-less technologies, which must also be pervasive to enhance outdoor exploration (Arango-López et al., 2017; Arango-López, Gutiérrez Vela, Collazos, Gallardo, & Moreira, 2021; Magerkurth, Cheok, Mandryk, & Nilsen, 2005; Montola, Stenros, & Waern, 2009). Head-Up Games (HUGs) emerged for their minimal use of graphic interfaces and screens (Soute & Markopoulos, 2007; Soute et al., 2010, 2017a; Zimmerman et al., 2015). According to the HUG approach, interactive technologies in outdoor experiences must not become a source of disruption requiring excessive player attention. In contrast to games that use mobile devices as main touch points, HUGs exploit embedded gaming technologies that do not force the players to attend to a screen and fit seamlessly into play thus encouraging physical activity and social engagement.

As described in the following sections, our approach also promotes screen-less, pervasive smart objects that aim to encourage nature discovery in a way that is totally independent of the usage of mobile apps and screens. While HUGs especially focus on structured, rule-based outdoor games, our approach promotes tangibles as unobtrusive intermediaries for free interaction with natural materials. This could indeed favor emotions and engagement, and improve children's attitude towards understanding and learning from nature (Yannier, Hudson, Wiese, & Koedinger, 2016). In addition, according to the study reported in Cumbo et al. (2014a), essential factors to be privileged by interactive tools for children's outdoor play are the direct interaction with natural elements (e.g., plants). Our approach largely promotes the "physical" manipulation of natural elements. Different from the HUG games proposed in Soute et al. (2010), outdoor activities are not constrained by ruled games but are left to children's spontaneous intentions as inspired by the outdoor play context. Some studies have indeed investigated the potential of open and flexible systems supported by configuration tools enabling customizable gaming experiences (Avontuur et al., 2014; Soute, Vacaretu, Wit, & Markopoulos, 2017b). Our approach pursues flexibility in game dynamics by means of basic devices, detached from any game rules, acting as companions for children's exploration.

Table 1
Design considerations for connecting children with nature and outdoors through technology originating from the literature.

	Design Considerations
C1	Include and support physical activity and play (Koepfler, Jalwal, & Plank, 2016; Radich, 2013)
C2	Tap into children's sense of adventure and imagination (Koepfler et al., 2016; Rogers, Price, Fitzpatrick, Fleck, et al., 2004)
C3	Activate children's senses (Koepfler et al., 2016; Rogers et al., 2004; Wilson, 2007)
C4	Encourage co-participation and co-engagement (Gutnick, Robb, Takeuchi, & Kotler, 2011; Radich, 2013; Rogers et al., 2004)
C5	Leverage close-knit social groups (Koepfler et al., 2016; Radich, 2013)
C6	Adapt materials and technology to outdoors (Koepfler et al., 2016)
C7	Favor direct interaction with nature elements and physical manipulation (Cumbo et al., 2014a; Cumbo, Paay, Kjeldskov, & Jacobs, 2014b; Manches & O'Malley, 2012; Rogers et al., 2004)
C8	Extend the experience beyond the novelty (Koepfler et al., 2016; Radich, 2013; Rogers et al., 2004)
C9	Allow collection and sharing of experiences (Koepfler et al., 2016; Radich, 2013; Rogers et al., 2004)
C10	Leverage the multimedia sensors (Koepfler et al., 2016)
C11	Bridge on-screen and off-screen activities (Gutnick et al., 2011; Koepfler et al., 2016)
C12	Limit passive/non-interactive interaction with technology (Koepfler et al., 2016; Radich, 2013)
C13	Support (and extend) traditional learning (Koepfler et al., 2016; Radich, 2013; Rogers et al., 2004)

2.3. Sound and outdoor experiences

Sound is fundamental for perceiving nature as alive and capable of inspiring creativity and health development (Wilson, 2007). It can play an important role in technology for children–nature interaction. However, there is a gap in how to leverage environmental sounds to connect children with the natural world.

Some studies have focused on the use of sound to augment children's outdoor play. SoundWear (Hong, Yi, Pyun, & Lee, 2020) is a wearable interactive device that allows children to retrieve, store, and share sounds for accompanying open-ended play outdoors. Evaluation studies showed how sound augmentation positively affects children's outdoor activities from physical, social, and imaginative perspectives. However, there is a lack of approaches allowing children to capture nature sounds and interact with them. To fill this gap, Sections 4–6 will introduce an integrated physical–digital system that allows children to gather and interact with nature sounds as a means to stimulate exploration and interaction with nature.

2.4. Design considerations

Besides illustrating the design and evaluation of interactive systems for reconciling children with nature, the literature proposes considerations that can guide the design of such systems. In most cases, the discussion revolves around well-known principles for children-computer interaction, but it still tries to specialize them to favor nature experiences and education. Table 1 summarizes relevant guidelines emerging from different sources. Regarding motivation, some works argue that technology should support physical activities to stimulate children's interest in the outdoors and activate their sense of adventure and imagination (Koepfler et al., 2016). The interaction with tangible objects should mediate the interaction with natural materials, and should then favor emotions and engagement to improve the kids' attitude towards understanding and learning (Yannier et al., 2016). The importance of favoring the direct interaction with natural elements is also remarked in Cumbo et al. (2014a, 2014b). These works highlight how the adopted technology should activate the children's senses to inspire them with nature and its beauty. For example, physical manipulation is considered an effective channel for information gathering, able to improve the experience memory (Manches & O'Malley, 2012). Rogers et al. argue that tangibles can aid in reasoning about the world through discovery (Rogers et al., 2004).

Open-air activities could be semi-structured (Soute et al., 2010), but they should also enable open-ended play, to inspire children's imagination, instead of constraining them into rigid lesson-based plans. Less rigidity also allows children with different preferences and abilities to participate in outdoor activities as they wish (Soute et al., 2017b). Furthermore, such outdoor activities should be children-led (Rogers et al., 2004).

Technology should support and leverage children's social groups and friendship circles, by promoting multi-participant, collaborative, and shareable outdoor experiences (Gutnick et al., 2011; Radich, 2013).

In terms of the physical characteristics of the devices, Koepfler et al. suggest that the adopted technology and the materials used to build the devices should be durable and protected from the elements (Koepfler et al., 2016).

Koepfler et al. highlight that children's engagement with a new technology fades away once the novelty wears off. Therefore it is important to devise strategies for extending in time the children's interest beyond the initial use. One such strategy is to allow children to collect and store data related to their outdoor experiences. Radich et al. suggest that technology should help children save their real-life experiences in the form of images, sounds, and stories, to allow them to revisit such experiences and share them with others (Radich, 2013). Another strategy is to leverage different sensors and outputs in mobile devices and use them to augment the outdoor experience with multi-sensory stimuli improving children's engagement (Koepfler et al., 2016; Rogers et al., 2004). According to the HUG experience, such features can be seamlessly embedded within a screen-less tangible device Zimmerman et al. (2015) and Rogers et al. (2004). However, Radich et al. also argue for bridging on-screen and off-screen activities (Radich, 2013), offering a diversified experience and different devices (with and without screens) for indoor and outdoor activities. This strategy can extend the technology-enhanced experiences beyond the initial novelty: unobtrusive technology could support outdoor activities and exploration, while other devices and applications can favor traditional forms of learning through digital materials, giving children access to new multimedia content.

Finally, Radich et al. argue that while using technology for children's exploration and creativity has its merits, younger children should be discouraged from adopting passive, non-interactive consumption of digital media (Radich, 2013).

3. Smart ecosystems for children–nature interaction

Guided by the insights distilled from the literature, we wanted to investigate technology innovation requirements to define an ecosystem of physical–digital systems for children–nature interaction. As illustrated in Fig. 1, and detailed in Table 2, in line with previous works in educational contexts, e.g., Papavlasopoulou, Giannakos, and Jaccheri (2019), we undertook design-based research (Chatzidimitris et al., 2014) that was initially informed by the literature analysis, and then proceeded with three different cycles of: (*i*) requirement analysis involving children and other relevant stakeholders (i.e., parents or teachers), (*ii*) system design

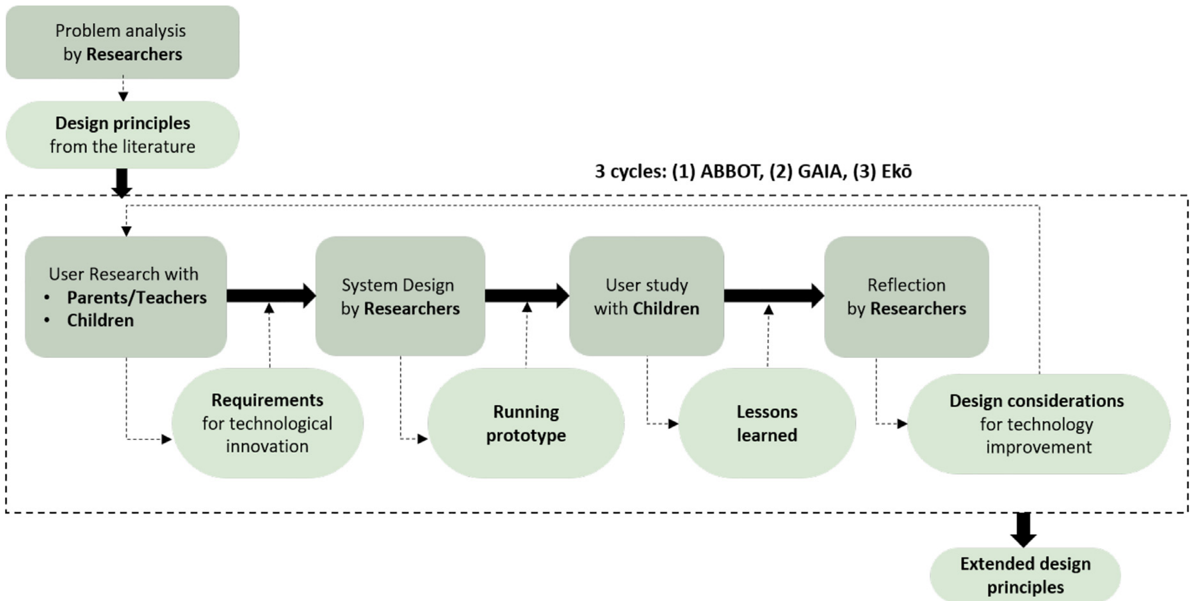

Fig. 1. Overarching method for the design of a smart ecosystem for children–nature interaction. The central phases underwent three cycles, each one leading to a different prototype.

Table 2
Details of the four phases followed in each cycle of the design-based research.

Phases	Data collection methods	Participants	Purpose
User research	Cycle 1: Interviews; card sorting. Cycle 2: Focus group. Cycle 3: Interviews; card sorting; sensory quiz	Cycle 1: Parents; children. Cycle 2: Teachers. Cycle 3: Parents; children	Identifying problems and opportunities as requirements for system design
System design	Technical specification, interaction flow	Researchers	Producing a preliminary prototype
User study	Cycle 1: Focus group; free play; questionnaires and interviews. Cycle 2: Free play; questionnaires and interviews. Cycle 3: Supervised play; questionnaire	Cycle 1: 170 kids (3–7 years old). Cycle 2: 72 kids (5–8 years old). Cycle 3: 60 kids (6–9 years old)	Observing and evaluating children's experience. Collecting insights for the next cycle
Reflection	Cycle 1: notes; recordings. Cycle 2: Notes; follow-up interviews Cycle 3: Notes	Cycle 1: Researchers. Cycle 2: Researchers and 30 children. Cycle 3: Researchers	Extrapolate design considerations for technology improvement

and (*iii*) system evaluation. Each cycle ended with a reflection phase resulting in implications for technology improvement on which the next phases were grounded. Overall, the process has led to design considerations aiming to refine the theory and practice of systems for children–nature interaction.

This section summarizes the first two cycles focusing on *ABBOT* (Delprino et al., 2018) and *GAIA* (Gennari et al., 2019). The third cycle, described in Sections 4–6, focused on new requirements for the sound-based perception of nature and on the design and evaluation of a system for the interaction with nature sounds, Ekō.

3.1. ABBOT

ABBOT is a pervasive interactive system for children in the early years of the primary school (Delprino et al., 2018). As illustrated in the left side of Fig. 2, its experience revolves around using a screen-less, wooden tangible that enables kids to take pictures of natural materials found during environment exploration and then record such pictures in a digital collection of materials. The camera is activated when the tangible is shaken; the transparent cap becomes enlightened when a picture is taken; putting two devices close to each other triggers the transfer of images from one device to the other. As a result of the outdoor activities, kids can play with digital materials at home, together with their parents, using interactive games on tablets that provide additional multimedia content explaining children's discoveries.

The development of ABBOT started with user-research activities that involved children and parents, from which it was possible to identify a series of design challenges, such as (*i*) capturing kids' attention on nature by means of activities stimulating their curiosity; (*ii*) involving kids in discovery tasks while making them feel safe and comfortable through activities not requiring much effort; (*iii*) favoring the interaction with other children; (*iv*) enforcing a learning phase to be held at home with the help of parents. A "learning-by-exploring" process was thus conceived to stimulate kids' curiosity about nature while letting them gather new content, supported by a smart toy for outdoor activities and a tablet app for accessing additional material at home or at school. A user study involving 82 kids from a kindergarten (3–5 years old), and 88 kids from an elementary school (6–7 years old) assessed the kids' attitudes towards collecting materials and learning new content using ABBOT (Delprino et al., 2018). The study showed that ABBOT is effective in engaging and motivating

Fig. 2. Children playing with ABBOT (left) (Delprino et al., 2018) and GAIA (right) (Gennari et al., 2019).

children to explore the outdoors. The majority of kids participating in the study easily learned how to use the tangible object and the tablet app, and they did not show any hesitation about going outside and using the device to capture nature materials. They also expressed high satisfaction, especially the elementary-school children, given their ability to master the connection between the tangible and the tablet app to transfer the captured images.

3.2. GAIA

The validation study with ABBOT highlighted some limitations. In particular, ABBOT motivates children to spend time outdoors individually, while it did not prove to be much effective in stimulating interaction with peers. To make children interact with nature and also socialize, we designed a new device, GAIA (Gennari et al., 2019), specifically conceived for use by groups of children (see the right side of Fig. 2). Similar to ABBOT, and following the HUG approach, GAIA is a screen-less tangible device. It is a band that can be attached to outdoor elements (for example trees or even street lamps in parks). Each band has four disks that emit light and react with sounds and audio. When a child touches the buttons, GAIA tells stories that guide children on a treasure hunt asking them to look for specific elements in the outdoors, for example, trees belonging to a given species. The treasure hunt is collaborative by its nature; by solving it together, children are led to explore the nature around them.

A focus group with teachers of an elementary school allowed us to identify the value of such a device for stimulating structured activities, not simply as an object for free use by children. Its multi-sensory stimuli can enable educational activities, for example, those enforcing the relation between mental and motor processes. In general, the teachers positively embraced the device, even those who initially had expressed doubts about the use of technology to explore the natural world.

During a user study (Gennari et al., 2019), four devices were then installed on the trees of the garden of the elementary school. 72 pupils aged $5-8$ years, organized in groups of 5 participants each and supervised by their teachers, played in a treasure hunt. 3 researchers observed the game-play. Each device told one part of a story, acting as a checkpoint in a discovery path around the park. The pupils were left free to play, with the only indication, given by the teachers, on the tree to start from.

Children were fascinated by the lights and sounds emitted by the devices. All were very involved in the gameplay. Initially, they were eager to know what multi-sensory effects the installed devices could generate. They kept running from one tree to another, sometimes even without listening to the game quests. Then they started paying attention to the game and conveyed their exploration of the environment towards identifying the requested natural elements. If on one side this aspect can be ascribed to a lack of interest in the story told by the device, on the other side it can be interpreted as the intrinsic capability of the multi-sensory stimuli to attract children, with the positive side-effect of favoring children's excitement in the exploration of the environment. This "unfocused" behavior was, in some cases, corrected by the children themselves, who asked the other team members to collaborate to identify a strategy. Therefore, after the initial unstructured exploration, the groups paid attention to the quest, and altogether and collaboratively moved from one tree to another to solve the game. In two groups, this collaborative behavior also facilitated the inclusion of two children with intellectual disabilities.

An emerging aspect was the children's will to continue exploring nature. After solving the game, some kids kept looking at the foliage of the last tree and kept discussing the leaves the treasure hunt had asked them to find. Others kept looking at the trees after reentering the school, through the windows, and were thrilled when seeing a squirrel climbing on a trunk.

The intention to continue exploring nature also emerged from the follow-up interactions with the children. We interviewed 30 children at the elementary school, asking their opinion on GAIA and suggestions for its improvement. Most of them (20 children) expressed the desire to extend the duration of the game, by introducing more devices that would let them explore more natural elements. 7 children suggested installing other games on the GAIA – the one most mentioned was "hide-and-seek". A few children (only 2) asked for more collaboration within groups. The story guiding the treasure hunt had a moral (i.e., not leaving waste in the park), which kids could grasp; in particular, all the interviewed children kept reflecting and commenting on it during the interviews.

3.3. Design considerations and trade-offs

ABBOT and GAIA are coherent with the majority of the design considerations outlined in Section 2.4; however, some trade-offs were necessary. For example, while ABBOT favors direct interaction with nature elements (C7), it does not allow for hands-free play and direct manipulation of materials: children have to carry the tangible around in the park to take pictures of interesting things. However, such a design decision was necessary for enabling the collection and sharing of material (C9), which is a distinctive aspect that reinforces ABBOT's educational value. Contrary to this approach, GAIA allows hand-free playing; children are free to move around, and they manipulate tangibles mounted on trees but can also interact with any other material in the environment. For example, the treasure hunt defined for the user study with GAIA required children to look for specific types of leaves. This game dynamics certainly allows freedom in play (C1) and co-participation (C4), and leverages the social groups and friendships between children (C5). On the other hand, GAIA does not favor a structured collection and sharing of materials encountered outdoors (C9). Since this aspect might limit the extension of the activity beyond the initial novelty (C8), GAIA was provided with an End-User Development tool for the easy configuration of the device's interactive behavior (Gennari et al., 2019). GAIA indeed does not bridge outdoor activities with follow-up activities to deepen the outdoor experience and learn from the encountered natural elements (C11), but it looks more adequate for structured outdoor-learning activities, in controlled environments, such as school playgrounds. Finally, while ABBOT was meant to activate the touch sense for feeling nature materials, GAIA does not leverage or activate directly children's senses (C3). Rather it adopts multi-sensory output to engage children, which however might cause an unnecessary cognitive load and can distract children from the state of involuntary attention that allows them to enjoy the surrounding environment.

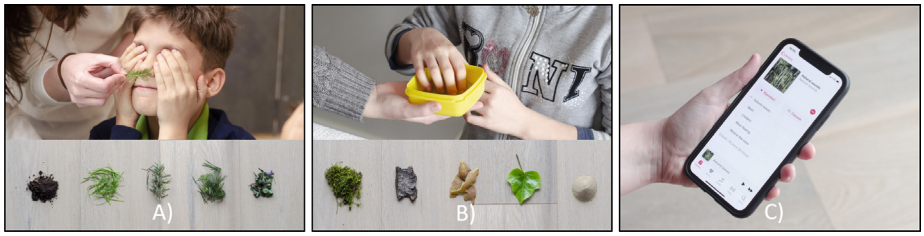

Fig. 3. Sensory quiz activities: (a) smelling five natural elements; (b) touching five natural materials; (c) listening to natural sounds.

All these considerations led us to identify the need for an *ecosystem of smart technologies*, i.e., multiple devices to be used, one at a time or in combination, to achieve varying goals that might depend on specific educational needs and usage situations. The multiplicity of stimuli could favor children's engagement along different channels, senses, and capabilities, thus resulting in a multi-fledged approach that can accommodate different needs and preferences. For this reason, as discussed in the following sections, we wanted to refine and extend our investigation to deepen how to amplify the *direct perception of nature through children's senses.* In our analysis, this dimension had indeed emerged as one of the most relevant factors for connecting children with nature, but it is still not adequately addressed in the literature.

4. Connecting children with nature through senses

Given the importance of stimulating children's senses, we concentrated our research on solutions allowing children to discover, capture and play with natural elements by maximizing the perception of the natural environment through senses. As for the previous design experiences, the starting point was investigating the relationship between children and the natural world and the influence that the use of electronic devices exerts on this relationship. In this new process, the focus was however on the senses as channels for conveying nature to children. A formative evaluation adopting mixed methods was initially conducted by involving children and their parents. The studies in this new process were approved by the ethical committee of the Politecnico di Milano (Approval no.: 12/2019).

4.1. Preliminary study with children

A preliminary study involved 8 children aged between 6 and 10, 3 boys and 5 girls. We reached out to the children's parents thanks to an announcement published on social media. The parents and the children decided to participate on a voluntary basis. Parents were then asked to sign a consent form to express their willingness for their children to take part in research activities.

4 children lived in a highly urbanized environment, and the others in a rural environment. They all were used to interacting with both technology and nature. The study focused on assessing children's familiarity with the natural environment and understanding of what feelings and impressions the children had regarding the outdoors as opposed to technological devices. As reported in Table 3, to maintain the children's interest high, we organized short and varying activities: a sensory quiz, a sorting-card game, and a semi-structured interview. The sessions lasted about 20 min for each child and took place in a place neutral and familiar to them. Three researchers moderated the activities.

4.1.1. Sensory quiz

The sensory quiz evaluated the children's familiarity with nature and the senses through which they were more in contact with nature. Considering that the majority of devices for nature exploration are based on the sense of sight, this sensory quiz was based on touch, smell, and hearing, while children had their eyes closed or covered.

Table 3
The three activities in the preliminary study with children.

Activity	Type	Duration	Support material
Sensory quiz	Hands-on	10 min.	Natural items, iPhone
Sorting card game	Hands-on	5 min.	Cards
Semi-structured interview	Verbal	5 min.	iPhone recorder

Smell quiz. Each child was given five natural elements all with a recognizable, intense smell: mint, rosemary, grass, soil, and a pine sprig (Fig. 3.A). Each child was asked to smell the elements, one at a time, and guess what they were. As represented in Table 4, the most recognized element was the rosemary. Children's comments highlighted that they succeeded as they were used to feeling it in the home and kitchen environment. Soil and grass, among the most common natural elements, were not recognized. Even mint, which we expected to be "easily" recognizable, was not easily identified.

Touch quiz. During the blind touch quiz (Fig. 3.B), the children were given five other natural elements, meaningful from a tactile point of view: moss, sand, kiwifruit skin, tree bark, and a leaf.

As represented in Table 5, the children responded more positively to the touch quiz than to the smell quiz. Almost all of them recognized the tree bark and the leaf. The sand, which could have confused them, was guessed correctly by most of them. However, only 1 was able to identify the moss and only half of them recognized the kiwifruit skin.

Hearing quiz. Finally, children had to listen to five sounds from nature, played through the phone of one researcher (Fig. 3.C): the wind in the leaves, the crickets, a running stream, buzzing bees, and the crumpling of leaves.

As reported in Table 6, the hearing quiz received the highest number of correct answers from the sample. Sounds like a stream and bees buzzing were recognized by all of the children, the other elements were also identified correctly by the majority. Nevertheless, children confused natural sounds, such as wind, with the sound of cars, or leaves with the sound of plastic.

Sensory quiz insights. The engagement and enthusiasm of the eight children highlighted how appealing a game based on sensoriality could be. Sounds were easier to recognize than smells and touch: the percentage of correct answers for the hearing was 77, 5%, while it was 20% for smell and 65% for touch. The many errors in the smell quiz and the difficulties that children showed during the touch quiz confirmed that, since these two senses can only be developed through direct contact, the participating children were not close enough to nature. From the children's comments, we also realized that hearing can be easily nurtured at a distance, e.g., by playing soundtracks on a digital device.

4.1.2. Card-sorting game

This activity focused on the participants' relationships with the natural and non-natural world. Children were given cards representing nature-friendly and non-nature-friendly objects, and

Table 4
Smell quiz results. Correct answers are highlighted in green.

	Child 1 (8y)	Child 2 (9y)	Child 3 (6y)	Child 4 (10y)	Child 5 (9y)	Child 6 (10y)	Child 7 (10y)	Child 8 (8y)
Mint	Basil	Parsley	Mint	Mint	Sage	Sage	Candy	Sage
Rosemary	/	Rosemary	Parsley	Rosemary	Rosemary	Rosemary	Origan	Rosemary
Grass	Leaves	Moss	Moss	Pepper	Pepper	Potatoes	/	Grass
Soil	/	Spices	/	Rocks	Sauce	Spices	/	Pepper
Pine	Leaves	Parsley	Parsley	Rosemary	Rosemary	Sage	Sage	Sage

Table 5
Touch-quiz results. Correct answers are highlighted in green.

	Child 1 (8y)	Child 2 (9y)	Child 3 (6y)	Child 4 (10y)	Child 5 (9y)	Child 6 (10y)	Child 7 (10y)	Child 8 (8y)
Moss	Soil	Grass	Broccoli	Grass	Soil	Soil	Grass	Moss
Sand	Sand	Salt	Breadcrumbs	Sand	Sand	Flour	Sand	Sand
Kiwifruit skin	Kiwifruit	Apple	Rock	Kiwifruit	Moss	Kiwifruit	Kiwifruit	Peach
Tree bark	Oak	Bark	Branch	Wood	Wood	Wood	Tree	/
Leaf	Leaf	Leaf	Leaf	Leaf	Leaf	Leaf	Leaf	Leaf

Table 6
Hearing quiz results table. Correct answers are indicated in the green boxes.

	Child 1 (8y)	Child 2 (9y)	Child 3 (6y)	Child 4 (10y)	Child 5 (9y)	Child 6 (10y)	Child 7 (10y)	Child 8 (8y)
Wind in the leaves	Car	Flood	Rain	Wind	Wind	Wind	Wind	Wind
Sound of crickets	Birds	Crickets	Night	Crickets	Crickets	Crickets	Crickets	Crickets
Running stream	Water	Stream	Stream	Stream	Water	Stream	Water	Stream
Buzzing bees	Bees	Bees	Bees	Bugs	Bees	Bees	Bees	Flies
Leaf crunch	Leaf	Plastic	Sand	Paper	Leaf	Paper	Leaf	Leaf

Fig. 4. On the left: children playing with the cards. On the right: the adopted cards.

adjectives expressing feelings about those objects. They were asked to combine the adjectives and the objects (Fig. 4).

As reported in Fig. 5, children often described both technological objects (tablets and phones) and packets of crisps as "beautiful" and "fun", i.e., through positive feelings. Fig. 6 shows that children are in general enthusiastic about nature, associating its elements with adjectives such as "fun", "useful" and "curious", and they are sensitive at the same time, as shown by the association of the flower card with the adjective "weak" (*"it can be damaged"*). They were very positive about playing in a park. However, with natural elements they also used adjectives such as "boring": *"We are used to a more fast-moving world!"*. In conclusion, the children seemed to be more attracted by outdoor dynamic activities than by nature itself.

4.1.3. Semi-structured interviews with children

The final phase of the study with the children consisted of a semi-structured interview organized to gather further information on:

- **Free-time spending preferences**, to understand which activities children like to have when they are not at school. Example question: "What do you like to do after school/in the afternoon?"
- **Relationship with technology**, in both indoor and outdoor contexts. Example question: "When you are at the park, do you want to play with your tablet?"
- **Environmental education**, to understand children's level of sensitivity to nature. Example question: "Do you think the waste bins in the park are important? Why?"

The results of the interviews, compared to those of the card-sorting game, showed that children have a mixed view of the outdoors. During the card game, the children associated outdoor concepts, such as "park" or "bicycle", with both positive adjectives like "curious" and negative ones like "boring". The interview then emphasized how children tend to prefer outdoor activities if such activities can entertain them (a playground, a bicycle, friends coming over): *"I don't like staying at the park when there's nothing to do"*. Not even one child spoke about having direct contact with nature and its elements.

Regarding the relationship with technology, the card game suggested a positive attitude to digital devices. The interviews instead highlighted that when children are outside and have something or someone to play with, they are not compelled to use any technological device: *"If I'm with my friends, I don't need a phone!"*.

The last questions regarding the children's vision of nature beyond playful activities or technology revealed that children are positively aware of the respect that nature needs: *"Waste bins are useful to keep the park clean, they are important for nature"*.

4.2. Interviews with parents

Children's parents, 5 adults aged between 35 and 63 (3 females, 2 males), were interviewed to gain insights on their perspectives regarding their child's attitude towards technology and their daily routine. Each interview lasted about 30 min and was structured to gather information about:

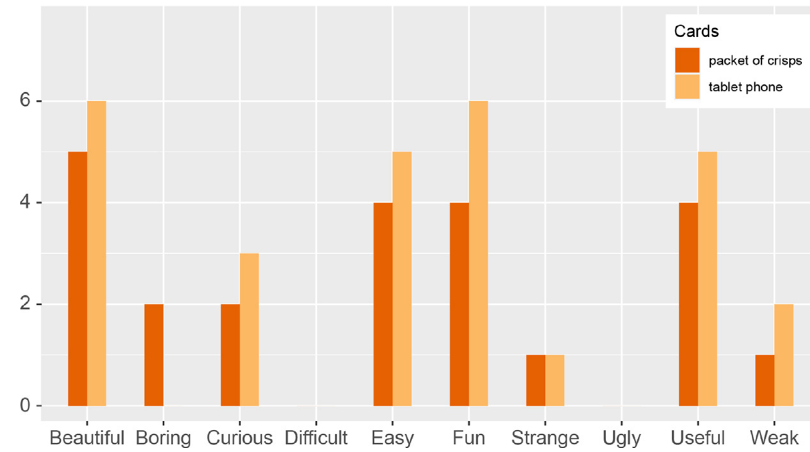

Fig. 5. Frequency of adjectives associations with non-nature-friendly objects (tablets/phones and packets of crisps).

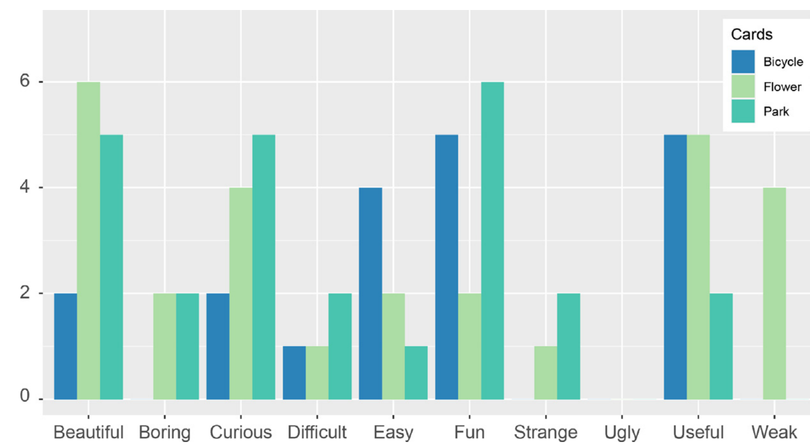

Fig. 6. Frequency of adjectives associations with nature-friendly objects (bicycle, flower, park).

- **How they organize and supervise their child's activities**
  Example question: "Do you organize your child's time based on a schedule?";
- **Child's relationship with technology**
  Example question. "Does your child have free access to technological devices such as tablets and mobile phones?";
- **Child's relationship with nature**
  Example question: "Do you think that your child's growth can be positively influenced by a more direct relationship with nature?".

The interviews highlighted that children have a large variety of after-school activities and parents admitted that sometimes it is difficult to organize outdoor playtime. The discussion especially focused on the parents' tension between the need of limiting technology use by children, and the importance and pervasiveness of technology in our lives. Parents said they try to limit the time their children spend with digital devices, but also: *"That's the reality and we have to live with it"*. Some parents admitted they allow their children to spend hours in front of devices and less time outdoors. Most times their children become nervous when they cannot use their digital devices or when the connectivity is not good enough. However, they become nervous also when they use technology extensively. Lastly, the parents described the relationship of their children with nature as low in curiosity til the point that children lack basic notions: *"My son is often confused when it comes to talking about nature's seasonality"*.

4.3. Insights

With respect to the design considerations discussed in Section 2, the preliminary study assigned priority to some aspects and also highlighted new elements:

- Children can get closer to nature by using not only their sense of sight but their sense of hearing as well — this resulted as the most developed sense in our research;
- Nature sounds can be easily experienced at a distance and this can let children recall their experience in nature and also memorize the experience and the natural elements they refer to;
- The experience with nature must be mediated by dynamic, physical activities, which must be easily tackled in the short time children can spend outdoors;
- Children must be educated about nature; digital devices can be actively used for indoor activities supporting education.

Based on these findings, and following the guidelines derived from the literature, we designed Ekō, a new integrated physical–digital system aimed to motivate children to explore the outdoors in search of sounds.

5. Ekō: Experiencing nature through sounds

Ekō integrates different physical and digital components bridging outdoor and indoor experiences with nature sounds. *Five recorders* (Fig. 7.1) allow children to collect sounds outdoors; a

Fig. 7. The Ekō components and interaction process. Ekō recorders are used in the nature environment to look for and register nature sounds. The control base enables the transfer of the recorded sounds to the Ekō app, where they can be played and composed within audio–visual mashups.

control base (Fig. 7.4) for indoor use, i.e., at home or at school, stores the collected sounds and allows the children to mash them up to produce audio–visual artifacts; *a tablet app* (Fig. 7.5) is used in combination with the control base for refining the audio–visual mash-ups and accessing digital content on the nature elements discovered outdoors.

5.1. Outdoor experience

Outdoors, children use the recorders to capture and store nature sounds (see Fig. 7.1). In line with consideration C1 in Table 1, this dynamics aims to motivate physical outdoor play. It also invites children to experience the outdoors through sounds from nature (C3), with the opportunity to socialize with other peers thanks to the availability of multiple recorders (C5). The recorders are embedded in wooden cases, suitable for outdoor play and in harmony with nature (C6). Their shape and the modality of use are simple and minimal to privilege portability and reduce distractions from the outdoor experience. Each recorder has one button to start and stop the recording, and another one to reproduce the recorded sounds. A LED light then provides visual feedback on the status of the recorder itself: it is off when there are no recorded sounds, flashes during the recording session, and is on (for a few seconds) to indicate that the sound has been saved after the recording. This multi-sensory feedback, even if minimal, can stimulate children's engagement with the device (C10).

As for the direct manipulation of nature elements (guideline C7), the recorders can be considered intermediaries for the interaction with sounds. Children are required to manipulate recorders purposely as a way to remind them of their "mission" as nature explorers in search of sounds. The recorder size still allows the children to use their hands for manipulation, for example for touching the nature elements that can generate sounds. The device in their hands represents the tools for capturing sounds, and this mission can activate their sense of adventure and imagination (C2).

It is worth noting that the design of the Ekō outdoor experience did not directly address co-participation and co-engagement in social groups (guidelines C4). However, as discussed in Section 6, the conducted user study highlighted the Ekō potential for stimulating children's collaboration during outdoor gameplay.

5.2. Indoor experience

In line with guideline C8 in Table 1, the tablet app provides an educational and playful experience that can also stimulate the child to go outside again by activating a cycle of discovery and learning.

Like in ABBOT, the app is a digital place where the children can store the materials collected outdoors (C9). Children can then play with the sounds creatively by composing audio–video mashups (C12) that can also be accessed or modified later (C8) and shared with others (C9). Children can retrieve additional content related to the collected sounds. These interactions aim to enhance continuously an authentic and genuine relationship between the natural and the digital world (C11), giving value to the educational dimension that the technology can amplify (C13). Overall, the experience allows non-passive interaction with technology (C12) since it requires children to search for sound and creatively generate multimedia artifacts.

The control base (see Fig. 7.4) is the key to the app functioning, and for bridging the outdoor experience with the indoor one. It has five slots that can house the recorders used outdoors. Thanks to an embedded Raspberry Pi microprocessor, as soon as a recorder is placed in a slot, the control base reads and uploads the recorded sound files to an HTTP server using a local WiFi network. The tablet app accesses the same server to get the recorded files for later use in the audio–visual mashup composition. The control base also acts as a playful dashboard for the composition of audio–visual content: the positioning of the recorders within specific housing slots determines the graphic and music elements the child can later combine and play within the app. As shown in Fig. 7.4, each housing slot has a geometric shape. When a recorder is placed in a slot, a mapping is created between the slot shape and the sound downloaded from the recorder. The sound and its mapping with the geometric shapes are transferred to the app. In the app, the children can then create animations by coordinating the geometric shapes with the nature sounds collected outdoors.

5.3. Educating through digital play and motivating to return outside

Besides allowing the children to interact with the natural sounds they collect outdoors, in line with consideration C8 in Table 1, the tablet app aims to stimulate continued interest and engagement thanks to a system of rewards and challenges. As illustrated in Fig. 8, it consists of four main areas. Two areas take on the fundamental phase of *pre-discovery*, by stimulating and preparing the child for the outdoor Ekō experience. In the *landscape area* (Fig. 8.A), a geolocation function helps select the landscapes the children can find in the areas around them. The

Fig. 8. Screenshots from the tablet app: (A) the landscape area; (B) a card providing content on a nature element; (C) the composition area; (D) the composition archive area.

aim is to suggest to the children the natural sounds that can be found near their current location, to motivate and prompt them to explore their area to record their own sound versions and find new ones. The landscapes present clickable animated elements that lead to in-depth *description cards* (see Fig. 8.B) offering content on the natural elements that can be found in a selected landscape, and sound samples that can be freely reproduced.

Two additional areas address the *post-outdoor experience*. The *audio–visual composition area* (Fig. 8.C), can be accessed only if newly recorded sounds are uploaded into the app. It presents an initial audiovisual configuration that depends on the positioning of the recorders in the housing slots. The child can then play with the sounds and the visual shapes by both changing the recorder position on the control base and acting on a control panel available in the app (see the bottom part of the screen in Fig. 8.C). The child thus creates a personal and unique audio–visual composition (consideration C12) that can be named, saved, and looked at afterward. The *archive area* (Fig. 8.D) stores both the single sounds recorded outdoors and the audiovisual compositions created indoors (consideration C9).

6. User study

A user study was conducted to assess children's attitudes towards Ekō, besides understanding whether using sound as the primary channel of interaction with nature was an effective design choice to engage children with the natural environment. The study in particular aimed to verify if the design of the physical device was unobtrusive and promoted a more direct connection with nature, if the outdoor game-play was engaging for the chosen age range, and if the app design and the composition paradigm for the audio–visual mashups were age appropriate.

6.1. Participants

The evaluation study involved 62 children (36 male and 26 female) belonging to two age groups: *Group1* consisted of 28 children (21M, 7F) of 6–7 years old; *Group2* consisted of 33 children (14M, 19F) of 8–9 years old. They all belonged to the same summer camp classes held in an elementary school in Cornaredo, a town in the Lombardy region of Italy. They knew each other and were used to playing together. They participated in the study as part of their activities during the summer camp. We explained the aim of the research, and they participated voluntarily. By agreement with the summer camp educators, there was no selection; all the children attending the summer camp were asked to participate in the study. Parents were then asked to sign a consent form to express their willingness for their children to take part in research activities. The consent form was defined in accordance with the institutional consent mechanism which was cleared by the authors' institution Ethics Committee (approval no.: 12/2019) and included a commitment to adhere to Data Protection legislation. We provided the summer camp educators with consent forms and information sheets, which were distributed to parents prior to the study being carried out. We also made sure children wanted to take part in the study at the start of the activities.

6.2. Settings and materials

The study took place at the summer camp facility, which is surrounded by a public park that, even if located in an urban area, provided a quiet environment where the outdoor activities were conducted. The whole evaluation lasted 6 h, including breaks, with each child being involved for a maximum of 50 min. 5 researchers managed the activities. 6 summer camp educators helped supervise the children and, when necessary, explained the activities.

A basic Ekō prototype was built and used for the evaluation. It comprised two recorders, a playable demo of the composition mechanisms, and an interactive prototype of the app showcasing the most important functions. During the exploration activities requiring children to use the prototype, data were collected through on-site observations, recordings of the playing activities, and notes of the researchers' observations.

6.2.1. Final satisfaction questionnaire

For collecting satisfaction data directly from children, as suggested by works reported in the literature (Dexheimer et al., 2016; Putnam, Puthenmadom, Cuerdo, Wang, & Paul, 2020; Wrońska, Zapirain, & Mendez-Zorrilla, 2015) and following guidelines for surveys with children (Read & MacFarlane, 2006), we

Table 7
Details of the four activities in the Ekō user study, carried out in 3 rounds with 20 children each.

Phase	Duration	Location	Type of participation	Support material
Introduction	10 min	School playground	Groups of 20 children (3 rounds)	Tablet showcasing Ekō's interactive prototype
Exploration	15–20 min	Park	2 groups of 10 children/1 researcher + 1 educator (for each group for all the 3 rounds)	Ekō recorders
Composition	5 min approx.	School playground	1 child + 1 researcher	Ekō recorders and audio–visual composition demo
Interview	10 min approx.	School playground	1 child + 1 researcher	Tablet

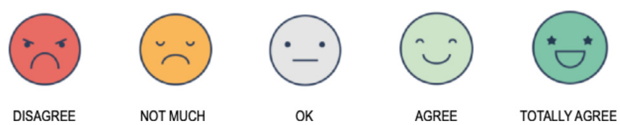

Fig. 9. Smiley-o-meter 5-point Likert scale used in the final questionnaire (Read, 2008).

defined a variation of the System Usability Scales (SUS) questionnaire including three groups of questions.[1] The first group asked the children to choose a nickname to identify themselves, to indicate their age, and to report briefly on the sounds they had recorded during the activity. The second group of questions aimed at detecting the level of satisfaction towards the overall experience and preferences towards the sound recording phase compared to the interaction with the app. The other questions then focused mainly on the interaction with the tablet application, its ease of use, and the level of satisfaction with the offered functionality.

To ease the text comprehension, we kept the questions short. We reduced as much as possible the use of open-ended questions that required children to write. For closed questions, ratings were collected through the pictorial Smiley-o-Meter 5-point Likert scales taken from the Fun Toolkit (Read & MacFarlane, 2006) ranging from "disagree" to "totally agree" (see Fig. 9).

6.3. Procedure

The participating children were divided into three groups of about 20 children that attended in an alternate way four steps: introduction, exploration, app use and sound composition, and final interview (see Table 7). Two researchers introduced the study and coordinated the exploration. One researcher supervised the play session with the composition demo, and one administered the questionnaire during the final interview. One researcher supervised the whole evaluation to ensure consistency across the different groups.

The *introduction* lasted around 10 min and was held in the school playground. The children were explained how the activities would have been carried out and were introduced to the topic of natural sounds. They were shown the app prototype with examples of sounds they could find in the nearby park.

For the *exploration*, the group was then split into 2 groups of about 10 children. Each sub-group was shadowed by one researcher who coordinated the exploration in the park. In addition, one educator accompanied each group to supervise the children. The educators were instructed to give the children as little help as possible. Before the exploration started, the researcher explained how to use the recorders; then, one by one, the children were given the Ekō recorders and were left free to explore the park (Fig. 10.A) in search of a sound of their choice to record (Fig. 10.B). If they appeared frustrated or needed help with using the recorder, the researcher would give suggestions to help them. Also, due to their age, the children were closely followed by the researcher, the rest of the group, and an educator. To minimize any disruption of the experience, the children were instructed to be as quiet as possible. For each sub-group, the exploration lasted a total of 15–20 min.

After recording at least one sound, each child was brought back to the school playground, where they participated in the next step focusing on the *app use and sound composition* (see Fig. 11.A). This activity lasted around 5 min for each child depending on the engagement and the age of the child playing. Before the test started, each child was given a brief explanation of the app organization and its interface. Given the pandemic regulations, the researchers were asked to conduct any activity in the outdoor space of the school, in a usage context different than the one the app had been thought for. We, therefore, decided to keep the activity short and asked them to focus on the elements bridging the outdoor and the indoor playing, i.e., the composition area and the sound archive area. The children were left free to play on their own. Only if a child seemed stuck on a particular interaction, the moderator suggested what to do next.

At the end of the play activities, the children answered the *questionnaire* about their satisfaction with the different elements of the Ekō experience (see Fig. 11.B). Due to COVID-19 restrictions, the questionnaire was given digitally, via a tablet. For the younger children, the moderator read the questions, while the older children completed the questionnaire without any help. Nonetheless, the researcher supported the children when they showed difficulty in understanding a question. Depending on the children's will, the researchers had the chance to discuss and take note of further observations. The completion of the questionnaire and the discussion in total took a maximum of 10 min. In the end, the children were rewarded with a sticker of their choice.

6.4. Data analysis

During the study we collected: (1) the children's answers to the final questionnaire; (2) the notes taken by the researchers; (3) audio–video recording of the different activities.

6.5. Analysis of questionnaire data

Given the lack in the literature of reliable benchmarks for interpreting the results of SUS versions adapted for children, for the analysis of the collected data we decided not to compute any SUS average score (as it would be required with a population of adults). Therefore, the analysis mainly focused on the qualitative interpretations of the children's quantitative answers, sometimes complemented by insights extracted from the open-ended questions focusing on the exploration experience. The answers to these questions were also triangulated with the other collected data in the thematic analysis described in Section 6.6.

[1] The list of administered questions is available at: https://tinyurl.com/EKO-finalQuestionnaire.

Fig. 10. Children exploring the park with an educator (A) and one participant while recording the sound of birds chirping (B).

Fig. 11. Participants playing with the demo supervised by a researcher (A), and answering the questionnaire together with a researcher (B).

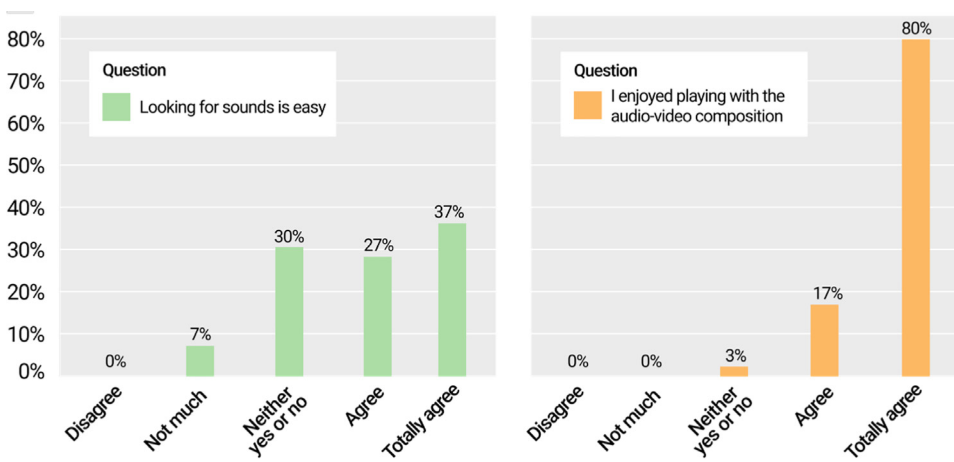

Fig. 12. Chidlren's answers for two questions about the interaction with sounds.

6.5.1. Satisfaction with sound exploration

Overall, the outdoor exploration experience with Ekō was perceived positively. Every child was able to record at least one sound. 31% of the children recorded more than one sound, with a maximum of 5 sounds for 2 children in Group2 (8–9 years old). When asked to report on the recorded sounds, a few children, especially in Group2, were able to specify which insects (bees, crickets, cicadas, flies) and birds (blackbirds, pigeons, sparrows) had produced the sounds. 57% of the children would have loved very much to record more sounds.

68% of the participants totally agreed with the statement *"Playing with Ekō is easy"*; 28% agreed; one child from Group1 (6–7 years old) was neutral; one, still from Group1, disagreed. When asked to choose what they preferred most between searching for nature sounds and playing with the app, 63% of participants selected the outdoor experience. Moreover, when rating the statement *"I'm satisfied with the sounds I recorded"*, 90% of the participants expressed the highest satisfaction ("totally agree"), with the remaining 10% indicating a good level of satisfaction ("agree").

However, sound exploration was also perceived as challenging, especially by the older children in Group2. As shown in Fig. 12, the statement *"Looking for sounds is easy"* had rather mixed ratings: 37% of children totally agreed (22 children in total, only 8 from Group2), 27% agreed (16 in total, 9 from Group2), 30% were neutral (18 in total, 11 from Group2), and 7% did not agree much (6 in total, 5 from Group2).

If we look in more detail at the sounds collected during the exploration phase, it is possible to distinguish two main categories, *passive* and *active*. The first are those sounds that do not require any specific action for the children to generate them, such as sounds of birds, the wind, and insects. The second category refers to sounds that the children produced by manipulating materials not always involving strictly natural elements.

The instructions given by the researchers were geared towards natural sounds, but the specific task given to the children was to collect all the sounds they would find interesting. Thus the recorded sounds were heterogeneous and there were differences between the two age groups. The younger children recorded a comparable number of passive and active sounds (20 passive sounds vs. 21 active sounds). The active sounds were mostly produced by stepping on nature surfaces and objects (dry leaves, grass, soil, wooden bridge), and unlike the older children, in some cases sounds were produced by means of artificial objects (metal tubes, a railing, a trash can). Older children recorded more active sounds (24 passive vs. 30 active) that almost exclusively related

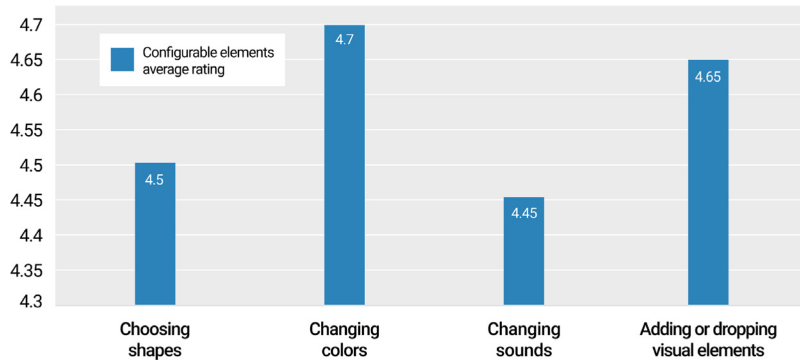

Fig. 13. Children's average rating for the configurable elements in the audio–visual mashups (scores on a scale from 1 to 5).

to natural elements — the only exceptions were the steps on a wooden bridge and a branch beaten against a metal pole.

A different attitude between the two age groups thus emerged, especially in relation to the active sounds. In fact, Group1 showed a greater sensitivity towards the natural environment, as children tried as much as they could to record the sounds the environment was offering. The sounds of Group2, instead, were produced through intrusive actions that also damaged the environment: the children broke sticks and beat them against trunks or metal poles.

Overall, the children's enthusiasm for sound exploration clearly emerged. When rating the statement *"I'd like to play with Ekō in different locations"*, 50 children were completely positive (85% of the whole sample, 80% from G1, and 94% from G2). They also adopted a proactive attitude, as they wanted to explicitly pinpoint further locations in which they would like to use Ekō (*"I might try it when I'm on vacation on the mountain"*), and the sounds they would like to collect (*"The sound of the waves"; "A rooster crowing"*).

6.5.2. Satisfaction with the tablet app

In general, the children found the app easy to understand (63% totally agreed, 24% agreed, 11% were neutral, 1 child in Group1 totally disagreed), with a slightly more positive attitude from the Group2 children. The 80% of children highly appreciated the audio–visual composition function (see Fig. 12). 92% of them were very satisfied with their mashups, and the 85% said they would like very much to create other mashups.

As shown in Fig. 13, when asked to assign a rate from 1 to 5 to the different composition options, they in particular preferred the actions on the visual elements, i.e., changing the colors and adding/dropping the visual components, more than acting on sounds. This may be due to the noisy situation in which the evaluation was conducted, which made the acoustic feedback less noticeable than the visual effects. This aspect however deserves further investigation.

6.6. Thematic analysis

A thematic analysis was conducted on the researchers' notes and the video recording transcripts. Notes were taken individually by the researchers on children's significant behaviors and externalized comments; researchers' personal post-experience considerations were also collected. The researchers' notes were integrated with the video and audio analysis. Some 70% of this material was independently double-checked by two researchers. The initial reliability value was 80%, thus the researchers discussed the differences that especially related to the interpretation of videos and reached a full agreement. The two researchers then analyzed the integrated material looking for recurring themes through an inductive thematic analysis following first an in-vivo coding scheme (Manning, 2017) and then affinity diagrams to cluster codes into themes (Preece, Rogers, & Sharp, 2015). The analysis highlighted the themes discussed in the following.

Sounds give a new perspective on nature. Children seemed more engaged than usual with their surroundings when searching for sounds to record. One child, in particular, noted that *"Sounds seem more 'ferocious' when we listen to nature quietly"*, and this can be interpreted as greater attention children posed on sounds compared with their previous experiences. Other children also observed that *"nature seems different and more fascinating when searching for sounds"*.

The novelty of the Ekō experience seemed to make nature more interesting to children, who would otherwise find it not stimulating. When during the initial presentation an educator asked children how they could play with nature, some of them noted: *"We cannot because we cannot pick flowers or damage them in any way"*. Others further remarked that *"especially for this reason nature is boring"*. The comments collected after the Ekō use let us think that the exploration, as supported by the system, allowed children to identify a more engaging, still respectful, way to experience nature.

Collective play. Despite our initial expectation for the Ekō's gameplay being more suitable for individual players, Ekō also accommodated group play. Children did not seem disturbed by other children's involvement, rather they collaborated with the others. Thanks to open-ended play, children of similar ages tended to aggregate together in outdoor exploration. Children also helped each other by suggesting what to record or how to generate new sounds. Therefore, Ekō was found to be suitable for collective play as well (C5) and, to some extent, for supporting co-participation and co-engagement (C4): on several occasions, children were motivating others to listen to sounds or to produce new sounds.

Interaction with the environment and participant's age. During the exploration phase, the children were asked to search for sounds to record or, if they could not find any, to try to generate one. Although the instructions were the same for all, age seems to influence how children interacted with nature. The older children, in fact, seemed more proactive in generating sounds themselves by brushing leaves or breaking small branches picked up from the ground, even if this proactive behavior could damage the environment. Younger children instead needed more prompts from adults to generate sounds artificially, but they showed a greater attitude towards listening to nature sounds.

Preventing disrespectful behaviors. As a side effect, the children's collaborative behavior, although rarely, was disruptive to the environment. To prevent this, the intervention of the researcher or educator was necessary to explain to children how some actions were disrespectful to nature. However, by establishing boundaries for limiting damaging behaviors, the adults had the opportunity to educate children. This lets us think that smart toys like Ekō can contribute not only to expanding the children's knowledge of nature but also, indirectly, to helping educators transfer the right attitude towards nature. Future extensions of the Ekō device and its game dynamics should follow this direction.

Continuity of play. To a lesser extent, it emerged that a few children did not consider outdoor exploration and playing with the app as two activities being part of the same experience. Besides the settings in which the activities were held, probably this perception can be ascribed to the long break between the two activities: due to the size of the groups (around 20 participants per round), the children had to wait for some time before playing with the app. While waiting, they were free to play among themselves, and this probably contributed to the feeling of disconnection between the two phases. It is also worth noting that, given the experimental settings that leveraged especially the outdoor exploration, the children could not try the app in an adequate context, as it would instead be indoors, at home, or in their classrooms at school. Furthermore, only the composition area was disclosed to them. However, this issue also lets us think that a tighter connection between the outdoor and the indoor experience should be devised.

Advantages of unobtrusive interfaces. New reflections unexpectedly emerged in relation to the unobtrusive design of screenless tangibles. For prototyping the devices supporting outdoor activities, we customized commercial recorders that were also equipped with an integrated screen. Only half of the recorders had the mini-screen turned off so that it did not display any confirmation message when recording sounds; only the LED provided feedback on the correct functioning. As per our observations, the absence of the screen made the children more confident in using the device. In particular, those who used the recorders with the active screen looked too much at the screen, trying to understand if the recorder was working (despite being told it was not important for the recording). Instead, the children who played with the screen turned off appeared more confident and willing to take for granted that the recording started working just by pressing the buttons, without being distracted from the experience with nature. This insight aligns with the findings reported in the literature about the benefits deriving from the head-up games (Soute et al., 2010).

Hands-free playing vs. deliberate device handling. Ekō does not allow hands-free play, and therefore it might not favor the direct manipulation of natural material. However, the goal of this choice was to promote the active behavior of children during exploration, which might increase their attention to the sounds available outdoors. In the Ekō vision, handling a recorder and pushing a button to record a sound demands a deliberate act by children, which is needed to close with success the look-up of an interesting sound. The children's observations collected during the study let us think that this deliberate mechanism also motivated them to identify sounds that otherwise would be ignored.

7. Discussion

This paper has presented design-based research (Papavlasopoulou et al., 2019) that undertook multiple design and evaluation cycles, to identify problems, solutions, and principles related to our overarching research question: how can technology be used as an unobtrusive intermediary to (*i*) motivate children to explore nature and (*ii*) improve their perception and knowledge of nature through interaction with natural materials? All the conducted studies highlighted the value of screen-less technology not distracting children from their experience with the natural world. Each study then addressed specific channels and modalities to motivate children to strengthen their relationship with nature. The collected insights progressively moved our attention to nature perception through the senses. The Ekō design and evaluation in particular addressed the capability of sounds to let the children perceive nature and recall and learn from the outdoor experience afterward and at a distance.

The results of the Ekō evaluation confirmed the effectiveness of centering the outdoor experience on sound exploration for engaging children and letting them perceive the surrounding world. The final questionnaire highlighted the high satisfaction of children with sound-capturing activities and their desire to capture even more sounds. The gathered results in general suggest that sound could be a proper channel to promote the interaction of children with nature, being able to capture their attention and amplify their perception of nature elements, overcoming some of the challenges and common barriers to outdoor engagement, like children's perception of nature as boring and uninteresting.

Even the reported difficulty in the outdoor experience can be ascribed to their intention to discover more in an environment (i.e., an urban park) where sounds might be lacking. This difficulty was perceived especially by the older children, who were also very active in generating sounds by themselves when the environment lacked nature sounds. This can be interpreted as the Ekō capability to create engagement and a positive attitude towards discovery, creativity, and imagination (Koepfler et al., 2016; Rogers et al., 2004).

Ekō triggered original reflections on the potential of technology to instill in children the proper attitude towards the natural world. In the context of the children–nature relationship, smart toys can positively influence children's individual and collective sensitivity and ecological awareness. The use of Ekō and other similar toys could not only expand knowledge of the natural environment but also support the development of respectful habits for the adults of tomorrow.

The experience with Ekō also highlighted how these interventions must be tailored to the specific children's age. In particular, while the youngest must be encouraged to explore, to develop their listening skills and appreciation for nature sounds, older children need dynamic activities that must, however, help them maintain responsible behavior.

Overall, the Ekō design and evaluation shed light on new insights and nuances of already consolidated aspects, which led us to extend further the set of design considerations from which our research had started.

7.1. Further design considerations

Learning from the insights gathered from our design-based research, we distilled additional design considerations, which refine general principles for interaction design for children with reflections on how to use physical–digital systems for connecting children to nature (see Table 8).

Technology and game dynamics should be non-disruptive to the environment and the natural elements (C14). Children should be encouraged to experiment with the elements they find in nature and outdoors. Collecting and saving the material encountered during outdoor experiences are fundamental aspects for educational purposes; however, the technology adopted and the activities organized around it should inherently minimize any damage, disruption, or disturbance of the environment and its inhabitants. Possibly, the technology and the related outdoor activities should involve game-play mechanisms to establish boundaries and prevent behaviors that may damage the environment.

Table 8
Additional design considerations originating from our design-based process.

	Additional design considerations
C14	Adopt non-disruptive technology and game dynamics
C15	Attract children's attention, not on how&what technology is doing, rather on what is being done with it
C16	Support activities for different ages and experiences
C17	Provide multiple and flexible modalities for nature exploration
C18	Analyze behaviors as captured by *smart nature ecosystems*

Given the attraction that children have for technology, reducing the device-generated stimuli in outdoor exploration can help *children focus less on understanding what and how the technology is doing, and rather pay attention to what is being done with the natural environment* (C15). The experience with Ekō showed that, as the focus must be on exploring nature, additional information, or stimuli, even the feedback for the correct functioning, provided by the devices adopted outdoors may require an unnecessary cognitive load and can be distracting from the state of involuntary attention that allows children to enjoy the surrounding environment.

We also argue for supporting *diversified, layered activities, with different levels of complexity accommodating different age groups and usage experiences* (C16). The user studies conducted with Ekō showed that children of different age groups experienced the proposed systems differently. Supporting varying activities then requires flexible systems that can be easily personalized, for example by means of configuration environments also enabling non-technical stakeholders (e.g., parents and teachers) to customize the system behavior and the game activities thanks to adequate paradigms for the End-User Development of physical–digital systems (Gennari, Matera, Melonio, Rizvi, & Roumelioti, 2022; Gennari et al., 2019).

To achieve outdoor experiences that can accommodate the need of everyone, *multiple open-ended modalities of play* must be provided (C17). The technology designed for connecting children with nature should allow children the flexibility to play and explore nature individually, in pairs, or groups, as they wish, exploiting different interaction modalities and perception channels. This can accommodate children's preferences and also diverse and inclusive education strategies, which might depend on the context of use (class-level activities at school, open-air activities after school, individual use), and also on the characteristics of the children involved. Putting fewer restrictions, and keeping the activity open-ended can further help leverage pre-existing social groups and friendships among children (as required by C5).

The last two considerations let us also identify the need for ecosystems of multiple devices for creating *smart-nature playgrounds*, i.e., complex systems that can offer other benefits than motivating children to experience nature. Playgrounds have great potential to attract children to spend time in the open air; they can contribute to socialization and children's personal growth. However, they might also be spaces where children might hold wrong behaviors, not only those damaging the surrounding environment but also those excluding or stigmatizing their peers. Even in playgrounds where children can be monitored by professionals and educators (e.g., at school), these behaviors might be difficult to identify. Smart technologies, like the ones described in this paper, and in particular pervasive smart objects combined with gamification paradigms, can favor the collection of data (C18); data analyses, e.g., based on AI models, can then help examine children's behaviors, and spot aspects to be corrected. In the long term, this can help educators (parents, teachers, and other stakeholders), not only identify strategies for motivating children to play in the open air but also to define policies to strengthen social norms against exclusion.

7.2. Limitations

COVID constraints limited the assessment of factors beyond the effectiveness of the designed systems in engaging children.

Validity for learning. The evaluation did not assess properly the learning benefits. Educating children about nature was a need that emerged when interviewing parents and teachers; the tablet app included areas purposely designed to favor learning about nature. However, due to COVID limitations, we observed the app usage in inadequate contexts, i.e., held outdoors and lasting a few minutes, not sufficient to assess learning-related aspects.

Validity for behavior change. Similarly, we were not able to assess the benefits of changing children's behavior and improving their attitude towards nature and outdoor play. Long-period evaluations would address this goal.

8. Conclusion and future work

This paper has discussed the design of integrated physical–digital systems that aim to reconcile children with nature. The presented systems leverage the attraction that children have for technology, at the same time adopting unobtrusive solutions, able to amplify children's sense-based perception of nature without distracting them from immersive experiences. By discussing the adopted design-based process and the collected insights, the paper also contributes to principles guiding the creation of physical–digital systems for nature exploration.

Even if the results of the conducted evaluation studies are encouraging, the systems designed so far have limitations in the usability of the devised tools, for example, the difficulties observed for the use of the Ekō physical and digital components, and also the limited perception of continuity between the outdoor and indoor experience. Our future work will improve these aspects. In addition, to address the limitations deriving from COVID restrictions, we have planned new studies in collaboration with elementary schools, for evaluating the entire ecosystem of the designed tools in proper usage contexts including indoor activities, and in the long period.

As a fundamental contribution, we aim to lay the groundwork for the design of ecosystems of technologies for smart playgrounds in outdoor environments. Besides a deeper investigation of the factors that can motivate children to spend time outdoors, this goal requires the definition of adequate design toolkits and methodologies, which can facilitate the creation and configuration of integrated physical–digital systems by stakeholders who are not experts in technology, e.g., parents and educators. Our current work is devoted to defining such toolkits through which children themselves can program their own devices. An important goal within this framework will also be to introduce children and parents to responsible design, improving children's attitudes and sensitivity towards nature and the use of technology as well. This last aspect can in particular enable sustainable lifestyles and well-being (Gennari et al., 2022; Gennari, Matera, Morra, Melonio, & Rizvi, 2023).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maristella Matera reports administrative support was provided by Polytechnic of Milan.

Data availability

Data will be made available on request.

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Selection and participation

Children participating in the Ekō evaluation were attending a summer camp in an elementary school in Cornaredo, in the Lombardy region in Italy. They were involved in the study as part of their activities during the summer-camp time. The purpose of the study was explained to them, and they were given the opportunity to participate voluntarily. By agreement with the educators, there was no selection. Parents were asked to sign a consent form to express their willingness for their children to take part in research activities. The consent form was defined in accordance with the institutional consent mechanism which was approved by the authors' institution Ethics Committee (approval no: 12/2019) and included a commitment to adhere to Data Protection legislation. We provided the summer-camp educators with consent forms and information sheets, which were distributed to parents prior to the study being carried out. We also made sure children wanted to take part in the study at the start of the activities.

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