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Using E-textiles to Design and Develop Educational Games for Preschool-aged Children

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ABSTRACT: This paper reports on the design and development of educational games and materials that utilize affordable e-textile technology. The researchers employed a design-based approach whereby preschool children used three e-textile materials in two cycles to inform on the development of interactive materials from ordinary objects and bodily interactive games. The study's data were collected and analyzed according to the design-based research framework through iterative cycles of interviewing, video recording, and note-taking. The paper describes the characteristics, pros, and cons of e-textiles and what to consider when using them to create interactive educational materials for preschool-aged children.

Keywords: E-textile, Wearable technology, Preschool education, Design-based research (DBR), Executive functions

1. Introduction

The educational value of e-textiles has been on the agenda for researchers for some time (e.g., Fields et al., 2021; Peppler & Glosson, 2013). Most e-textiles are easy to employ within the preschool context, enabling the transformation of ordinary objects, toys, and clothing into digitally interactive materials. Developing interactive materials from the objects already familiar to children, such as toys and clothes, helps children to become more easily familiarized with them (Vega-Barbas et al., 2015). More importantly, as the current study will exemplify, e-textile technology enables the development of bodily interactive games (e.g., Doménech et al., 2018) which have, among other treatments, been shown to cultivate Executive Functions (EFs) in children (e.g., Best, 2012; Gao et al., 2019; Rafiei Milajerdi et al., 2021; Xiong et al., 2019) and young people (López-Serrano et al., 2021).

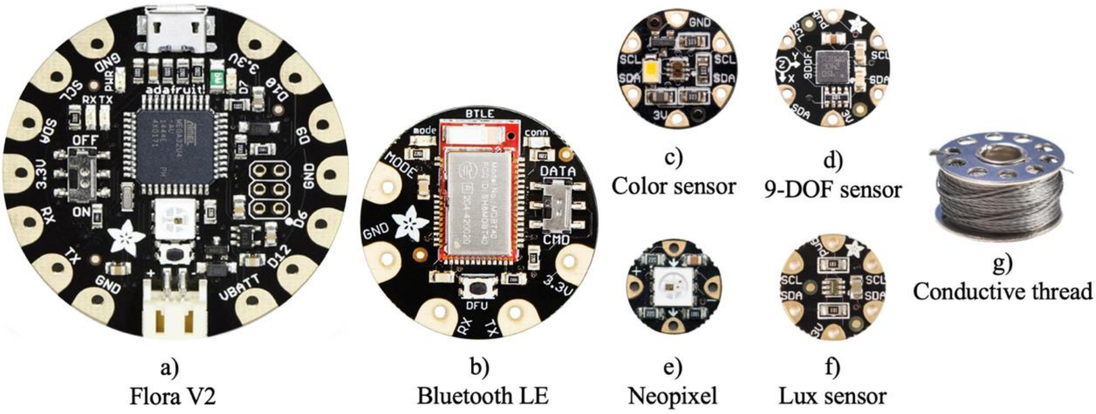
Although other technologies in the market can provide some of the same functionalities that e-textiles are claimed to serve (i.e., bodily interactions and maintaining the connection with the real world during use) such as Microsoft Kinect and HoloLens, these technologies are more expensive, allow for little to no modification as they have readily-available hardware, and may not be considered appropriate for preschool-aged learners. Further, developing games or educational materials with these types of technology may be far more complicated than developing games with e-textiles. We contend that bodily interactive games that harvest the power of e-textile technologies can help enhance EF skills and investigate EF intervention characteristics stated in the literature (e.g., Diamond & Ling, 2016; Gashaj et al., 2021; Rafiei Milajerdi et al., 2021). However, the design issues related to e-textiles have only been briefly addressed in the literature, and as such there is no guidance for researchers or educators to refer to when seeking to utilize e-textiles. This gap is considered even wider when we look at the design of e-textiles for educational purposes, and specifically for younger-aged children.

The current study employed a design-based research (DBR) to discover how e-textile technology can be utilized to develop educational games for preschool-aged children. The study aimed to contribute to the literature, and specifically to the field of human-computer interaction, by reporting on the outcomes of a DBR project undertaken with preschool children and teachers over two iterative cycles. The study further puts forward a suggested guide for the deployment of e-textiles when developing interactive educational e-textiles for preschool-aged children, and the pertinent design issues that should be considered.

1.1. Literature review

The term electronic textiles or "e-textiles" refers to a wide variety of electronic components such as mainboards, sensors, and conductive materials that are incorporated into clothing and wearable accessories that are aimed to handle specific tasks such as sensing physical properties and communication (Coccia et al., 2021; Ismar et al., 2020). E-textile applications extend the functionality of electronic systems, enabling them to become portable, customized, and ubiquitous (Komolafe et al., 2019). Being malleable and in harmony with the body, e-textiles can help to diversify tangible experiences and encourage bodily interaction (Ugur Yavuz et al., 2021). The main e-textile components used to develop materials in the current study are presented in Figure 1.

Figure 1. E-textile components used in the study



Note. Components by Adafruit are used: (a) programmable microcontroller for governing other electronic components and workflow, (b) Bluetooth LE for facilitating wireless communication, (c) color sensor for detecting the colors of objects, (d) accelerometer/gyroscope/magnetometer for detecting motion, (e) Neopixel for emitting different colors, (f) lux sensor for detecting light levels, and (g) conductive thread for connecting components of a circuit.

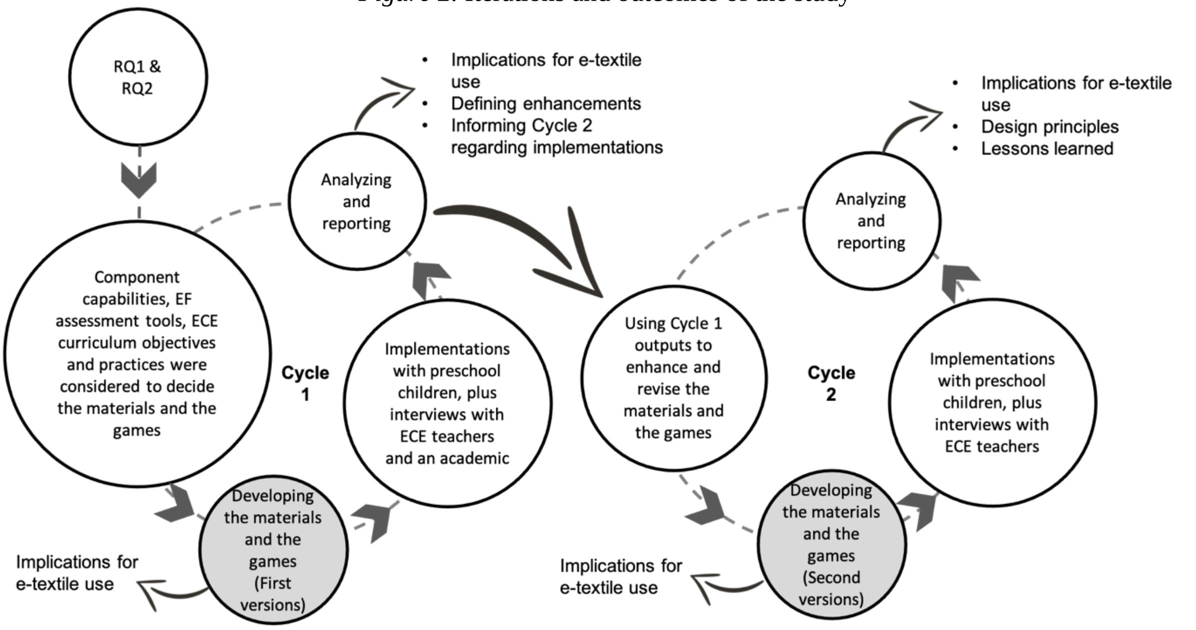
A wide variety of applications have utilized e-textile materials. Although the purposes of e-textile-based artifacts may vary, as Chen et al. (2021) indicated, e-textile design is an interdisciplinary process that integrates both engineering and textile design. It also requires decision-making at various levels of production, realizing that functionality goes hand in hand with expertise in creating e-textile materials, as well as considering the personal preferences and cultural expectations of the target group (Kafai & Peppler, 2014). Studies that discuss e-textile design are still emerging, and the available information addresses several general areas of concern. For example, Almusawi et al. (2021) explored physical education teachers' perceptions regarding wearable use during physical education, and revealed that the teachers perceived comfort (e.g., convenience, inclusion, and wearability), safety, and customizability (e.g., esthetics) as important. Working with children between the ages of 1 and 7 years old, Honauer et al. (2019) explained the characteristics of digitally interactive soft toys; stating that they should be durable and washable, have simple and obvious interactions, and include tactile feedback. They also added that actions should produce familiar and immediate effects. Nonnis and Bryan-Kinns (2019) considered intuitive use and durableness in their material design process. Similar issues that have also been considered in other studies are esthetics, function, and wearer acceptance (Balestrini et al., 2014); lightness and durability, combining multiple senses, instantaneous feedback mechanisms, and real-life movement-based interaction (Norooz et al., 2015); providing feedback, incorporating multiple senses (i.e., lights, sounds, and vibrations), hiding and protecting the battery, children's motivation to play with the item, understandability, intuitiveness, and comfort (Vega-Barbas et al., 2015).

Numerous materials with distinct qualities and purposes can be developed using e-textiles. However, the guiding frameworks for e-textile design in terms of educational purposes are yet to be established. The current study aims to advance the e-textile design literature by reporting on the design considerations that may contribute to the formation of a reliable framework.

2. Research design

The study employed Design-Based Research (DBR) to investigate the design issues related to the production of e-textile materials. DBR can be defined as "an emerging paradigm for the study of learning in context through the systematic design and study of instructional strategies and tools" (The Design-Based Research Collective, 2003, p. 5). Iterative processes should lead to design principles, which can then be employed by other researchers or practitioners (Amiel & Reeves, 2008). The current study consisted of two iterative cycles that worked on four bodily interactive e-textiles. The purpose of Cycle 1 was to reveal the characteristics of the e-textiles utilized in the study, and to determine material revisions through implementations and interviews. Cycle 2 mainly included testing the effectiveness of each applied revision by using the same methods as applied in Cycle 1, and then concluding the applicable design principles (see Figure 2). Three of the designed games were aimed to be used with two wearable e-textile materials (i.e., a belt bag and a thigh band) that could interact with a tablet computer, whilst one game was played with a non-wearable standalone material. The study was completed over a 4-year period. Significant dates during the study's lifecycle are provided in the Appendix (see Figure A1).

Figure 2. Iterations and outcomes of the study



2.1. Research questions

The following were formed as the main research questions of the study:

- What are the affordances and constraints of e-textiles for developing bodily interactive games for preschool-aged children?
- What are the design principles and the lessons learned that guide the design and development of bodily interactive e-textiles for preschool-aged children?

2.2. Participants

Criterion sampling (Patton, 1990) was used to select 19 preschool-aged children between 48 and 72 months old from two different preschools. Six teachers from Cycle 1, together with three from Cycle 2 who were also present in Cycle 1, participated in the study. The teachers were selected from three different preschools. An academic specializing in Early Childhood Education (ECE) also participated in the study. Both the teachers and the academic were selected according to convenience sampling. Demographic information of study's participants is presented in Table 1.

Table 1. Demographic information of participants

Cycle	No. of teachers	Average teaching experience (years)	No. of children	Average age of children (months)
Cycle 1	6	6.6	10	58
Cycle 2	3	9.6	9	67

2.3. Development of games and materials

Structuring games (i.e., mechanisms, rules, game flow, interaction ways) is a challenging process that requires several issues to consider. In the current study, we started by listing the capabilities of e-textile components, which enabled the development of draft game ideas (e.g., a Neopixel's ability to emit more than one color would enable producing numerous color sequences). Simultaneously, EF assessment tools and ECE curriculum objectives and practices were also examined. In the current study, we aimed to address three core EFs, inhibition or inhibitory control, working memory, and cognitive flexibility (Center on the Developing Child at Harvard University, 2011; Diamond, 2012). Each proposed game idea was then evaluated considering resources (i.e., cost, time, and technical feasibility) and then the most applicable were decided upon with the approval of the ECE academic.

The digital games were developed using Adobe Animate CC 2015 and the connection between wearables and the tablet computer was established by Bluetooth. The digital games were designed so as to provide both visual and auditory reinforcement, and also verbal feedback and instruction (except *Light Order* game since the material did not possess that ability). Verbal feedback and instructions were prepared with the help of a participant ECE teacher.

2.3.1. Light Order game (LO)

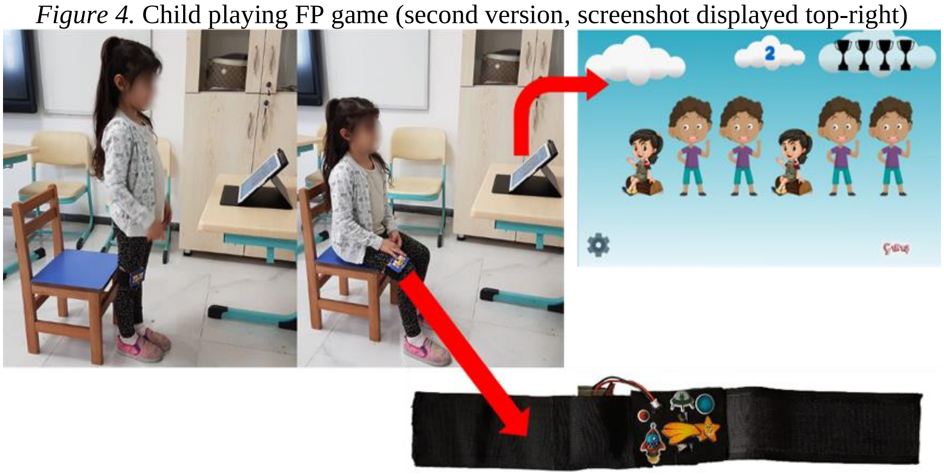
The first game idea involved remembering a color sequence and then repeating it without further sight of the initial sequence. Neopixels, which can be programmed to emit different colors, were used to create the color sequences. A color sensor was then used to detect the responses of the user. An image from the second version of the developed material is shown in Figure 3. The game requires children to use their working memory skills.

Figure 3. Child playing LO game (second version)

2.3.2. Follow Pattern game (FP)

The second game idea involved viewing a pattern (e.g., top-right image in Figure 4), recognizing the pattern structure at that time, and then repeating the pattern through sitting and standing movements after the initial pattern was no longer visible. The game aimed to address the working memory skills of the user. A 9-DOF IMU placed on a thigh band was used to detect the user's body movements, which is considered a feasible way to detect sitting and standing movements. An image from the second version of the developed material is shown in Figure 4.

Figure 4. Child playing FP game (second version, screenshot displayed top-right)



2.3.3. Do as I Say/Do game (DISD)

The third game to be evaluated was named *Do as I Say/Do*, for the sake of simplicity. The game required the user to manage their focus of attention on one type of stimuli whilst ignoring another (i.e., inhibitory control). We evaluated different game ideas and ECE objectives with a participant preschool teacher and decided upon a game that combined two games that are commonly played with preschool-aged children, *Camel-Dwarf* and *Do as I Say Not as I Do* games. In the traditional *Camel-Dwarf* game, children are expected to stand up when they hear the word *Camel* and sit down upon hearing the word *Dwarf*. The new game is very similar to the *Do as I Say Not as I Do* game, in which the teacher provides auditory instruction and provides a visual distractor, or vice versa. However, in the new game, visual distractors are confined to sitting and standing, whilst the auditory stimuli are limited to the words *Camel* and *Dwarf*. An image from the second version of the developed materials is shown in the Appendix (see Figure A2).

2.3.4. Object Sorting (OS)

The fourth game was inspired by two cognitive flexibility tests, Dimensional Change Card Sort (DCCS; Zelazo, 2006) and Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948). The purpose of the game was to sort the object at the center of the screen to the right-hand or left-hand side of the screen according to the feedback received. An interactive belt bag with two light sensors functioning as buttons was used to sort the objects on a tablet computer screen. An image from the second version of the developed materials is shown in Figure 5.

Figure 5. Child playing OS game (second version, screenshot displayed top-right)

As previously stated, ECE objectives were also considered whilst developing the games. Table 2 shows the objectives that each game addresses.

Table 2. Games and ECE objectives addressed

Game	ECE Curriculum objective	Objective domain(s)	EF domain
Light Order	1. Gives attention to an object/situation/event 2. Remembers what is perceived	1, 2: Cognitive	Working memory
Follow Pattern	1. Gives attention to an object/situation/event 2. Remembers what is perceived 3. Creates patterns with objects	1, 2, 3: Cognitive	Working memory
Do as I Say/Do	1. Gives attention to an object/situation/event 2. Comprehends the meaning of what is listened to/watched	1: Cognitive 2: Language development	Inhibition
Object Sorting	1. Gives attention to an object/situation/event 2. Groups objects or assets according to their properties	1, 2: Cognitive	Cognitive flexibility

2.4. Data collection and analysis

DBR interventions generally adopt mixed methods that utilize diverse means and procedures (Anderson & Shattuck, 2012). The current study adopted interviewing, video recording, and note-taking as the data collection methods. Using multiple data collection methods enabled the triangulation of findings by comparing the data obtained from each method. Additionally, the study's iterative structure made it possible to interview the same participants at different stages in the process, facilitating the triangulation of data from multiple sources (Merriam, 2009). The iterative structure of the study necessitated that, following the first cycle, the researchers analyzed all the data, made decisions about each digital game, revisions and enhancements to the e-textile materials, and their application.

2.4.1. Interviews

DBR involves collaboration between researchers and practitioners to bring solutions to education problems (Anderson & Shattuck, 2012). In terms of the current study, an academic from ECE field and preschool teachers were interviewed iteratively as part of the collaborative approach to the study. During semi-structured interviews, the participants were each asked to state their opinions regarding the following: (a) the game designs, (b) the strengths and weaknesses of each design, (c) how the materials and games could be enhanced so as to make them more appropriate to the preschool children's developmental level, and (d) their opinions regarding utilizing these games and materials in ECE. Interviews with the participant ECE teachers were conducted after they had either observed the children engaging with the games and materials or had watched footage of children playing the games. The purpose was to allow the ECE teachers to observe real-world interactions instead of them trying to imagine how children would engage with the proposed games and materials. Also, the ECE teachers were each provided with the actual e-textile materials and digital games so that they could use them at their will to gain adequate insight into the game itself and the e-textile material mechanism employed. Prior to analyzing the interview data, audio recordings of the interviews were transcribed, and reliability was also addressed according to the intercoder agreement protocol as suggested by Creswell and Poth (2016).

2.4.2. Video recordings

Design-based studies generally require the handling of an extensive amount of data such as video recordings (Collins et al., 2004). Erickson (2006) suggested video recording as a method that could be used to explore learner-instructional material interaction. In the current study, the implementations applied with the participant preschool children were video-recorded (68 sessions in total) while the children played the developed educational games and interacted with the e-textile materials they incorporated. This method of recording is termed *observational recording*, in which the subjects of a study are recorded while they are busy with the activity of interest (Penn-Edwards, 2004). The filming was made from a fixed point using a tripod so as not to distract the children. The participant preschool children played the games individually in a vacant classroom because each game required their full attention. The average game durations for Cycle 1 and Cycle 2 were 13/19 mins for the *LO*, 11/17 mins for the *FP*, 5/7 mins for the *DISD*, and 6/9 mins for the *OS*, respectively. As Erickson (2006) noted, video analysis requires developing methods to attend to phenomena of interest through multiple viewings. In the current study we analyzed all the video data extensively and for several times in order to detect issues regarding gameplay, e-textile use, and game-e-textile-child interaction.

The inductive approach, in which footage is analyzed exploratively without following a sound theory (Derry et al., 2010), was applied in the transcription of the video recordings. The researchers' instructional design background and experience with e-textile projects, as well as the e-textile literature, guided the selection of instances to be coded, such as situations that prevented the preschool children from playing the games as intended, the children's prominent behaviors (e.g., casual movements made whilst game playing), technical problems and limitations, and features that supported ease of use of each game and material. While the nature of Cycle 1 of the analysis was explorative, Cycle 2's analysis was largely confirmative. In other words, the findings from the video analysis of Cycle 1 guided the video analysis in Cycle 2 through enabling comparison of whether phenomena observed in Cycle 1 were also present in Cycle 2. The video analysis process applied can be summarized as follows:

(1) Situations of interest were transcribed together with timestamps in Cycle 1 and Cycle 2.
(2) Transcriptions were analyzed according to qualitative content analysis (Merriam, 2009) with MAXQDA software used in Cycle 1 and Cycle 2. This included two steps:
    - Open coding – a method in which the coder tries to identify any potentially valuable data chunks.

- Analytical coding – grouping codes under subcategories, and then structuring the main categories.

(3) Observation checklists with comment areas were prepared based on the content analysis in Cycle 1 (e.g., items on the OS checklist included: a) The child applied too much pressure on, hit, or rubbed the belt bag, and b) The child had difficulty in covering the circles on the belt bag). The checklists prepared in Cycle 1 were revised based on the content analysis in Cycle 2 (e.g., the LO checklist was revised to include the item "The child had difficulty in understanding the negative feedback sound produced by the Piezo Buzzer element," since the first version of the material was unable to provide a negative feedback sound).

(4) Another researcher watched and coded each video recording ($n = 4$) using checklists created in Cycle 1 and Cycle 2. The process included corroborating the behavior (agreeing or disagreeing with commenting) and categorization.

(5) The researchers compared and discussed the codes they had assigned. A shared understanding of the data was achieved in both cycles.

2.4.3. Design notes

One of the research goals of the current study was to reveal the affordances of the e-textile components used. For this purpose, the researcher who designed the e-textile materials took notes whilst they were developed. Design notes included coding requirements (e.g., basic or complex) and practical knowledge of the electronic components such as their ideal working conditions and environmental factors deemed pertinent to their application.

3. Findings

This DBR study revealed some useful findings and lessons with regards to the development of materials for preschool-aged children using e-textile technology. Four categories emerged from the qualitative data analysis: (a) technical issues; (b) usability; (c) visual design; and (d) perceived usefulness and instructional quality.

3.1. Technical issues of e-textile components

E-textiles can be used to develop interactive interfaces and wearables through components enabling communication, detecting physical inputs such as light, color, motion, and producing stimuli such as light and sound. However, they also posit various technical limitations and challenges. A summary of the technical issues related to e-textiles used in the current study are presented in Table 3.

Table 3. Summary of the technical issues encountered

Component	Function	Issues	Indication
Bluetooth module	Communication between e-textile material and tablet computer	Pros: Provides movement flexibility.	Children played the games while doing casual movements or moving according to the background music's rhythm.
		Cons: Requires advanced algorithms.	Communication delays affected perceived responsiveness.
Color sensor	Detecting colors as answers	Pros: Everyday objects can be turned into interactive tools.	Squares and hands made of felt were used in this project.
		Cons: Requires preliminary work to define color ranges for the objects to be used. Position and distance of objects to the color sensor and ambient lighting affect detection.	Color range of felt objects were explored under different conditions (e.g., various distances, positions, and lighting).
Conductive thread	Used to create circuits	Pros: Enables flexible and washable circuits. Can be sewn onto fabric.	Circuits in the *LO* used conductive thread sewn onto felt.
		Cons: High resistance. Vulnerable to short circuiting.	Creating circuits required delicate work and consideration to avoid short

		Less reliable than insulated wire for data transmission Susceptible to friction.	circuits. Isolated wires were more stable and reliable in designs using BLE connections. Friction wore off threads and caused connection problems.
Light sensor	Functioned as buttons	Pros: Easy interaction. Basic coding. Cons: Shadows may trigger unintended activation. Ambient lighting may affect algorithms.	Children had no difficulty covering the light sensors placed on the belt. Light sensors of belt bag v1 had frames that left a small gap for diodes on the sensors, which sometimes led to false activation since the frames cast shadows when the children moved. Algorithms were tested and updated according to ambient lighting.
Neopixel	Used to emit different colors	Pros: Easy to manage. Versatile as emits numerous colors. Cons: Non-primary colors (i.e., not red, green, or blue) may be less precise to the human eye. High-RGB value colors are eye-straining and appear whiteish. Low-RGB values do not mix sufficiently to produce intended color.	Six Neopixels were easily used in the *LO* game material to create color sequences. Children had difficulty identifying non-primary colors. Experiments showed that very high and very low RGB values did not work as intended.
9-DOF IMU	Used to detect sitting and standing motions	Pros: Versatile as detects various positional data. Can be used to detect body movement. Cons: May require complex algorithms and calculations, especially in projects requiring combined measurements.	The developed thigh band used a 9-DOF IMU to detect sitting and standing motions. A thigh band was designed since it enabled detecting motions with relatively simple algorithms.
Piezo buzzer element	Used to give auditory stimuli in the *LO* game	Pros: Easy to use and code. Cons: Inability to produce advanced or verbal sounds. Sounds produced may be too similar.	Simple algorithms were written to use the component. The researchers gave verbal feedback in the *LO* game Children confused different positive reinforcements given for various purposes.

3.2. Usability of the developed materials

The study's results showed that while designing educational e-textiles, four issues should be considered to increase their usability and effectiveness: (a) Intuitiveness of the interactions; (b) size of the materials; (c) perceived responsiveness; and (d) stability and sturdiness.

3.2.1. Intuitiveness of the interactions

The processes of deciding on games and materials included considering interaction styles being intuitive. We established in-game action-response consistency (e.g., children sat to imitate the sitting position). Interaction types were putting felt objects on the color sensor (*LO*), sitting and standing to imitate those positions (*FP*), conforming to rules by sitting or standing (*DISD*), and covering the light sensor on the left or right to sort falling objects (*OS*). Video recording analysis showed that the children engaged with the developed e-textiles without difficulty.

3.2.2. Size of the materials

The sizing of materials is dependent on their being wearable or not. Four of the six teachers in the study expressed that non-wearable materials should be sufficiently large to allow for easy interactions, and that children should be able to use it on their own. One teacher put it this way: *"I think the [level-setting] button is small… I do not want everything to be under the control of the teacher. First, the teacher teaches, then we [teachers] help the children. After that, children start to do it by themselves."* Therefore, we redesigned considering the feedback received. Figure A3 and Figure A4 in the Appendix illustrate the dimensions of the first and second versions of the *LO* game material. Six children in Cycle 2 were asked to use the level-setting button and all of them used it with ease.

When it comes to wearables, however, the size suggestion issue is reversed because wearables affect mobility and comfort. We developed two forms of wearables, a thigh band and a belt bag. The size of the belt bag did not cause any problems and was kept the same in both cycles (see Figure A7). However, the thigh band was changed considerably in Cycle 2 (see Figure A5 and Figure A6), and which resulted in fewer problems (i.e., shifting/slipping due to loose clothes worn by some children) noted after making the band more compact, and no further or repeat mobility difficulties were observed. Additionally, two of the participant teachers commented on the second version thigh band and confirmed its size to be more appropriate.

3.2.3. Perceived responsiveness

The way that interaction took place between the children and the materials they used affected the perceived responsiveness of the materials. Data extracted from the video recordings revealed that the children applied too much pressure on the sensors, hit, or rubbed them when they received delayed or no feedback at all. In two of the games (*LO* and *OS*), the children exhibited these behaviors. In the *LO*, the color sensor was not found to work as intended, mainly due to the incorrect placement of objects on the sensor, and in the *OS*, the children considered the material to be unresponsive due to receiving feedback one second after a light sensor having been covered.

3.2.4. Sturdiness and stability

Analyses of the video recordings and interviews conducted with the teachers revealed that both the wearable and non-wearable materials need to be sturdy and stable. Sturdiness is deemed a critical aspect of materials in this context considering the target group's age-specific characteristics. E-textile materials can consist of small electronic components that could inadvertently be swallowed or become lodged in a child's windpipe. The electronic components used in the initial prototype materials were considered vulnerable since they were left exposed. The material prepared for the *LO* game had the electronic platform and the circuits uncovered, the 9-DOF IMU and the electronic platform in the second version of the thigh band were left unprotected, and the light sensors of the first version of the belt bag were framed but also left uncovered. One of the teachers noted that the material should be intact, sturdy, and that it should be hard to tear off any component. The teacher stated that; *"Another thing is that no parts of the material should be able to fall off or disintegrate. They [the small pieces on the material] are very prone to being swallowed by young children."* Another teacher highlighted the curiosity of preschool-aged children: *"Keep in mind that, after a while, children will often become curious about the material and will naturally insert their fingers into it and attempt to break it."*

Several design changes were applied to ensure that the materials used in Cycle 2 were robust and safe. These considerations are listed as follows:

- Strengthening the textile base that contains electronic components (e.g., five felt layers were used for the UFO material).
- Hiding adjunct components (i.e., electronic platform, conductive thread-made circuits, Bluetooth module, battery, Piezo buzzer element, wires, some sensors) in the design. Additional textile layers (e.g., felt) or plastic covers could be options.
- Protecting electronic components that children interact with (e.g., light sensors framed by felt circles and covered with a transparent film).

Stability refers to a wearable material's ability to maintain its position as intended. The thigh band, for example, required improvements in order for it to safely remain in place on the thigh without slipping or shifting position. In Cycle 1, the thigh band continually slipped, which interfered with two of the games (*FP* and *DISD*). In Cycle 2, the thigh band was subsequently minimized and the surface in contact with the wearer's clothing was redesigned (i.e., hot glue was used to increase friction at the contact surface). In this way, the redesigned version in Cycle 2 reportedly presented fewer stability problems.

3.3. Visual design of the developed materials

The study's findings indicated that visual design is a critical component of e-textile development. The common areas where issues related to visual design are: Esthetics, having a context or theme, and using visual elements as cues.

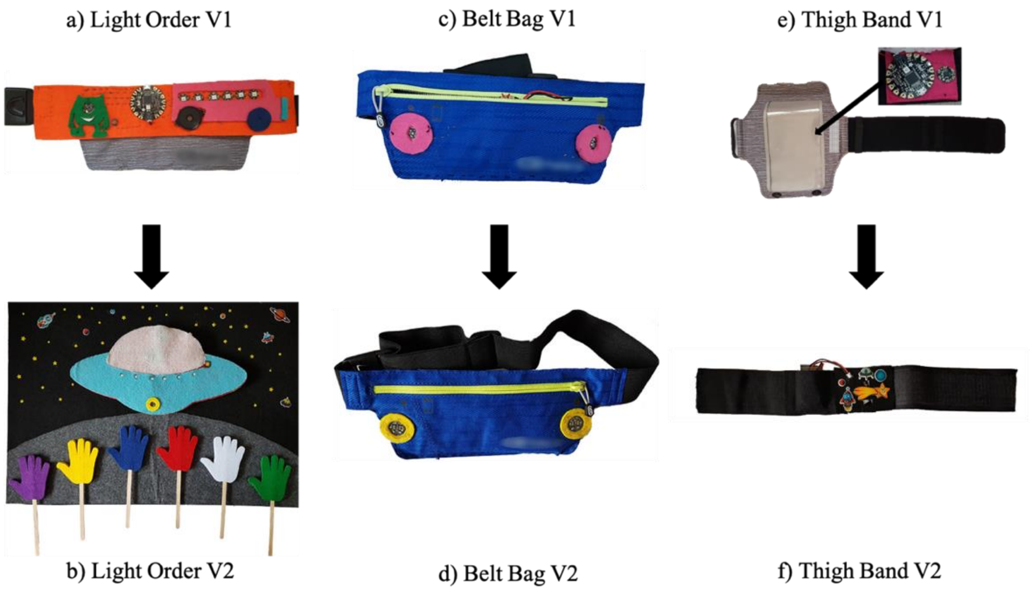
3.3.1. Esthetics

Esthetics refers to the appearance of a material and relates to its appeal to and perceived pleasure of its users. One of the teachers referred to the characteristics of preschool-aged children and indicated that, *"Since we are working with children, the material [LO v1] could be improved visually."* Another teacher recommended improving the thigh band visually, expressed that; *"If you wanted to place the material on the market, a visually improved material would be better. It seems more like a piece of a machine right now."* We subsequently applied two improvements to the materials:

- Hiding adjunct components also provided a simplified visual design.
- Colors used were reconsidered (color palette was used to select colors).

Figure 6 shows the developed materials from the first and second iterations.

Figure 6. Visual improvements on both versions of e-textiles



3.3.2. Having a context or theme

The participant teachers and the academic suggested that the *LO* game material would be enhanced if it had some aspect of visual integrity. In other words, using components in a way that represents a certain context or has a particular story can make a material appear more attractive. In the first version of the *LO* material, for example, a teacher liked the idea of putting lights inside the bus and using them as windows. For the second design, the academic demonstrated how the material could be shaped like a UFO, adding a space-themed felt for the background, and using hand-shaped stick-on felt shapes. After seeing the second version of the material, one of the teachers commented that, *"I like the design of the material; it is cute. Space is an engaging subject for children. When they see the UFO, they will like it."* Adopting a theme or context allowed for the storification of the game rules. The participant academic and one of the teachers composed stories for the *LO* game. The teacher's story was about aliens who would climb aboard the UFO, but in a certain order. The lights on the UFO therefore show the correct order, whilst the hand-shaped felt objects represent the aliens' hands. Our experiences with the children also showed that adopting a theme or context helped to make explaining games that much easier, and were perceived as being more attractive.

3.3.3. Visual elements as cues

Visuals can contribute to gameplay in good designs, and equally make a game more complex in poor designs. In both versions of the *LO*, several of the children started from the right-hand side in verbalizing the color sequence although the game actually required the opposite. One of the teachers suggested using visual cues such as redesigning the game so that the lights start from the left and turn on one by one, saying: *"The lights can turn on one by one to show in which order the colors will be kept in mind."* She also noted that an arrow sign that points to the starting point of the Neopixel row could be added.

The designs ensured that children could see and realize each of the interactive components. Frames used for sensors worked as visual clues since they showed where to cover or place the felt objects. Visuals can also be used to promote the correct attachment of wearables.

3.4. Perceived usefulness and instructional quality of e-textiles and games

The participant teachers also mentioned how they perceived the instructional quality of each of the games and materials during their interviews.

3.4.1. Active participation and motivation

The teachers stated the features that they liked in each game. For the *LO*, one of the teachers noted that the game being electronic and having lights could help to draw the attention of the children. For the *FP*, another of the teachers stated that typically children's focus will be drawn to a computer or television, and then passively watch whatever is playing on the screen. The same teacher expressed her appreciation that the *FP* did not appear to isolate students from their surroundings, stating that:

I especially like this in the material: Normally, children focus on something on the computer or television and watch what is playing [...] However, in this activity, children wear a thigh band and follow the instructions provided while watching. That is, children do not just sit and watch. It is very nice; indeed, I wish more children could be provided with this kind of game.

Another teacher stated that bodily interaction can also attract the attention of children, which can make games appear more entertaining to them.

3.4.2. Creativity of the materials

The teachers stated that the materials were both different and creative. One of the teachers indicated her views on the *LO* game, saying; *"I think that the idea of detecting colors is both different and creative."* Another teacher specified that the use of body movements to create patterns in the *FP* was considered different, noting that; *"Actually, movement is nice because the shape, color, and number patterns are common. This is a bit different, but it can be diversified.*" Finally, a third teacher indicated her views on the *DISD* game, saying that *"The logic of the game is excellent, and I think there is nothing similar on the market. I have not seen anything like this."*

4. Discussion and conclusion

In this study, DBR processes were conducted with the aim to reveal the design principles and lessons learned while designing educational e-textiles for preschool-aged children, as well as the affordances and constraints of e-textiles. The study's results suggest that e-textiles can be adopted for the development of games and materials aimed at preschool-aged children; however, several considerations should be made besides concerning children's developmental characteristics: (a) Technical capabilities of electronic components; (b) usability of developed materials; and, (c) visual design features. Also revealed were the participant preschool teachers' perceptions towards e-textile materials and educational games through game-material systems exemplified in the current study.

Although e-textile technology can be seen as a way of developing new intuitive means of interaction (De La Guia et al., 2016), it is still not considered to be that mature and posits certain technical limitations (Kan & Lam, 2021). Therefore, knowing component capabilities and their limitations plays an essential role in any materials development (McCann et al., 2005). For example, while Bluetooth technology can be used to provide interactions in e-textile projects (Gonçalves et al., 2018), the use of conductive thread may result in short circuits (Peppler & Glosson, 2013). To give another example, knowing that color sensor readings may be liable to change according to distance, area of view, and environment lighting (Earl, 2013) can be beneficial to the utilization of the component. The current study also reports additional issues with regards to the use of e-textile components in the study.

Game mechanisms and the design of materials are highly dependent on selected e-textile components. Two features of e-textile components are prominent. First, e-textile technology provides many different interaction options. This level of flexibility provides interactions that are more prone to "natural play behavior" (Rosales et al., 2015, p. 47). Second, e-textile technology allows accessories to function beyond their authentic purposes (Rosales et al., 2015) and enables turning everyday objects into interaction means and thus, increases intuitiveness, familiarity, and friendliness (Vega-Barbas et al., 2015). The perceptions of the participant teachers also highlighted the potential of e-textiles being used creatively to increase children's motivation, and in helping facilitate a more active level of participation.

Usability is critical in e-textile design (Fernández-Caramés & Fraga-Lamas, 2018). Supporting natural (Peppler & Danish, 2013) play-like actions, e-textiles also enable intuitive interactions, which is also important for usability as noted by Kan and Lam (2021). Material size is an important consideration, especially when developing size-suitable materials to be worn by preschool children that need to be readily adjustable, easy to use, and comfortable. According to Wright and Keith (2014), a wearable device should be comfortable by its very definition. However, being small in size can also be a problem if young children are going to be using the material themselves, as Kazemitabaar et al. (2017) stated. As the fine motor skills of children have yet to mature at the preschool age; the objects and components that they interact with should be sized accordingly. Another issue regarding usability is the perceived responsiveness of the materials and thus the degree of children's perceptions regarding the material's ability to produce a timely response. Any design or technical issues that produce response delays can lead to decreased motivation in child users (Kara & Cagiltay, 2020); this in turn can lead to repeated actions, applying more force to the material than necessary, or extended action duration (Dakova & Dumont, 2014). Finally, sturdiness and stability are the key features that any e-textiles should offer. The materials should be durable (Ismar et al., 2020; Kan & Lam, 2021; Kazemitabaar et al., 2017) in terms of both safety and sustainability, and stable so as not to disrupt the flow of the game.

The visual/esthetic design of e-textile materials is another factor to be considered (Chen, 2020; Kan & Lam, 2021; McCann et al., 2005). Clothing forms part of human fashion, and esthetics should therefore be considered together with functionality (Kafai & Peppler, 2014). Several guiding principles can be emphasized regarding designing visually pleasing e-textile materials:

- The esthetic design of the material should be simple, and if possible, non-interactive components (e.g., electronic platforms and the power source) should be hidden within the design. Honauer et al. (2019) also recommend hiding all electronics within the materials.
- The placement of components should be appropriate for the intended purpose of the game. For example, if children need to see Neopixels to play the game, they should be apparent in the design.
- Appropriate colors that do not interfere with the gameplay (i.e., in desktop games) should be utilized in the construction of materials.
- An exciting, stimulating context or a theme for desktop games can help to make games more attractive and can therefore facilitate game introduction (e.g., rules) through supporting storification.
- Visuals on e-textile materials can be designed in such a way that they contribute to the gameplay itself (e.g., indicating game rules or correctly attaching a wearable e-textile).

E-textiles can be used to create educational materials that are tailored to meet the needs of preschoolers by considering the various design principles and issues highlighted in the current study. Preschool teachers' attitudes toward the use of e-textile technologies in preschool education seem to support this idea. The principles and issues presented in this study may also apply to similar tangible preschool materials. Although the designing and developing of educational e-textile materials require certain technical skills (e.g., Peppler & Danish, 2013), enabling various bodily interactions, the ability to enrich everyday objects with interactivity, and maintaining a physical world connection whilst engaging with them seem to present significant advantages of utilizing e-textile materials.

Whilst investigating the instructional effectiveness of the developed e-textile materials was beyond the scope of the current study, future studies could aim to explore this issue.

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Appendix A

Figure A1. Study timeline

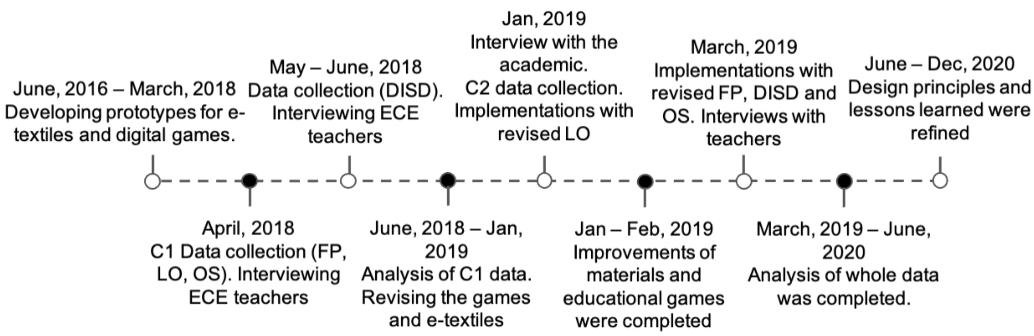

Figure A2. Child playing DISD game (second version, screenshot displayed top-right)

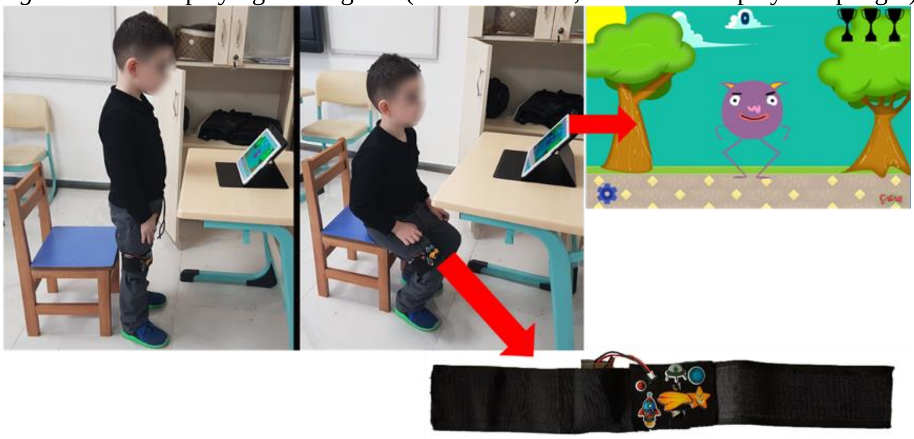

Figure A3. LO game material dimensions (first version)

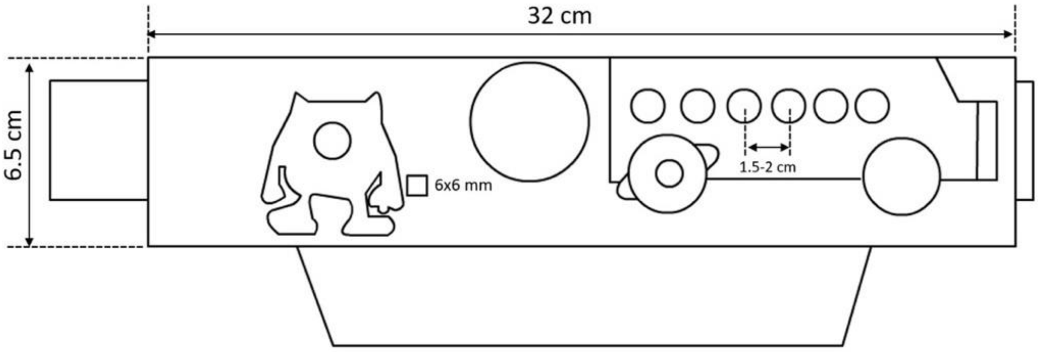

Figure A4. LO game material dimensions (second version)

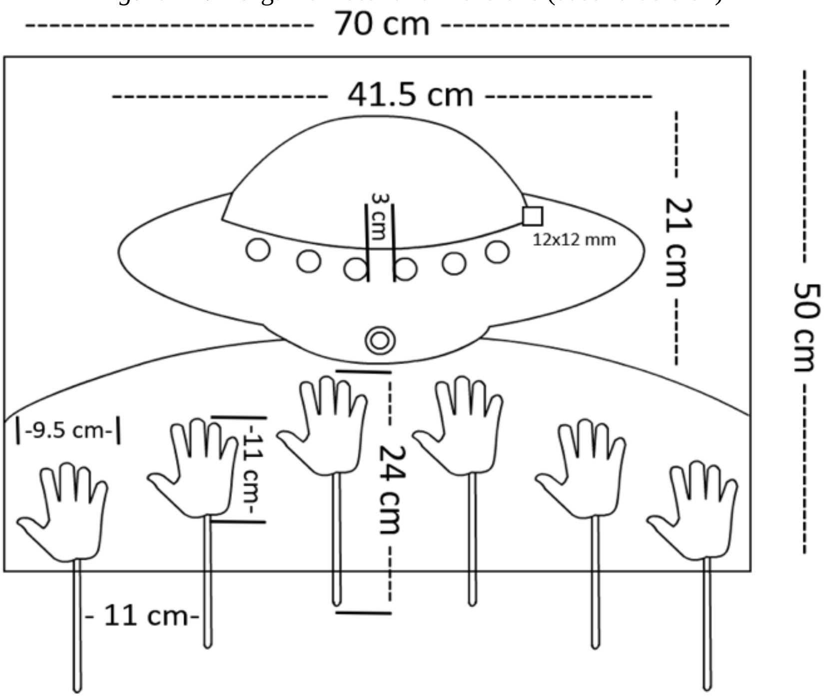

Figure A5. First version thigh band dimensions

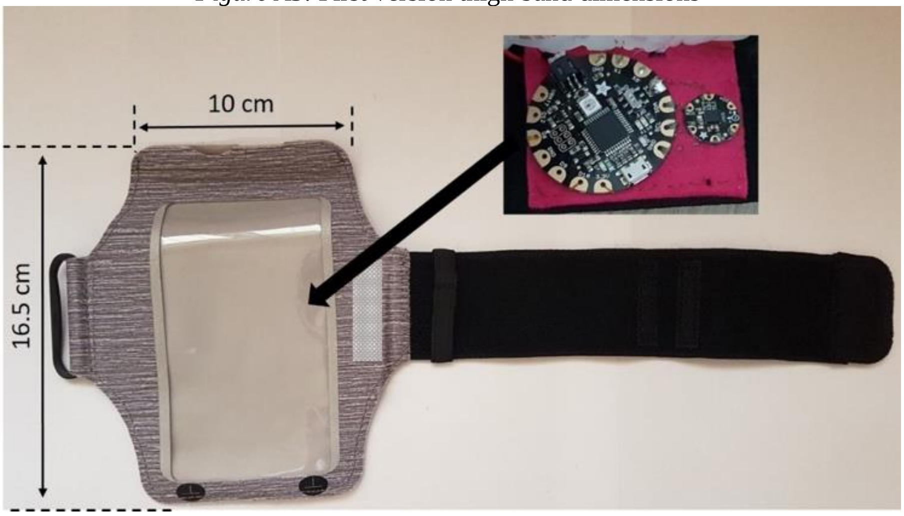

Figure A6. Second version thigh band dimensions

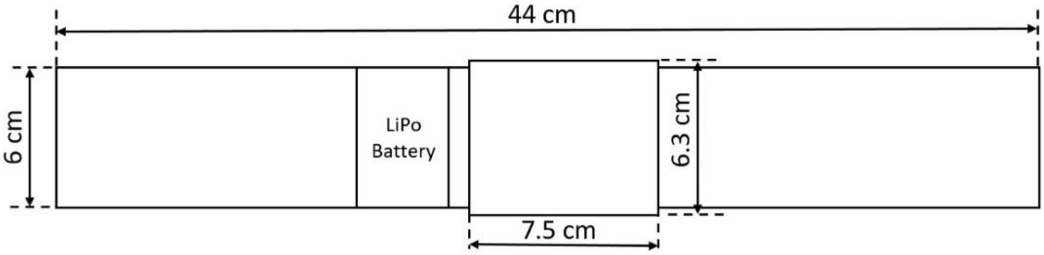

Figure A7. Belt bag dimensions (second version only differed by frame size)