TangiBooks: Design and Creation of Paper-Based Tangibles with Embedded Electronics for Teaching Programming Concepts

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Abstract—The growing need for programming and computational skills has led to a demand for teaching approaches that can appeal to a broader audience. We explore the design and creation of tangible objects and interactions to make introductory programming concepts more engaging and less tedious. We introduce TangiBooks, a platform that uses paper-based tangibles with embedded electronics and augments paper with sensory interactions like visuals, sounds, haptics, and kinesthetics to reinforce learning. The platform is implemented as proof-of-concept and offers four self-contained lessons on key concepts such as algorithms, variables, conditionals, and loops. Results from our observational study (12 adult learners, 6 instructors) showed that participants found TangiBooks to be playful, appealing to their senses, and valuable for sparking curiosity, with potential pedagogical benefits for promoting reflection among learners. TangiBooks has implications for HCI researchers in furthering the design space of paper-based tangibles in the learning domain and empowering instructors to innovate and personalize lessons.

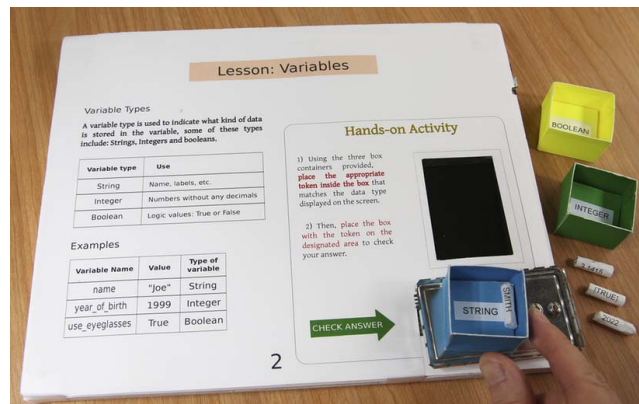*Index Terms*—tangibles, learning programming, CS education

Fig. 1. TangiBooks extends the interactivity of paper-based (top) lessons with embedded electronics underneath. Users learn about variables by interacting with TangiBook-Kinesthetic using a box metaphor where the variable acts as a data container. In this activity, the user has to select the right data (cylindrical-shape token) and place it inside the right type of variable (box).

I. INTRODUCTION

Learning computer programming is a complex and often daunting task, characterized by its demanding and tedious nature [1]. Additionally, the dry and monotonous aspects of programming can further discourage learners [2], [3]. However, in recent years, researchers have explored innovative approaches to enhance the learning experience by incorporating tangible objects into programming education [4]. Tangibles, known for their inherent playfulness [5], [6] have shown promising results in promoting student engagement across various fields [7]–[9]. Notably, tangibles combined with electronics have gained popularity as effective tools for programming instruction, exemplified by platforms such as LEGO Mindstorms [10], Arduino [11], LilyPad [12], T-Maze [13], and Dialando [14].

Despite the potential benefits of electronic tangibles in learning, their practical implementation presents several challenges. One such challenge is the increased cognitive load and technical expertise required for their configuration, which often makes teachers hesitant to adopt them extensively in classrooms [15]–[17]. Additionally, electronic tangibles can be distracting for novice learners due to the open-ended and complex nature of the physical hardware, hindering learners' ability to focus on the instructional content [18].

In this paper, we present the design and creation of *TangiBooks*, a set of tangibles with embedded electronics in a book format taking inspiration from the idea of tangibles in learning, but emphasizing interaction with paper and the physical form. Our proof-of-concept implementation complements and extends previous works on hybrid paper-digital interfaces [19]–[23] by augmenting the paper experience with sensory interactions such as haptics, sound, visuals, and kinesthetics, further enriching the experience for learners [24]. We created paper-based lessons in TangiBooks for introductory programming concepts, such as algorithms, variables, conditionals, and loops, using a lightweight and playful approach focusing on the learning experience [25], [26]. Our design consists of a hidden physical device under each book with embedded electronics that can detect the each paper individually and provide sensory-enriched experiences, but the hardware does not need to be configured by end-users.

To assess how TangiBooks are used and perceived, we conducted an observational study with 18 participants, including

12 adults who had an interest in learning programming and 6 CS instructors. We focused on capturing participants' initial reactions and to what extent they felt engaged with the different tangible interactive lessons. We also captured the perspectives of instructors and how they would envision using TangiBooks in practice. We found that the overall user engagement with TangiBooks was high, with almost all learners and instructors finding each TangiBook to be fun to use and appealing to their senses. In particular, participants consistently appreciated the sensory-enriched interaction enabled by using their hands (e.g., with TangiBook-Kinesthetic shown in Fig. 1). Learners also described how TangiBooks made them feel more engaged with the programming lessons compared to other forms of learning and even increased their curiosity. Instructors expressed enthusiasm for using TangiBooks in their classrooms and discussed ways in which they could extend and customize the content reusing the platform provided by TangiBook.

Our main contributions are: 1) the design and creation of proof-of-concept paper-based tangibles with embedded electronics in a book format that augment the paper experience with sensory interactions such as haptics, sound, visuals, and kinesthetics to teach introductory programming concepts; and, 2) initial study findings that show how learners valued TangiBooks for promoting engagement and sparking curiosity and how instructors expressed potential pedagogical benefits of TangiBooks for promoting reflection and retention of concepts.

II. RELATED WORK

A. Learning with tangibles and multisensory experiences

Key development on tangibles and manipulatives for learning have come from Friedrich Froebel and Maria Montessori [27]–[29]. They have being used to help people learn complex or abstract topics [30], [31], such as math [8], [9]. Some recent works are also exploring their usage for teaching computer programming [4], [32] and even specialized topics such as data visualization [33]. Some insights have shown that learning algorithmic thinking with tangible objects eases transition to computer programming [34], [35]. Furthermore, with the arrival of new tools for makers such as Arduinos [11], [14], we are seeing a myriad of new tangible objects embedded with electronics for teaching general abstract concepts [27], computational thinking [13], [14], [36], and even machine learning [37]. Our approach in TangiBooks takes inspiration from the idea of tangibles and manipulatives, but leverages the advantages of paper [25], [26] while offering familiarity of the book format as the main medium of interaction.

Some studies have suggested that using multisensory experiences helps users to understand complex data concepts by using more information bandwidth [38] and promote memory [39], [40]. They are also beneficial for teaching literacy [39], English [41], Math [42], [43], and even computing concepts [24]. We build on prior works ideas related to the integration of different multisensory experiences and explore how paper-based tangibles can be enhanced with sound, touch, visuals, and kinesthetics. Our observational study also sheds light on learners and instructors' perceptions of multisensory-enabled devices and to what extent they can be useful and engaging.

B. Playful approaches for learning programming

Playful approaches for learning have long been explored in different contexts [44]–[46], including for teaching programming (e.g., using LEGO Mindstorms [10] and Scratch [47], [48]). Some authors explored the use of board games [49] and computer games such as Minecraft [50]–[52]. Others have explored the use of smartphones as tangible objects and digital blocks projected over tabletops (e.g., TAPASPlay [53]), digital storytelling [54], and even physical activities in classroom [55]. Our approach with paper-based tangibles is complementary to these existing playful approaches, but differs in two key ways. First, we focus on teaching programming concepts rather than specific code syntax or abstract computational thinking. This level of explanation is not only useful for new learners, but also useful for audiences, such as conversational programmers [56], [57] who are less interested in solving programming problems. Secondly, our approach enables learners to interact with paper as the primary medium, allowing us to create a playful experience by leveraging benefits of paper for more focused learning [25], [26].

C. Hybrid-paper digital interfaces

Han et al. [21] provide a rich synthesis of how electronics have been used to enhance the potential of paper and invent new hybrid paper-digital interfaces. For example, Electronics Poppables [19] extends traditional books to include pop-up mechanisms with thin, flexible, paper-based electronics. Flux-Paper [58] explores how paper could respond to magnetic flux. Qi & Buechley [59] show how to animate paper by using metal alloys. Other researchers have explored printing or attaching electronic circuit on paper to provide extended features, such as Untoolkit [60], Foldio [61] and PaperPulse [20]. Relevant investigations for teaching programming and computational thinking using circuits over paper include PaperCircuit [62] and Chibitronics [63], [64]. IllumiPaper [65] explores the possibilities of augmenting paper with retroilumination, while PaperID [66] further augments paper capabilities with RFID tags. We take inspiration from these prior works on enhancing the capabilities of paper by not only embedding electronics, but also enabling sensory-enhanced experiences. Furthermore, our approach is unique because it does not integrate the electronics on the paper per se, but on a separate device, offering the potential to reuse the electronics platform across several lessons, hiding its complexity behind a piece of paper and providing a single, distraction-free surface for interaction.

III. DESIGN CONSIDERATIONS

To explore the design of paper-based tangibles for learning, we considered emerging research on tangibles, multi-sensory experiences and the use of paper with electronics, and key principles of human-centred design [67]. We synthesized the following four key design goals for creating our initial set of TangiBooks:

1) DG1: Provide a playful and engaging learning experience: Paper-based tangible lessons should provide an ease of entry, explicit progression, and appropriate levels of challenge [68] to better engage learners with the content. For an easier introduction to CS1 concepts, common everyday situations can be used to enhance the explanations [69], [70]. Furthermore, active and physical engagement, and elements of novelty and surprise can be used to enhance the perceived playfulness of learning objects [71].

2) DG2: Promote retention with sensory-enriched experiences: Since multisensory experiences are beneficial for improving student motivations [72]–[74] and for promoting long-lasting memory of complex concepts [40], [75], paper-based tangible lessons should engage users by stimulating different senses, such as sight, audio, and kinesthetics. This can foster an immersive and meaningful learning experience for mastering complex concepts compared to reading books or lecture notes.

3) DG3: Provide quick and valuable in-context feedback: Feedback has been shown to be crucial for effective learning [76]. Quick and valuable feedback, in the context of the material being learned, can promote better study strategies and improve performance [77], [78]. Accordingly, paper-based tangible lessons should give in-context feedback so that learners can reflect on their understanding of the material in real-time.

4) DG4: Minimalist approach to provide a seamless user experience: Novice learners in programming often face technical barriers in setting up the initial programming environment [79], especially with regular tangible-based hardware [80], [81]. Paper-based tangible lessons should be minimalist, easy to set up, and offer a simple and seamless [82] mechanism for loading new lessons, just like opening a book and turning to a new page. The focus should be on an *unplugged* user experience, free from distractions from a PC/Laptop or mobile to keeping users engaged [72].

IV. DESIGN AND IMPLEMENTATION OF TANGIBOOKS

Based on our design goals, we developed four proof-of-concept TangiBooks that tackle different programming concepts and explore a unique sensory-enabled interaction (summarized in Table I). We designed lessons on introductory programming concepts (algorithm definition, variables, conditionals, and loops) by reviewing CS1 programming courses [83]–[85] and consulting with instructors of such courses. Our current lessons (Appendix Fig. A3) are meant to demonstrate the features and functionality of the TangiBook platform, but can be redesigned and expanded to support instructors' different lesson requirements. Before describing each TangiBook in detail, we describe the common design features.

A. Common Features Across all TangiBooks

Each TangiBook consists of letter-sized plain printed paper that is overlaid on a physical base embedded with electronics (see schematics in Appendix Fig. A1). Users can seamlessly interact with the current page as the only surface and do not have to deal with any complexity in the base underneath,

TABLE I
TANGIBOOKS AND THEIR SENSORY-ENABLED USER INTERACTION

TBook-Haptic (Algorithms)	Uses different vibration patterns to provide feedback for right or wrong answers (Fig. 2).
TBook-Kinesthetic (Variables)	Allows users to manipulate physical objects and place them in a "box" to get immediate feedback (Fig. 1 and Fig. 5).
TBook-Sound (Conditionals)	Uses gestural (hand movements) over paper and sound as output (Fig. 4)
TBook-Visual (Loops)	Uses retroillumination and button presses to provide feedback (Fig. 3).

providing a more focused (DG4) learning experience [19], [25], [26], [59]. By integrating different electronic interactive elements that attract user attention, we provide a playful and engaging experience (DG1). TangiBooks further leverage human senses and augment the paper experience by using visuals, sound, haptics and kinesthetics, creating a sensory-enriched experience that promotes retention (DG2). Each TangiBook allows users to provide interactive input and shows specific, quick and valuable feedback for that lesson in-context (DG3), using the Page Detector module described below.

TangiBooks are designed to be simple, portable, with no complicated setup and no need to download software or use a PC or mobile device, minimizing distractions in learning [86], [87]. Each lesson is loaded by snapping a page and the base reads the existing holes to determine the current page (see section IV-F2).

B. TangiBook-Haptic

TBook-Haptic uses different vibration patterns to provide feedback and explains the concept of algorithms using an everyday situation example *"how to fry an egg."* In this interactive example, the user sees that the right sequence of tasks matters by considering all the listed steps of frying an egg and identifying two steps (*"crack eggs into the pan"* and *"grab eggs from the fridge"*) that are out of order. If the user make the correct selection, they feel a 250ms vibration.

The next page in the lesson provides an interactive activity related to an "*algorithm for online shopping*". The user reviews the steps for buying items that are in no particular order (see Fig. 2). The user has to determine the logical sequence by selecting one step at a time. If the user touches a step that is next in the correct sequence, TBook-Haptic provides feedback through a 250ms vibration at 2hz. A 150ms vibration at 30hz indicates that that the selected spot is wrong.

C. TangiBook-Kinesthetic

Tbook-Kinesthetic allows users to manipulate physical objects and place them in a box to get immediate feedback. The lesson introduces variables and simple data types using the metaphor of a box as a data container (Fig. 1). The user manipulate objects that represent a) variable types and b) data stored inside the variables and we explain different types of variables (integers, strings and booleans) using examples. For the activity, the user is given three boxes that represent these variable types and a set of four tokens with labels: ("2022", "Smith", "3.1415", "[True]"). In a small screen, a message
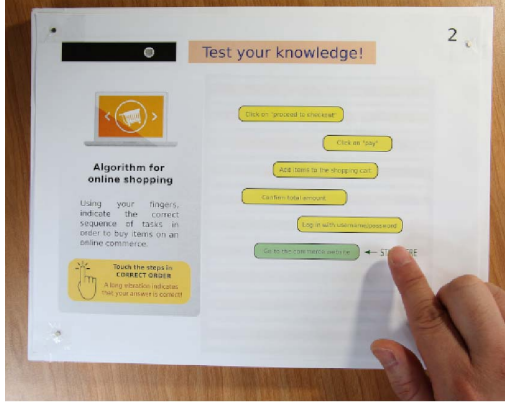
Fig. 2. TBook-Haptic senses the user touch through the paper in different spots, returning different patterns of vibration as feedback. In this activity, the user has to indicate (by touching) the right sequence of logic steps for completing an online purchase.
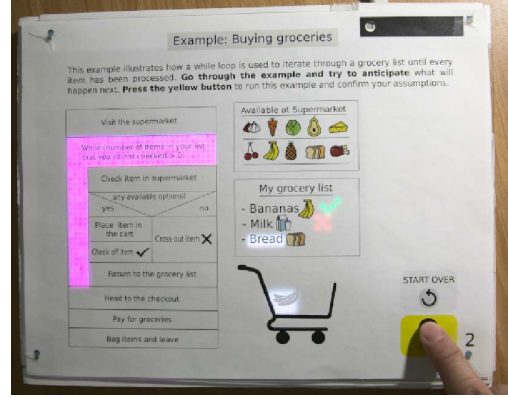

Fig. 3. TBook-Visual: Specific blocks in the N-S diagram light up through the paper, explaining the for-loop structure. Light is also used to reveal bananas inside the shopping cart when the algorithm arrives at the appropriate step.

asks for variable name, such as *"current_year."* The user can select an appropriately-labeled variable type box and add the appropriate token into this box. The user places both the box and the value token on a scale (shown in Fig. 1 and Fig. 5). A message indicates whether the combination of variable and data is correct or not. Similarly, the user selects a variable type and data for *"surname"* and *"Canadian"* (as a true or false statement) following the same procedure.

D. TangiBook-Sound

TBook-Sound uses a combination of hand movements (kinesthetic) for input and audio effects for feedback. This lesson explores the concept of conditionals (if-then structures using basic Nassi-Schneiderman N-S block diagrams [88]). We introduce a working example (Fig. 4) by using an analogy of an orchestra director that hovers a hand over the left or right sensor, a digital orchestra (our device) will play *Happy Birthday* or *Merry Christmas* tunes respectively.

The next page explains multiple conditionals: in addition to determining which tune to play by hovering over left or right sensor, the user can also use the vertical position (height) of their hand to control the tempo of the selected tune. If the user hovers over at a height greater than 20 cm, the tempo of the Happy Birthday or Merry Christmas tune increases. Lastly, we present a challenge to the user such that the orchestra will play either classic or contemporary music depending on the number of violinists, cellists, and pianists.

E. TangiBook-Visual

TBook-Visual explains loops by appealing to a visual sensory experience where users can interact with buttons that are hidden underneath each page. First, we explain the concept of loops using an example of buying fruits in a grocery store: the process of adding oranges one by one on a scale until a certain weight is reached. Next, we represent that example in a while loop using N-S block diagram notation.

Next we present an interactive N-S diagram about how a while loop iterates through a grocery list until every item has been checked (Fig. 3A). We ask the user to predict the

next step and compare by pressing the *"run"* button (which activates a light under the corresponding N-S block). When the user goes through the block "*place item in the shopping cart*", a previously hidden icon appears, indicating the addition of the item banana in the cart. Likewise, the grocery list displays a green check or a red cross depending if the item exists or not.

On the third page, the user checks their understanding of while loops using a classic programming-style loop (Fig. 3B), by answering a question about the final value variable *total_items*, using buttons. After the user has selected an answer, they will be shown how the code executes each statement. The user can also *"start over"* if they want additional practice.

F. Implementation

Each TangiBook consists of two parts: a set of paper lessons and a base device with embedded electronics to detect each individual paper (see Appendix Fig. A1). We started by sketching the lessons on paper and envisioned the future interaction by drawing some elements (such as buttons or sensors) and their positions. Upon iterating on the sketches, we drew the lessons digitally and in a protoboard we later tested our electronic design, verifying that all our components and intended interactions worked well. We used the C language for developing the firmware for each TangiBook using *Platformio*. The microcontroller for TangiBooks is the *Espressif ESP32* due to its low cost, different specs and features (e.g., many input/output pins), and technical documentation. We chose the *ESP32 Wemos LoLin32 lite* prototyping board due to its small size and integrated LiPo battery charger.

Next, we describe two aspects of the implementation that were common across all TangiBooks (the base device and the page-detector module). The specific details about the electronics modules and hardware implementation of each TangiBook can be found in the Appendix.

1) The base device: To allow users to focus on the interaction with paper, each TangiBook consists of a base layer (schematic in Appendix Fig. A1) of white foam board of 5mm thickness with key components hidden underneath: a) sensors (detecting input from users or environment), b) actuators (providing feedback to users), c) a microcontroller with auxiliary
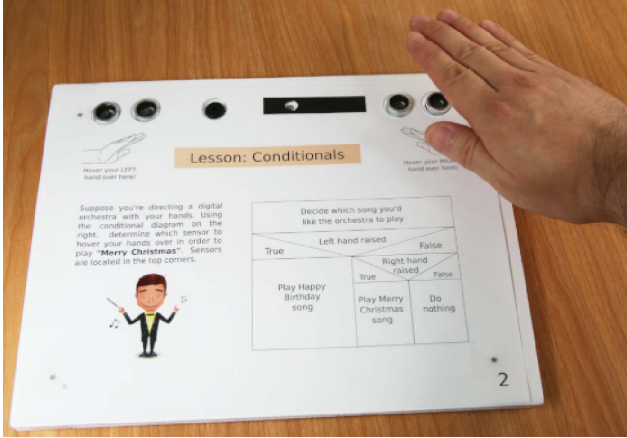
Fig. 4. TBook-Sound: Moving hands over distance sensors at top corners, the user plays the role of *orchestra director*. With that the user can control tune and tempo, exploring multiple conditionals programming concept.

components such as multiplexers, wires, resistors, etc. and d) a LiPo battery. When these components were firmly attached to the first base layer, we glued one or two more layers being mindful of cutting out parts for providing internal room to all electronics elements. Finally, a fourth layer of foam board with appropriate cuts for sensors was used to cover the TangiBook. Lastly, we glued and fixed with transparent tape four 1mm x 3mm neodymium magnets in each corner to ensure that pages are positioned correctly for the loaded page detector module.

2) The page-detector module: A common feature of all TangiBooks is that they can be used with different paper-based lessons using the *page-detector module*, being able to detect what page has been placed over the device and load the appropriate interactions, messages, or feedback specific to that page (see Appendix Fig. A1, part D). To implement this module, an array of 6 *Light Dependent Resistors* (LDR) change their resistance when light is detected. They decode the page by using binary numbers, considering 0 or 1 if the hole is covered or not. This gives up to $2^6 = 64$ different pages (minus the first and the last one, 62 pages).

V. OBSERVATIONAL STUDY

For our evaluation, we used a qualitative, observational approach so that we could focus on understanding the user experience and perceptions of learners and instructors with TangiBooks. We recruited 18 participants and used multiple data collection methods (think-aloud observations, questionnaires, and one-on-one interviews) to assess the initial reactions and levels of user engagement.

A. Demographics

We recruited two groups of participants through our campus mailing lists and snowball sampling. The first group (*learners)* consisted of 12 adults who were mostly students (6 males, 4 females, 1 non-binary) with the exception of one participant from industry (P6, female). The participants who were undergraduate or graduate students represented many different disciplines, including business, engineering, finance,

arts, psychology, and only 5 were from CS. All of the learners had an interest in learning programming, but varied in their actual experience with coding (P6, P9, and P10 did not have any formal coding experience).

The second group of participants consisted of *instructors* who had experience in teaching computational concepts at the undergraduate level. We recruited 6 instructors with experience teaching CS1-level (basic programming) courses at different institutions. Their experience in teaching programming ranged from 3 years to 20 years, including different programming languages and styles, such as procedural and object-oriented languages (Java, C/C++, Python, etc). We recruited the instructors through our campus and snowball sampling.

B. Procedure

Participants in both the learner and the instructor groups interacted with all of the TangiBooks. We asked the learner participants to answer a brief questionnaire after interacting with each TangiBook and carried out a follow-up interview. With the instructor participants, our form of data collection was one-on-one interviews that focused on different pedagogical aspects of using TangiBooks.

1) Initial Setup: The in-person study for both learners and instructors began with an initial demographic survey followed by an explanation of the goals of the study. Participants were introduced to a persona named *Alex* who is a coffee shop owner and wants to learn programming as she believes that it may be beneficial for her business to automate some tasks. Despite not knowing anything about programming, she is eager to start learning the basic programming concepts. Participants were asked to *think aloud* [89], [90] during the study and given a brief demonstration of how they should utilize this technique during all of their interactions with TangiBooks. After a short explanation, we introduced the participants to each of the 4 TangiBooks (haptic, kinesthetic, sound, and visual) and asked them to follow the given lesson. Since each TangiBook embodies a self-contained lesson, we presented each book in a random order.

For each TangiBook, participants had to a) read the background information about the programming concept, b) try out an interactive activity that further explained the concept and, c) check their understanding through a hands-on activity/quiz. On average, each participant spent up to 8 minutes completing each lesson and in total, each session lasted 45-60 minutes.

2) Post-Task Questionnaires: After participants in the learner group finished interacting with each TangiBook, they filled out a survey with six questions. Each question used a Likert-5 scale (strongly disagree to strongly agree) and asked users to rate engagement-related metrics [91]: i) the lesson was fun, ii) the lesson made me curious, iii) the lesson appealed to my senses, iv) the lesson made me feel frustrated, v) the lesson made me feel confused and, vi) the lesson made learning programming concepts easy. We tried to balance positive and negative questions to avoid being biased. We reminded participants to take novice programmers' needs into consideration before they completed this questionnaire.
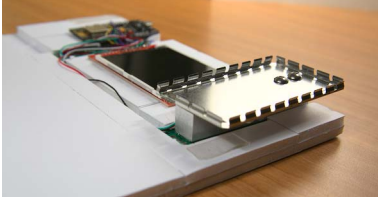
Fig. 5. TBook-Kinesthetic internals. Variables and tokens are encoded using weight (1kg weight sensor module is shown).

3) Follow-up Interview: After each participant (learners and instructors) had interacted with all of the TangiBooks, we conducted a brief follow-up semi-structured interview.

With the **learner** group, our focus was on assessing their perceived usefulness of TangiBooks in learning basic programming concepts and their experience while interacting with each lesson. As part of this interview, participants were asked about their learning preferences with physical-based devices and whether TangiBooks could be used for learners like Alex to understand basic programming concepts. Lastly, participants were asked about their perspective on learning through the combination of paper and electronic devices in contrast to using paper only or electronic devices only.

With the **instructors**, our focus was on assessing their perceptions of the pedagogical value of TangiBooks. We began each interview by asking about each instructor's teaching experience and what they thought were the main challenges their students face for learning computational concepts. We also asked about their experience in using physical elements or other similar devices in class and their perceptions of using TangiBooks to make learning more engaging.

4) Data Collection and Analysis: With participant consent, all study sessions were audio and video recorded and we also took notes. We analyzed learners' approaches of interacting with TangiBooks and used descriptive statistics for analyzing the questionnaire completed after using each TangiBook. We explored our data to gain insights about the experience the learners had with TangiBooks, focusing on engagement-related metrics, such as being enjoyable to use, sparking curiosity, and some reported perceptions of how TangiBooks could help beginners. The 12 learners answered the same set of questions for each of the 4 TangiBooks, with a total of 48 responses per question (this number was used to calculate all percentages).

To analyze the follow-up interviews, we used an inductive analysis approach [92]. We use labels P1 to P12 to refer to learners; and, I1 to I6 for instructors. To ensure that our coding schema was sound, the first two authors created a set of categories using two randomized participants and then shared their findings with each other. In the learners' interview answers, we looked for explanations and examples about why they answered the way they did in the survey. In case of the instructors' interview answers, we tried to understand their teaching needs and challenges and whether TangiBooks could be used to complement their teaching practices. We further iterated on the coding schema based on the emerging analysis and discussions with the research team.

VI. MAIN FINDINGS

We synthesized our main findings based on the perceptions of our two participant groups: learners and instructors.

A. How Learners Perceived TangiBooks

1) More engaging way to learn: Overall, we found that across all 4 lessons and 12 learners, 91.7% of responses agreed or strongly agreed that the *"the lesson was fun"*, The interaction with TangiBooks was described as being enjoyable and playful, with some participants comparing it to interactive books they used as children, while most learners (10/12) had not encountered anything similar before: *"It's easier to understand [concepts] using this approach than PowerPoint in the classroom"* (P1). P8 concurred: *"I think it's pretty fun to have another medium of understanding than just reading a concept on a page."* The gesture-based and object-based interactions in TBook-Kinesthetic and TBook-Sound were particularly new and a key reason for their enjoyment: *"You can physically take off the pages [from the device], that was cool! I think everything is like, really creatively done... combining these physical aspects together is very creative"* (P5).

The study results also showed that across all lessons, 83.3% of responses agreed or strongly agreed that *"the lesson appealed to my senses."* Learners liked the way TangiBooks "surprised" them by providing a personal and meaningful sensory experience: *"I liked TangiBooks in a sense that they have a story in which I can interact physically, and then, unexpected feedback was received, it could be light, it could be vibration... this was a pleasant surprise for me"* (P4). The experience with TBook-Kinesthetic and TBook-Sound were particularly memorable as participants could use their hands: *"having the physical object [box] metaphor makes it easier to understand [the lesson] because I can hold them [in my hand]"* (P8). P7, another non-CS student, explained that by *"using hands in this approach helps me develop a memory [of the concept]... I can refer to in the future."*

We were aware that an unfamiliar way to interact with tangibles could also lead to user frustration and confusion. However, the majority of participants did not feel frustrated (72.9% disagreed or strongly disagreed with the statement *"the lesson made me feel frustrated"* or confused (58.3% disagreed or strongly disagreed with the statement *"the lesson made me feel confused"*). Among the 25.0% of neutral responses and 16.7% of responses reporting confusion, the key reasons were related to overlooking some text or instructions in the lesson.

2) Potential to generate curiosity: Although it wasn't feasible for us to measure actual learning gains, we considered the potential of TangiBooks to generate curiosity and lower the perceived difficulty of lessons. We found that 95.8% responses agreed or strongly agreed with the statement that *"the lesson made me curious."* The learners reported that the physical interaction and playful progressive feedback in TangiBooks made them more excited and engaged, sparking more interest in the lessons and what would happen next. For example, P7 explained: *"I think this [TangiBooks] is a more exciting and engaging approach for learning because the*

interactivity can spark more interest." P9, an undergrad student in business who had a hard time trying to learn programming and gave up, added: *"[TangiBooks are] pretty intuitive and easy to follow. I was fascinated by how this works...if I was stuck [with] programming, I would prefer studying through this approach... if my teacher used this approach to teach programming, it could've possibly changed my career path."* The physical medium of TangiBooks was noted as a key reason for increased curiosity and motivation to continue learning. P10, a non-cs student who had failed to learn programming before was intrigued by the physical nature of TangiBooks and remarked: *"I think it is mind-blowing how this [TangiBook] is interacting with me. It is very small and looks like a regular piece of paper.. so for example with variables lesson, it was interesting to put a little piece of paper in the right box."*

Our results also showed that the majority of responses (83.3%) agreed or strongly agreed that the lesson made learning programming concepts easy. The learners particularly appreciated the hands-on playful activities offered by Tangi-Books: *"It's a lot easier to understand concepts when learning is associated with fun and playing around"* (P5). P11, another non-CS student, explained: *"These [TangiBooks] appeal to you and are useful for learning programming... it is actually quite hard to watch YouTube because almost all of those videos expect you to have some background. They don't teach you at this basic level... I do think [TangiBooks] are helpful because of the interaction with my hands."* Others commented that the TangiBook approach for teaching concepts using a physical interactive medium could be less frustrating compared to learning syntax and coding: *"looking at blocks of code can be unituitive and confusing but this physical visualization helps a lot and makes it less confusing"* (P9).

B. How Instructors Perceived TangiBooks

Overall, our instructor participants were excited about the potential of sensory-based interactions embedded in paper-based lessons to enhance learning by making complex concepts more appealing, memorable and interactive. They also commented on how TangiBooks could be customized to complement traditional teaching methods and offer a different pathway for students to learn programming concepts.

1) Potential to simplify complex lessons and promote reflection: Instructors indicated that TangiBooks could make complex lessons more memorable and engaging for their students. For example, I5 mentioned: *"learning programming is often a very dry process...sit at your computer, 8 hours in a row, just keep coding. Being able to break that cycle and do something physical is a welcome addition...if I go to a classroom with something physical like [TangiBooks]...that is the lesson [my students] will remember."* Another instructor (I4) commented: *"TangiBooks are grounded into the real world...the more physical the [interaction]...more memorable the lesson is."* Some instructors reported that TangiBooks could improve memorability because it could help students visualize difficult concepts. For example, I1 noted: *"I always prefer some sort of visualization, it makes a job as a instructor*

a lot easier. For example, for variables, it is a computational concept that I need to explain to my students. But, using this tangible object inside a box [TBook-Kinesthetic], I don't need to explain. The concept has a strong connection with something physical that is simple and faster to understand."

The instructors noted another interesting benefit of using TangiBooks in the classroom: it could help learners focus on understanding the programming concepts before diving into coding. This approach of slowing down and reflecting on the concepts could reduce the frustration that often comes with dealing with syntax errors and configuring IDEs. For example, I6, a instructor with 16 years of experience: *"As a teacher, I really like [TangiBooks]. This is a really different approach, very creative...usually, a main problem is that students need to sit back and think on what they want to use instead of rush into coding. TangiBooks may help provide a different approach to this problem."* TangiBooks were also noted to promote reflection: *"TangiBooks is a sweet spot between paper and electronic devices. Paper as we know lacks interactivity, but TangiBooks makes it possible to interact with paper media in a digital way...If my students go home only with the TangiBooks' sheets of paper and have already experienced TangiBooks in class,...[they can] get reminded of that experience they obtained with these lessons in paper"* (I1). I2 further commented that feedback plays an important role for students: *"the immediate feedback [in TangiBooks] was helpful to check my understanding and made me more confident of my answer."*

2) Customizing lessons using TangiBooks in the classroom: The majority of instructors (5/6) expressed enthusiasm for using TangiBooks in their classroom. Only one instructor preferred a more traditional approach where students start directly with coding. I3, a seasoned professor of CS1 (Intro to CS) explained that *"there may be people that [may] say... this is too childish for me! It can give the impression that this is childish but I would say this is a different way of learning!"*

Most instructors who were eager to try TangiBooks said that they would need to further expand and customize the lessons. But, they were pleased to see how they could create new custom lessons on paper using the existing TangiBook platform (rather than creating new hardware). For example, I4 desired to have customized options to complement her teaching style: *"I'd like to have custom pieces and adapt the [TangiBook] stories to my programming examples."* Some also suggested the possibility of sharing such custom lessons with others in the future. For example, I5 mentioned: *"I would like to see more like this [TBook-kinesthetic], something physical that I can see [and] interact with...I like to get something customizable, so others instructors may have their own version of it. I think many people can contribute and use their knowledge for getting multiple benefits."*

One concern raised about using TangiBooks in practice was scalability, as some instructors have large class sizes in intro programming: *"The main concern I think is who is going to carry all this?" (I6)*. But, I3, I5 and I6 all suggested that TangiBooks could still be useful in smaller classes or tutorials and could even be a "cool way" for instructors to demonstrate

a complex concept during lectures in larger classes.

VII. Discussion

Our paper contributes the design and implementation of TangiBooks, a platform that integrates paper-based tangibles with embedded electronics to teach programming concepts. We introduced 4 TangiBooks that offer different sensory interactions for touch, kinesthetics, sight, and sound. Our study with learners and instructors showed that TangiBooks provide an engaging and playful learning experience, simplify complex topics, and promote retention and reflection. Instructors were eager to customize TangiBooks to fit their class needs, while learners found the hand gestures used to interact with TangiBooks enjoyable and memorable. Moreover, TangiBooks showed the potential to spark curiosity among learners, including those previously struggling with programming concepts, which can open up exciting future design opportunities.

A. *Expanding the scope of sensory-augmented tangibles*

One key aspect of our work is that we extend paper tangibles with a platform of embedded electronics and sensory-augmented experiences, which most participants considered found to be engaging and helpful for learning. However, users noted that some TangiBooks were more appealing to senses than others, with the TBook-Kinesthetic and hand gestures in TBook-Sound being more favored. Our results imply that there is potential for further leveraging kinesthetics and audio-enabled interactions for improving learning by incorporating new interactive elements into TangiBooks. For example, one approach may be to investigate how to further explore the kinesthetics interactions by adding additional elements such as pressure sensors, gyroscopes or accelerometers so users can manipulate new elements differently. Another approach may be to explore the use of more interesting hand or body gestures for input. Although the olfactory and taste are human senses that still represents some challenges for HCI researchers [93]–[95], it may be worth investigating how they could be leveraged to be used with tangibles to make learners feel more engaged, especially with complex concepts.

B. *Expanding TangiBooks to social settings*

Each TangiBook implementation is currently self-contained, thus may be use in social settings which can facilitate learning [96], [97]. It may be worth investigating how TangiBooks could be used in pairs or small groups of learners, similar to how eXtreme Programming [98], [99] uses social settings to promote discussions and learning. But, more work is needed to tease apart how to design these social TangiBooks and make them useful and usable in pairs or teams. Our initial findings show how TangiBooks were perceived to be engaging and instructors were enthusiastic about trying this approach in the classroom. It would be worth investigating whether TangiBooks are useful in classroom or workshops settings that target new programmers. Lastly, by exploring the use of TangiBooks in a classroom setting, researchers can gain more insight as to why novice learners struggle with computational concepts and further make the process more approachable.

C. *Developing authoring toolkits for instructors*

TangiBooks extend the current literature by proving a new platform that researchers and practitioners can build upon. Through TangiBook platform, we envision instructors developing their own lesson content and templates. One fruitful area worth exploring is the development of toolkits for creating lessons that can be repurposed and personalized to suit instructors' different needs. We imagine that instructors will be able to pick one example from a lesson template library and customize its content, sequence of interactions, paper lesson design and even the output messages.It has been well-studied how educators often form communities of practice to share ideas and insights with one another [100], [101] and rely on their social connections to learn how to use and customize their classroom tools [102], [103]. Thus, bringing in these ideas into TangiBooks would be a natural extension, providing agility to adapt their lessons as needed while also leveraging TangiBooks' sensory-enabled playful experiences.

D. *Limitations*

The current set of TangiBooks were designed and implemented as proof-of-concept to explore the incorporation of interactive physical artefacts into the teaching basic programming concepts. Whether our approach will work equally well for more complex computational concepts remains to be explored. Although the design of TangiBooks is made of common off-the-shelf components, some engineering effort will be needed to scale this approach in large classes. Once TangiBooks have been created at scale, deployments in real-world classrooms and longitudinal studies of TangiBooks could further help tease apart learning benefits.

VIII. Conclusion

We presented the design of TangiBooks with a proof-of-concept implementation for teaching basic programming concepts using paper-based tangibles with embedded electronics. The approach incorporates different sensory experiences (e.g., touch, kinesthetics, sound and sight) and integrates them directly into the paper-based tangibles. Our observational study with 12 learners and 6 instructors gave insights into the hands-on experience of interacting with TangiBooks. The rich responses suggest interesting directions both for more variations of TangiBooks and different types of studies with these learning experiences. The results suggest that this hands-on tangible approach has the potential to broaden access to learning programming and make it more playful. Our long-term vision is to empower instructors to leverage the TangiBook platform to create their own customized lessons on paper and foster community-based sharing.

IX. Acknowledgements

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In this Appendix section we provide extra information about the hardware used to build TangiBooks and the technical specifications of its different components. We are also including details about the proof-of-concept lessons used for teaching programming concepts.

A. Hardware used for TBook-Haptic

TBook-Haptic detects the user's touches on the paper in 10 different locations and provides vibration as feedback (Appendix Fig. A1, part C). We used 10 foam rectangles of 15mm x 135mm and on top of each rectangle, we attached a copper tape of 5mm x 135mm. This copper tape was connected using wires to one of the 10 ESP32 analog input/output lines that could detect the touches by changes in capacitance. On the back of each 15x135mm foam rectangle, we glued a small 1027 coin vibration motor to provide the haptic feedback. Each foam rectangle is suspended on each side by two small 5mm x 15mm foam support, allowing to isolate the vibration only to that foam rectangle (instead of affecting the whole TangiBook). The *"correct"* vibration feedback is achieved by 2hz with a duration of 250ms, the *"incorrect"* vibration feedback is achieved by a 30hz vibration with a duration of 150ms. An schematic of TBook-Haptic can be seen in Appendix Fig. A1.

B. Hardware used for TBook-Kinesthetic

TBook-Kinesthetic detects different elements by measuring weight on an attached weight sensor module (scale) with a metal plate (Appendix Fig. 5). This TangiBook detects when an object with the correct weight has been placed otherwise shows a error message. This is repeated until the 3 correct combination of weights has been detected. The variable type and data values are encoded using tokens and boxes with a combination of weights unique for each correct answer. A 80x45mm metal plate is used as a top part of one 1kg weight detector with less than 0.1g of measurement error. The user places the boxes with a token inside. The boxes are made of 25x35x35mm colored cardboard and a shallow, second box of 5x35x35mm containing a combination of M5 nuts is placed in each box. For example, the integer box (green) has 2 x M5 nuts, string box (blue) has 4 x M5 nuts and the boolean box (yellow) has 8 x M5 nuts. The tokens that represent values are made of a 20mm x 1/8inch stove bolt (the values "2022", "3.1415", "Smith", "[True]" tokens are made of 1, 2, 4 and 8 nuts respectively). Messages and instructions are displayed on a small 3.5 inches SPI color LCD screen embedded in the base.

C. Hardware used for TBook-Sound

TBook-Sound detects when the user has hovered over the ultrasonic distance sensors placed at the top left and right corners (Fig. A2. The system plays different tunes using a small passive buzzer accordingly to what distance sensor was hovered. For measuring the distance between the hand and the sensors, we used the popular and inexpensive HC-SR04
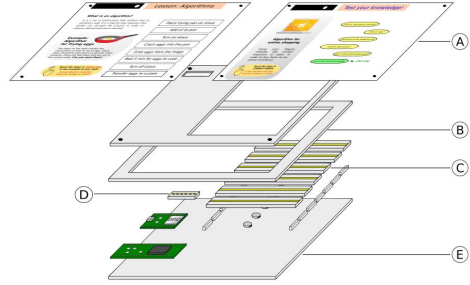
Fig. A1. TangiBooks schematics. The base device is created using a series of stacked foam boards. Common parts include: a) standard paper with printed lessons and neodymium magnets at corners; b) the first (top) and second (mid) foam layers d) the page detector module and, e) the foam base that contains sensors, actuators, a ESP32 Wemos LoLin32 microcontroller and a LiPo battery. TBook-Haptic also includes c) a 15x135mm rectangles with 5mm copper tape, vibration insulator and 1027 coin vibration motor at bottom.
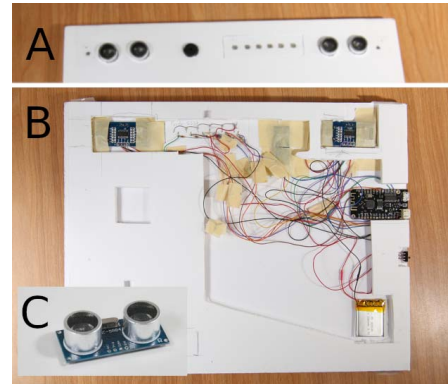
Fig. A2. TBook-Sound: Page detector sensor and sensors at top (A). The internals are shown (B). The HC-SR04 distance sensor we used in this TangiBook (C).

distance sensor module. For playing the tunes, we used one MH-FMD 3v passive buzzer module.

D. Hardware used for TBook-Visual

TBook-Visual detects users key press and displays information using an LED matrix panel. The key presses are detected using common 5x5mm switch buttons in a pulled-down configuration. For displaying messages, we used a P3 64x64 192x192mm LED matrix panel, mostly used in signage totems in malls and large displays in concerts settings. The messages that appear on the LED matrix are a simple 64x64 color GIF animations that are loaded to the ESP32 using SPI Flash File System (SFFS). The page number corresponds to a file with that specific number as a name, plus ".*gif*" extension (e.g. "*1.gif*" for page 1). When the user press the *"run"* button, the ESP32 display the next frame on the GIF animation. When the user pres *"start over"*, the animation is reloaded and the first frame is displayed. Because of an uneven surface of the P3 panel, a plexiglass acrylic sheet was installed to stabilize the surface. Thus, users can write over the paper without any inconvenience.

E. Lessons Designs

Fig. A3. Each TangiBook lesson starts by first explaining the basic programming concept (left images) and then letting the learner explore the concept through an interactive element (right images).