Evolution of a Tangible Letter Learning Game Through Design-Based Research Development

Heidy Maldonado, Tangible Play, heidy@tangibleplay.com
Ariel Zekelman, Tangible Play, ariel@tangibleplay.com

Abstract: Inspired by Fröbel and Montessori manipulatives, we followed Design-Based Research methods in the creation of a tangible letter learning game for three- through five-year old children. In this paper we cover the iterative design and evaluation cycles, and the constraints and tradeoffs explored across implementations, as the game evolved from Alpha to Beta phases. We incorporate explicit feedback and analytics of play data from the Beta experience of two-hundred seventy-three children across two different contexts (school and home) to discuss current design concerns, future work, and possible implications.

Introduction

Children's letter knowledge is the foundation of literacy. The alphabetic principle is the understanding that there are systematic and prescriptive relationships between written letters and spoken sounds. Given its importance as the first step towards academic achievement and attainment, neuroscientist Dehaene (Dehaene, 2009) recommended that for young children "all teaching efforts should be initially focused on a single goal, the grasp of the alphabetic principle." This paper chronicles the intermediate stages in the process of developing a new tangible application for tablets designed to help children learn to *recognize* letters by their shape and name, to *form* these letters, and to *associate* their shape with the letter sound.

The past century has seen significant research that furthered our understanding of how children learn letters alongside radical technological discoveries and advancements. Despite the fact that many learning experiences have been adapted to the digital medium, the majority of children worldwide learn their ABCs following the same methods, and with the same materials, as children did a hundred years ago. We have digital alphabet eBooks rather than paper ones, and hundreds of apps that aim to help children in learning their letters. Yet digital adaptations of traditional teaching methods do not always offer the same learning potential across all different implementations and media.

Drawing inspiration from Fröbel, from observations of children playing with these manipulatives, and following the tenets of design-based research (DBR) methodology (Design-Based Research Collective, 2003; Wang & Hannafin, 2005), we iteratively evaluated and re/designed a letter learning game for children three through five years old. Our work aims to adapt the advantages of physical manipulatives–and specifically, those manipulatives with a proven track record of positively impacting children's learning of the shapes and names of letters–as tangible interfaces.

In this section we begin with a brief review of previous research and existing ways of teaching that inspired us. The "Implementation" section focuses on how our cross-disciplinary team evolved the initial design through sequential iterations of evaluation and development, combining quantitative and qualitative methodologies, concluding with our current future directions. Contributions of this research are aimed at both the practical level as well as the theoretical: for the former, the lessons learned as we implement 19th century manipulatives as a tangible interface to scaffold children's letter learning are adding to the literature towards understanding the characteristics that make tangible interfaces successful. By sharing our steps as we implement the DBR methodology across our international team, we hope to provide a template for developing educational applications that balance engagement and learning, bringing together innovative research and cutting-edge technologies. And once our tangible letter learning game is widely available, we hope to use the anonymized aggregate data to contribute to literature advancing the understanding of how children progress as they learn to recognize letters by name and shape, as they make these forms, and as they associate letters with their sounds.

Learning your ABCs

In the United States, letter naming facility of young children is an excellent predictor —if not the best predictor— of reading success and achievement through to the 7th grade and beyond (Adams, 1994; Treiman, 2000). Cultural differences exist as to whether letter names or sounds are first taught to children at home and in classrooms, yet in the United States visual identification of a letter by name is emphasized before letter sounds and phonological awareness (Ellefson, Treiman, & Kessler, 2009), as research suggest that letter name knowledge facilitates development of letter sound knowledge (Phillips, Piasta, Anthony, Lonigan, & Francis, 2012).

Learning letter names requires developing a familiarity with letter forms, in particular, attuning towards distinctive features of letters to understand the differences between similar letters (Both-de Vries & Bus, 2014). Traditional research assumes all letters are equally challenging to learn, yet recent studies explore the factors that make some letters easier to learn than others: earlier letters in the alphabet are more likely to be correctly identified by learners than letters that look similar to each other, and than letters that share phonemes in their names with other letters (Phillips et al., 2012; Justice, Pence, Bowl, Wiggins, 2006; McBride-Chang, 1999). In studies evaluating letter recognition and letter creation in the United States, the letters that were reliably identified and written correctly include “O”, “B”, “A”, “X”, “T”. Letters that were more challenging to identify while remaining easy to write are “L”, “T”, “H”, “I.” And among the most difficult letters to recognize and write are “V”, “U”, “Q”, “N”, “J”, “G”, “Z”, and “Y” (Phillips et al, 2012; Puranik, Petscher, Lonigan, 2012).

Novices differ from experienced readers in their speed at identifying the salient or distinctive areas of letters (Both-de Vries & Bus, 2014). Children learning to read find it particularly challenging to understand that differences in orientation of similar component marks lead to different letter identification—for example, differentiating between “m” and “w”, or between “p”, “d”, “q”, and “b” (Both-de Vries & Bus 2014). And the “b”-“d” pair is particularly challenging for children to distinguish as they share both visual similarities and phonemes in their names, giving rise to using a finger mnemonic of “bed”(left hand makes a “b” shape, right hand a “d”) to help with identification (Stiny, 2006).

Dehaene (2009) suggests that the reason Maria Montessori’s letter learning method of tracing sandpaper letters with a fingertip has been proven to have a positive effect on the reading skills of young children (Bara, Gentaz & Colé, 2007; Lillard, 2016) is due to the fact that this method emphasizes tactile exploration of the differences in orientation of letter components. In Montessori’s method, children learn their letters by breaking down each letter into its sequential strokes, and experience the letter itself through touch, tracing its shape in sandpaper outlines. Today, many digital apps aim to replicate Montessori’s manipulatives (such as MobileMontessori, Montessorium) yet the tactile discovery may be more important to the learning process than the motion. A study comparing letter formation outcomes between Montessori sandpaper letters and the sequential construction of a letter on a screen found that the learning gains were only detected in the group who experienced the sensorimotor “act of exploring the letter in itself” (Bara, Genatz, Colé & Sprenger-Charolles, 2004).

Manipulatives, physical objects such as these sandpaper letter shapes that support children’s learning, are common across cultures and have been integrated into early childhood education through the efforts of first Fröbel, and later Montessori. Each of these pioneers developed a curriculum of structured activities based on modular, simple, developmentally-appropriate manipulatives, that emphasize the importance of involving the child’s senses in the exploration. While Montessori’s curriculum activities and manipulatives focused on constrained, puzzle-like designs that encourage the acquisition of abstract concepts, Fröbel’s emphasize open-ended experimentation and promote construction of natural and man-made forms (Zuckerman, 2010). Friedrich Fröbel developed a set of *gifts* for the original kindergarten: most of these are wooden, geometrical pieces that allow children to explore formation of complex shapes, patterns and relationships. Named in order of presentation in accordance with Fröbel’s designed path “inexorably toward ever greater abstraction,” (Brosterman & Togashi, 1997) the *eighth*, or *stick laying gift* (composed of groups of sticks in one-inch increments), and the *ninth*, or *ring laying gift* (composed of full, half- and quarter-circle arcs) lead children towards the first exercises in letter formation and basic arithmetic.

Combining traditional manipulatives with the digital medium

Over the past twenty years, researchers have sought to merge Fröbel’s and Montessori’s manipulatives with digital technologies, aiming to combine the potential benefits of the latter with hands-on learning activities. For instance, *digital manipulatives* seek to engage children in different types of thinking and develop novel interaction patterns (Manches & O’Malley, 2012; Resnick, Martin, Berg, Borovoy, Colella, Kramer & Silverman, 1998; Zuckerman, 2010) by inserting the technology within the manipulatives themselves. In contrast, *tangible interfaces* mediate communication with a computing device, using a variety of physical objects and surfaces as means of manipulating and representing digital information (Brooks & Reardon, 2016; Ishii & Ullmer, 1997).

Numerous tangible learning environments have been developed (Horn, 2018), given the appeal and potential of using our bodies and physical artifacts to interact with digital systems (Ishii & Ullmer, 1997). Yet tangible learning environments do not always lead to positive learning outcomes (Horn, Crouser & Bers., 2012; Manches & O’Malley, 2012). Interactions with manipulatives are modulated by complex interactions between the manipulative itself, the subject matter, the learners’ ability, goals and expectations, culture, and context, including how these manipulatives are introduced (Horn et al., 2012; Manches & O’Malley, 2012).

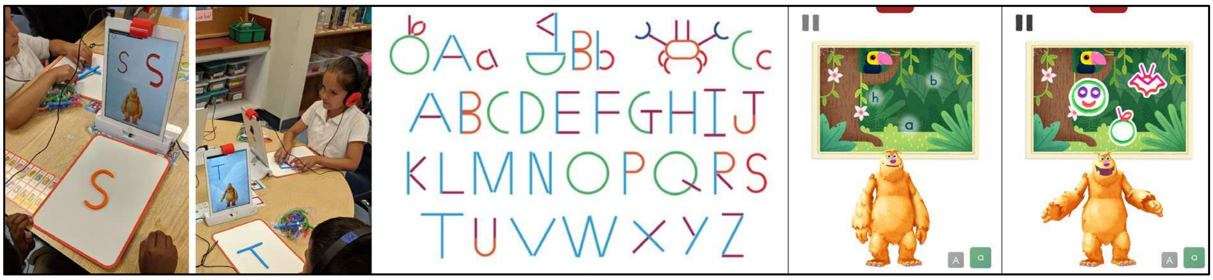

Figure 1. Left: Children in school composing letter “S” and letter “T” using with the Tangible ABCs app on the Osmo platform. Notice the red Osmo mirror reflector and white iPad base. Middle: some of the letters and objects that may be constructed using Osmo’s sticks & rings. Right: Postcard for letter selection before it is started, showing the letter “b”, “h”, and “a” (left). Note the upper and lowercase buttons in the lower right-hand corner. And completed postcard showing the animated completed doodles in place of the letters.

Increasingly, the devices that *tangible interfaces* link with are tablets, as more than 68% of households in the United States own at least one internet-enabled tablet computer (Holmstead, 2017). Their portability and accessibility are driving similar prevalence worldwide (West & Ei, 2014), as touchscreens are particularly appealing to younger children who are not yet ready for keyboard and mouse interactions (Anthony, 2019; Hourcade, 2007). Tablet hardware accessories for younger children are prevalent in the marketplace, making the sight of an infant using these devices quite familiar despite the serious concerns about young children using these devices. Among these concerns is the risk of any device with an internet connection for exposing children to inappropriate content, whether explicitly disturbing, aimed at a different age group, or merely content that would benefit from critical—and limited—consumption, such as advertisements. In addition, the amount of screen time by young children has been negatively associated with developmental outcomes (Madigan, Browne, Racine, Mori & Tough, 2019) and the recommendations by the American Academy of Pediatrics (2016) for children three through five years of age is at most an hour per day of “high quality” content on screens.

On the other hand, tablet interventions focusing on developing literacy in preschool and kindergarten settings have been shown to increase motivation, confidence and concentration of young children, as well as fostering student engagement in the content (Beschorner & Hutchison, 2013; Clarke & Abbott, 2016; Dobler 2012; Flewitt, Messer & Kucirkova, 2015). Among the reasons for these positive effects are touchscreen interfaces and discoverable application designs, which make it both less intimidating as well as easier to understand for pre-readers (Flewitt et al., 2015; Lynch & Redpath, 2014; Neumann & Neumann, 2014). However, interactive animations presented in eBooks and online alphabet-focused apps may hinder letter learning if they distract children by shifting their focus away from the letters (Evans, Nowak, Burek & Willoughby, 2017). Many current tangible applications for letter learning focus on letter recognition by providing children with letter-shaped pieces or lettered blocks with which to stamp or assemble words and experiment with phonics (Marbotic Smart Letters; TigglyWords Learning System; Brooks & Reardon, 2016; Fan, Antel, Hoskyn, Neustaedter & Cramer, 2017) rather than focusing on teaching letter formation.

Implementation

We chose to develop on the Osmo platform (playosmo.com), this tangible interface system is used in over 30,000 classrooms and a million households worldwide in conjunction with an Apple iPad or Amazon Fire tablet. Osmo uses proprietary “Reflective AI” technology for the device to detect game pieces placed in front of it in real-time (see Figure 1). This is achieved by placing an angled, down-facing mirror on top of the front-facing camera of the device (red reflector in Figure 1) and setting the tablet on a specialized base. Osmo’s computer vision models allow the app to understand what is presented in front of the device and react according to game-specific rules, augmenting the experience with audiovisual feedback. There are over twenty different games aimed at children five through ten years old developed specifically for the Osmo platform, with varying degrees of explicit educational aims and costs. Several games can be accessed for free once the base is purchased. Educational games cover subject matter ranging from spelling, math, drawing, geo-spatial manipulation, to computational thinking (playosmo.com, Hu et al., 2015) and more. Until our collaboration came about, there had not been a product developed on the Osmo platform for learning letters names and forms.

Design-based research (DBR) is a systematic methodology aimed at developing educational theories and products through iterative design, development, analysis, and implementation (DBR Collective, 2003; Wang & Hannafin, 2005). The development of our playful learning tangible game for learning letter shapes and names is guided by DBR's five principles, that projects must be Pragmatic, Grounded, Iterative, Integrative, and Contextual (Wang & Hannafin, 2005). DBR projects must be centered in solving a real-world situation (pragmatic); draw from theory and context to understand the situation (grounded); iterative and flexible in evolving through constant assessment and evaluations of how well a proposed solution addresses the situation; integrate a variety of disciplinary research methods including quantitative and qualitative assessments; and lastly, contextualized to the setting where the research is conducted and the solution implemented (DBR Collective, 2003; Wang & Hannafin, 2005). In this section, we discuss the intermediate steps in our DBR process conducted to explore and evaluate ideas and prototypes, refining both the software and hardware at every step of the way.

The initial explorations were evaluated through observation sessions in California, following an interative design-test-redesign cycle (Maldonado & Zekelman, 2019). To prove the concept for the learning game and evaluate the silicone sticks and rings pieces, an alpha prototype app that suggested and recognized thirteen unique letters was distributed to volunteers across the United States. Two aspects of the Alpha app proved very popular: "Mo the Monster," an on-screen animated guide character, and the introduction of postcard collections as a meta-game. Previous research has shown that emotive characters directly impact learning outcomes, as well as feelings of being supported (Brooks & Reardon, 2016; Lauricella, Gola & Calvert, 2011; Maldonado, Less, Brave, Nass, Nakajima, Yamada, Iwamura & Morishima, 2005; Maldonado & Nass, 2007). Through Osmo's "Reflective AI" technology, Mo comments on the children's creations through fun animations, emotive feedback, and guiding play towards the learning objectives. These interactions explicitly foster a parasocial relationship between the child and Mo, which research has shown maximizes opportunities for learning (Gray, Reardon & Kotler, 2017; Hirsh-Pasek, Zosh, Golinkoff, Gray, Robb & Kaufman, 2015; Lauricella, Gola & Calvert, 2011).

Traditional alphabet books highlight one letter per page presented next to a depiction of a word that begin with the letter (eg: "Z is for zebra"). Yet research has shown that even "rather plain pictures" when presented next to a letter shape will attract the child's attention away from the letter and may interfere with their learning of the letter shapes or sound (Both-de Vries & Bus, 2014). We aimed to make letter shapes more memorable by presenting the letter and image sequentially in time, rather than collocated within the same "page." Additional, in response to children's desire to save and share their creations, a "meta-game" for the app emerged where the tabletop art would be digitally preserved as a shareable image. Thus, children's images of completed letter-object pairs would be captured and stored in a shareable postcard image. Activities were grouped into postcard-sized groups of three letters, with their three corresponding doodles, set in a graphical postcard that matched the theme. Postcards would be selected by the child featuring the example letter constructions as images within, yet they would be saved with the child's doodle creations for sharing and reviewing (see Figure 1, right).

Beta evaluation

The Beta phase included 75 schoolchildren from a "Title 1" school with a linguistically diverse population, where at least 40% of the students are from low-income families considered to be living at or near poverty. The school children used the app for a total time of one hour during a single school week and provided in-class feedback about the experience to the teacher. Simultaneously, we conducted a Beta in-home evaluation across the United States, evaluated through both quantitative and qualitative methods.

A period of intense redesign followed the Alpha to get the app ready for this larger and longer evaluation during the Beta period. Among the many improvements made between the app between Alpha and Beta test phases were supporting additional letters, richness of the animations, and improvements to the image capture processing algorithms. Aiming to provide educational content for more knowledgeable children, the same 13 letters from the Alpha were now implemented for both lowercase and uppercase, along with 26 doodles. Interaction patterns in the Beta version of the app start with the child receiving a choice of two randomly selected graphical postcards from "Mo the Monster's" travel book.

Each postcard includes three stick and rings letters. A postcard with a drawing of a jungle would have, for example, the letter "b" high in the trees, the letter "a" on the floor, and an "h" next to the toucan (see Figure 1: Right). The child selects a letter at a time, choosing the order of the letters to compose. Once a letter is chosen, the postcard image fades from the screen and the Monster is presented alone with an idealized letter, until the child composes a letter using tangible pieces and presses the "OK" button. The app then captures the image, replacing the idealized example on screen with the actual image of the child's creation.

This image of the child's created letter is used as the beginning of a word on screen, such that the letter "b" appears as a color image of the child's creation with black letters following horizontally to form the word "bat". As this happens, Mo the Monster speaks: "I know a word starting with b: bat! Could you make a bat using the sticks and rings?" Once the fun doodle is completed, the color image of the child's bat creation is animated and saved onto the postcard in the position where the letter was, with a possibility of editing the design and retaking the photo. Next, the child would select the letter "a" for "apple," or perhaps "h" for "happy" and the interaction pattern would restart for the new letter (see Figure 1: Right). When all three letters have been completed, the postcard is saved in the virtual "travel book" and the child is prompted to choose a new postcard.

Method

We selected a geographically-distributed set of ninety volunteer families who had appropriate devices, children three- through five years of age, who owned the Osmo base, and who would be available during the testing period. The range of ages of the 198 children that reported playing the game started at two years of age and ended at twelve, as most of the selected families had multiple children who were curious about the experience. Median child age was five years old, and 38% of children playing the game were four years old or younger. Volunteer families did not live in or within a 45 miles radius of the most technologically-savvy metropolitan areas in the US (Silicon Valley, Seattle area, New York City area, or Los Angeles area), as we were interested in knowing whether the design affordances were easy to understand. Applications and communication with Beta Testers were carried out solely electronically, through online forms and emails, including technical support.

Selected families were asked to sign an NDA and were advised they could stop their participation at any time with no repercussions. Participants received the prototype sticks and ring pieces in the mail and were provided with a link to download the Beta ABC app; as compensation they were guaranteed free release versions of the final product if and when it was commercially released. Volunteers agreed to play at least for twenty minutes over a two-week period, and to complete an honest post-experience questionnaire. Moreover, they gave permission to have us analyze their anonymized play data from the Beta ABC app. As for demographics, the families considered themselves to be middle-class, 11% were homeschooling their children, and 30% had at least one household member working as a teacher.

Results

In terms of the school experience, the teachers' reactions were extremely positive and reported that the children enjoyed it. As the range of letter-knowledge among children enrolled in the same grade proved very wide, we were relieved to learn that the lack of judgement on the creations made the experience fun for all children. The teachers' main request was for the app to provide feedback on the quality of letter being composed, such that children could begin to understand when the letter created was not the asked-for letter.

In terms of the analytics of home play data, Beta Testing families played the game an average of 2.44 times (*Mdn*=2) for an average duration of 32.90 minutes (*Mdn* =23.28 minutes). They completed an average of 8.7 letters (*Mdn* =6), an average of 7.83 doodles (*Mdn* =6), and an average of 4.89 postcards (*Mdn*=2). The fact that the average letters and doodles were higher than the median indicates that a few of the Beta Testing families completed more letters and doodles than the median. Average time to compose a letter was 86.55 seconds (*Mdn*=60.69 secs) yet varied depending on the letter. "E", "N", "Z", "R", "J", "K" were among the letters that took longest, and "C", "O", "D", "L", "P" among the ones that took the shortest amount of time to complete. Quantitative results from the survey based on a five-point Likert scale were very positive: 87% of families indicated that they were "Very" or "Extremely" satisfied with the experience. Seventy-five percent of families indicated on the five-point scale that the experience was "Very" or "Extremely" educational. From the survey's freeform questions, the top requests were to improve the image captures, and to evaluate the letters created.

A more concerning result was that only 44% of families indicated on a five-point Likert scale that their children would be "Very interested" or "Extremely interested" in replaying the postcards. Reading through the free-form responses helped make sense of this result, and of the larger average number of completed letters vs. completed doodles: children did not mind repeating what we considered to be the less fun construction of letters, as long as the following doodle reward was unique and fun. The moment the doodle repeated or was not seen as fun, children were no longer interested in completing the doodle or postcard. As one parent wrote in, "My kids would replay with more excitement if they were asked to build different items that start with the same letter."

Evolution of the design

While the results from the Beta Evaluation were very encouraging, the freeform responses also highlighted limitations. First among these were the requested validation (or verification) of the constructed letters, and improvements of the image capture, which we address below. Yet if we were to add validation of constructed letters, given that children could start playing while knowing very few letters, additional scaffolding (Pea, 2004) was needed for them to learn the process of constructing a letter, including stroke order. On the other hand, for older or more knowledgeable children to continue learning by playing the app, specific target areas for phonics could be included, such as digraphs, long vowels, and blends. And the wide range of letter knowledge among children playing the app prompted us to consider making the app responsive or adaptive to the children's abilities.

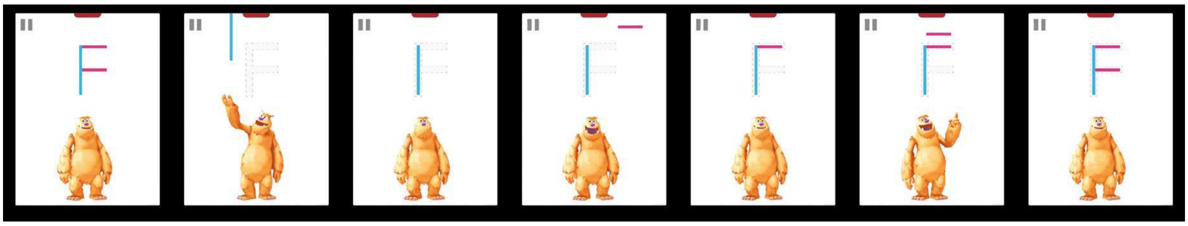

Figure 3: Animation scaffolding the creation of the letter “F” by the character of Mo the Monster. From the archetypal example on the leftmost image, the letter shape is gradually filled by the corresponding sticks and ring pieces in the correct positions and stroke order, until the letter is completed.

Currently we have implemented a solution where the app asks for the child’s age after installation. This implementation then automatically selects one of three difficulties, while providing the scaffolding options as individual toggles for the parents through the app’s settings screen. For example, younger children automatically see an animation scaffolding letter formation each time a new letter appears in their interactions (see Figure 3). Older children instead see words from a larger vocabulary set that include sounds with digraphs, long vowels, and blends—and with more challenging reward doodles that require a greater degree of fine motor control.

The most common request from parents and teachers, that of letter validation, required significant redesign: judging a letter created by a learner is more nuanced than a binary determination of whether the creation matches an archetypal letter shape. The sticks and rings were originally designed to allow children multiple ways of creating letters: for any human-recognizable letter there are several ways that our sticks and rings pieces could be used to form them. During the observations conducted prior to the development of the app (Maldonado & Zekelman, 2019), we noticed that younger children would at times ‘mirror’ the letter they were constructing from the example provided. These children would not, or could not, recognize that the flipped letters they formed did not match the letter example presented on screen. Flipped letters could be very close to the examples provided, for example, a mirrored diagonal piece in the “N.” Or perhaps a perfect letter “b” when asked for the letter “d.” In both these examples, the child is demonstrating greater letter knowledge than a child that creates a letter “O” (per our earlier review, one of the easiest to learn and fastest to create in-game) when asked to make a letter “N.”

Besides building a large corpus of human-recognizable letters that could be created with the included sticks and rings (see examples in Figure 1), we also created alternative versions of these with vertical and horizontal flips. Our current prototype uses machine learning to determine a confidence score between the child’s creation and each of the template alternatives of the requested letter. Based on the template match with the highest score, Mo the Monster provides feedback. For example, if the letter is flipped the character could say: “Whoa, the letter is backwards! To fix it, flip it this way!” while animating the correct adjustment required. It is only when the created letter receives a high confidence score that the remaining part of the doodle word is displayed. This implementation would allow quantification of the letter composition errors made by a large sample of children as they play with the app, and contribute to understanding of early childhood literacy.

Future work

In terms of product development, we are exploring a few directions concurrently by prototyping, testing, redesigning, and repeating the process until we reach a satisfactory solution. First, we are evaluating different alternatives to deliver the feedback on letter formation, both with respect to the content of the message, as well as the delivery mechanism: is it the Monster host that is confused by the imperfectly formed letter, or an unseen judge? In second place, we would like to explore ways to capture the progression of a child’s letter construction over time. This feature could be appreciated by parents and teachers, as well as used to fine-tune the interactions in ways that prioritize learning letter shapes while maintaining the fun, creative doodles. Expanding the number of doodles and postcards was among the Beta Testers’ requests, yet it may not contribute directly to learning letter names and sounds, recognizing or constructing their shape. We would like to evaluate the possibility of whether the additional doodles indirectly contribute to the children’s learning by increasing the amount of time played.

Conclusion

In this paper we have discussed the theoretical background and inspiration for the design of a new tangible application for tablets designed to help children learn to recognize letters by their shape and name. The evaluation of the Tangible ABCs app at teaching letters is not yet complete, yet we offered a detailed look into the process of applying Design-Based Research principles through sequential iterations of testing and development that combine qualitative and quantitative assessment methods. As the app development continues towards broad release, we are looking forward to analyzing the early adopters' anonymous aggregated data and usage patterns. This analysis will ensure that we maximize the learning opportunities for all children. independent of their starting level and background. This quantitative analysis will also contribute to the very rich field of early-literacy research by chronicling children's progression as they learn to *recognize* letters by their shape and name, to *form* these letters, and to *associate* the shape with the letter sound. Lastly, we hope our implementation may be followed by many more instances of educational products that balance engagement and learning, bringing together innovative research and cutting-edge technologies, with the DBR methodology guiding the development process.

References

Adams, M. J. (1994). *Beginning to Read: Thinking and Learning About Print*. MIT press.

Anthony, L. (2019). Physical dimensions of children's touchscreen interactions: Lessons from five years of study on the MTAGIC project. *International Journal of Human-Computer Studies*, 128, 1-16.

Bara, F., Gentaz, E., & Colé, P. (2007). Haptics in Learning to Read with Children from Low Socio-Economic Status families. *British Journal of Developmental Psychology*, *25*(4), 643–663.

Bara, F., Gentaz, E., Colé, P., & Sprenger-Charolles, L. (2004). The Visuo-Haptic and Haptic Exploration of Letters Increases the Kindergarten-Children's Understanding of The Alphabetic Principle. *Cognitive Development*, *19*(3), 433–449.

Beschorner, B., & Hutchison, A. C. (2013). Ipads As A Literacy Teaching Tool in Early Childhood. *International Journal of Education in Mathematics, Science and Technology*, *1*(1), 16.

Both-de Vries, A. C., & Bus, A. G. (2014). Visual Processing of Pictures and Letters In Alphabet Books And The Implications For Letter Learning. *Contemporary Educational Psychology*, *39*(2), 156–163.

Brooks, M., & Reardon, E. (2016). Sesame Street, Letter Blocks, And Augmented Reality: Increasing Engagement and Learning. http://uxpamagazine.org/sesamestreet-letter-blocks-and-augmented-reality/.

Brosterman, N., & Togashi, K. (1997). *Inventing Kindergarten*. HN Abrams New York.

Clarke, L., & Abbott, L. (2016). Young pupils', their teacher's and classroom assistants' experiences of iPads in a Northern Ireland school: "Four and five years old, who would have thought they could do that?". *British Journal of Educational Technology*, *47*(6), 1051–1064.

Cohen, M., Hadley, M., & Frank, M. (2011). Young Children, Apps & iPad. *US Department of Education Ready to Learn Program*, *200*, 5–10.

Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, *32*(1), 5–8.

Council on Communications and others. (2016). Media and young minds. *Pediatrics*, *138*(5).

Dehaene, S. (2009). *Reading in the brain: The new science of how we read*. Penguin.

Dobler, E. (2012). Using iPads to promote literacy in the primary grades. *Reading Today*, *29*(3), 18–19.

Ellefson, M. R., Treiman, R., & Kessler, B. (2009). Learning to label letters by sounds or names: A comparison of England and the United States. *Journal of Experimental Child Psychology*, *102*(3), 323–341.

Evans, M. A., Nowak, S., Burek, B., & Willoughby, D. (2017). The effect of alphabet eBooks and paper books on preschoolers' behavior: An analysis over repeated readings. *Early Childhood Research Q*, *40*, 1–12.

Fan, M., Antle, A. N., Hoskyn, M., Neustaedter, C., & Cramer, E. S. (2017). Why tangibility matters: A design case study of at-risk children learning to read and spell. *CHI2017 Proc*, 1805–1816. ACM.

Flewitt, R., Messer, D., & Kucirkova, N. (2015). New directions for early literacy in a digital age: The iPad. *Journal of Early Childhood Literacy*, *15*(3), 289–310.

Gray, J. H., Reardon, E., & Kotler, J. A. (2017). Designing for parasocial relationships and learning: Linear video, interactive media, and artificial intelligence. *IDC2017 Proc.*, 227–237. ACM.

Hirsh-Pasek, K., Zosh, J. M., Golinkoff, R. M., Gray, J. H., Robb, M. B., & Kaufman, J. (2015). Putting education in "educational" apps. *Psychological Science in the Public Interest*, *16*(1), 3–34.

Horn, M. S. (2018). Tangible interaction and cultural forms: Supporting learning in informal environments. *Journal of the Learning Sciences*, 1–34.

Horn, M. S., Crouser, R. J., & Bers, M. U. (2012). Tangible interaction and learning: The case for a hybrid approach. *Personal and Ubiquitous Computing*, *16*(4), 379–389.

Hourcade, J. P. (2007). Interaction Design and Children. *Foundations and Trends in Human-Computer Interaction*, 1(4), 277–392. https://doi.org/10.1561/1100000006

Hu, F., Zekelman, A., Horn, M., & Judd, F. (2015). Strawbies: Explorations in tangible programming. *IDC2015 Proc.*, 410–413. ACM.

Ishii, H., & Ullmer, B. (1997). *CHI1997 Proc.*, 234–241. ACM.

Justice, L., Pence, K., Bowles, R., & Wiggins, A. (2006). An investigation of four hypotheses concerning the order by which 4-year-old children learn alphabet letters. *Early Childhood Research Qy*, *21(3)*, 374–389.

Lake, B. M., Salakhutdinov, R., and Tenenbaum, J. B. (2015). Human-level concept learning through probabilistic program induction. *Science*, 350 (6266), 1332-1338.
Lauricella, A. R., Gola, A. A. H., & Calvert, S. L. (2011). Toddlers' learning from socially meaningful video characters. *Media Psychology*, *14*(2), 216–232.
Lillard, A. S. (2016). *Montessori: The science behind the genius*. Oxford University Press.
Lynch, J., & Redpath, T. (2014). 'Smart' technologies in early years literacy education: A meta-narrative of paradigmatic tensions in iPad use in an Australian preparatory classroom. *Journal of Early Childhood Literacy*, *14*(2), 147–174.
Madigan, S., Browne, D., Racine, N., Mori, C., & Tough, S. (2019). Association between screen time and children's performance on a developmental screening test. *JAMA Pediatrics*, *173*(3), 244–250.
Maldonado, H., Lee, J.-E. R., Brave, S., Nass, C., Nakajima, H., Yamada, R., Morishima, Y. (2005). We learn better together: Enhancing e-learning with emotional characters. *CSCL Proc:2005*, 408–417. International Society of the Learning Sciences.
Maldonado, H., & Nass, C. (2007). Emotive characters can make learning more productive and enjoyable: It takes two to learn to tango. *Educational Technology*, 33–38.
Maldonado, H., & Zekelman, A. (2019). Designing Tangible ABCs: Fröbel's Sticks and Rings for the 21st Century. In *Proc. of the ACM International Conference on Interaction Design & Children* (pp. 326-333).
Manches, A., & O'Malley, C. (2012). Tangibles for learning: A representational analysis of physical manipulation. *Personal and Ubiquitous Computing*, *16*(4), 405–419.
Marbotic Smart Letters. (n.d.). http://www.marbotic.fr/smart-letters/.
McBride-Chang, C. (1999). The ABCs of the ABCs: The development of letter-name and letter-sound knowledge. *Merrill-Palmer Quarterly*, *1982-*, 285–308.
Mobile montessori quality educational apps for kids! (n.d.). https://www.mobilemontessori.org/.
Montessorium: Learning is a lifestyle. (n.d.). https://montessorium.com/.
Neumann, M. M., & Neumann, D. L. (2014). Touch screen tablets and emergent literacy. *Early Childhood Education Journal*, *42*(4), 231–239.
Olmstead, K. (2017). A third of Americans live in a household with three or more smartphones. *Pew Research*.
Osmo—award-winning educational games system for iPad. (n.d.). https://playosmo.com/.
Pea, R. D. (2004). The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity. *The Journal of the Learning Sciences*, *13*(3), 423–451.
Phillips, B. M., Piasta, S. B., Anthony, J. L., Lonigan, C. J., & Francis, D. J. (2012). IRTs of the ABCs: Children's letter name acquisition. *Journal of School Psychology*, *50(4)*, 461–481.
Puranik, C. S., Petscher, Y., & Lonigan, C. J. (2013). Dimensionality and reliability of letter writing in 3-to 5-year-old preschool children. *Learning and Individual Differences*, 28, 133-141.
Resnick, M., Martin, F., Berg, R., Borovoy, R., Colella, V., Kramer, K., & Silverman, B. (1998). Digital manipulatives: New toys to think with. CHI1998 Proc, 281–287. ACM Press/AW Publishing Co.
Stiny, G. (2006). Shape: talking about seeing and doing. MIT Press.
TigglyWords learning system for tablets. (n.d.). https://tiggly.com/tiggly-words-learning-system.
Treiman, R. (2000). The foundations of literacy. *Current Directions in Psychological Science*, *9*(3), 89–92.
Wang, F., & Hannafin, M. J. (2005). Design-based research and technology-enhanced learning environments. *Educational Technology Research and Development*, *53*(4), 5–23.
West, M., & Ei, C. H. (2014). *Reading in the mobile era: A study of mobile reading in developing countries*. UNESCO.
Zuckerman, O. (2010). Designing digital objects for learning: Lessons from Froebel and Montessori. *IJART*, *3*(1), 124–135.

Acknowledgments

The authors extend heartfelt thanks to parents, teachers, and children who played with different prototypes of our implementation, and appreciate the many teams involved in the design and implementation of the system, as well as the user research studies. The development team from Osmo/Tangible Play includes Jerome Scholler, Guillaume Poncin, Mark Solomon, John Coyne, Arnaud Brejeon, Michelle Pun, Bryan Cash, Zachary Pavlov, Sravan Karuturi, Tamir Husain, Rachel Palangié, Axel Arth, Karen O'Dell, Erica Valladao, Jon Dukershein, Laura Ngan, Vivardhan Kanoria, Bailey Williams, and Kenneth Fernandez, among others. The development team at Marbotics includes Marie Merouze, Megane David, Mathias Musset, Etienne Cunin, Cyril Wirtz, Alexandre Chamoy, and others. Cathy Tran, Frances Judd, Antoine Picard, Felix Hu, and anonymous reviewers provided helpful comments.