Mathmelodies: inclusive design of a didactic game to practice mathematics

MathMelodies: Inclusive Design of a Didactic Game to Practice Mathematics

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Abstract. Tablet computers are becoming a common tool to support learning since primary school. Indeed, many didactic applications are already available on online stores. Most of these applications engage the child by immersing the educational purpose of the software within an entertaining environment, often in the form of a game with sophisticated graphic and interaction. Unfortunately, this makes most of these applications inaccessible to visually impaired children. In this contribution we present *MathMelodies*, an iPad application that supports math learning in primary school and that is designed to be accessible also to visually impaired children. We describe the main challenges we faced during the development of this didactic application that is both engaging and accessible. The application, currently publicly available, is collecting enthusiastic reviews from teachers, who often contribute with precious insight for improving the solution.

1 Introduction

A large number of commercial applications exist to support learning of primary school children. While some of these solutions are in the form of websites or applications for traditional devices (desktop and laptop), recently these applications have been developed for mobile devices, in particularly for tablets. For example, more than 65,000 educational applications are available for iOS devices[1].

Most of these applications engage the child by immersing the educational purpose of the software within an entertaining environment, often in the form of a game, generally with sophisticated graphic and interaction. Unfortunately, this results in most of the existing applications being inaccessible to visually impaired children which are already discriminated in the access to the print-based exercises and would actually benefit significantly from the autonomous use of educational applications. Also, the lack of accessible mobile applications can limit the social inclusion of visually impaired children.

In scientific literature many different interaction paradigms have been investigated to make entertaining educational games accessible to visually impaired children. These interaction paradigms include, in particular: auditory user interfaces and audio-haptic interaction. Educational auditory games have been

[1] Source: `http://www.apple.com/education/ipad/apps-books-and-more/`

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proposed both as desktop applications and recently as mobile applications [1]. While auditory user interfaces solve many interaction challenges [2], they also require attention and good memory skills [3]. Hence, especially in education (e.g. in presenting mathematical puzzles), auditory feedback alone is not the best solution. Auditory user interfaces have been extended with haptic or tactile feedback in order to help blind people to construct a mental representation of the scene. Audio-haptic educational games have been proposed both with general purpose haptic devices [4] and with new hardware devices employing vibro-tactile feedback [5,6], specifically designed to generate tactile stimuli which reinforce audio cues. These solutions proved to be more usable by blind people, but they are far more expensive and, as far as specific devices are concerned, they are currently only available as prototypes.

To address these problems, in this paper we present *MathMelodies*, an iPad application that supports primary school children in learning Mathematics. *MathMelodies* has been designed and implemented to be enjoyable by both visually impaired and sighted children. The software has been first developed as a university prototype and then, thanks to a crowdfunding campaign, engineered and distributed as a commercial application[2].

In this contribution we describe the main design challenges of *MathMelodies*. We adopted a user-centered design methodology, driven by a number of tests and on-the-field evaluations. In particular, we report the results of three evaluation sessions: an expert-based evaluation, a test conducted with the first prototype of the app and a more qualitative evaluation conducted on the commercial version of the application. Finally, we describe the feedback we have received so far and how they impact the application design.

2 Related Work

Non-visual interaction paradigms to make interactive games accessible to visually impaired people have been extensively studied in scientific literature. These paradigms are based on sensory substitution: the visual elements dynamically displayed on the screen are substituted with multimodal non-visual stimuli that guide the sight impaired player in the game [7]. The most frequently adopted non-visual interaction modes include auditory feedback as well as tactile and haptic stimuli.

Auditory feedback has been successfully employed to replace the sense of sight in many interactive games. In [8], Roden et al. illustrate a framework to generate audio game in a 3D audio environment. In [9], Vallejo et al. investigate sonification techniques in point and click games. Miller et al. [10] propose audio cues in games inherently based on audio feedback (e.g. where the player is required to reproduce a rhythmic pattern), but that are inaccessible to sight impaired people because of visual instructions. Ramos [11] and Ng [12] have recently evidenced the advantages of informative sounds in interactive games. Furthermore, in recent years, many auditory interfaces have been specifically

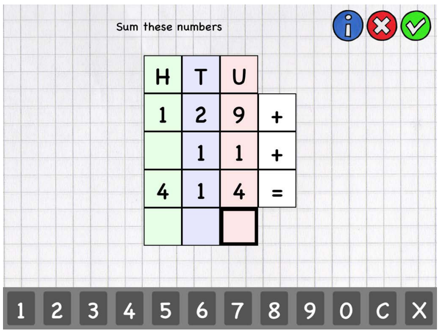
[2] https://itunes.apple.com/us/app/math-melodies/id713705958?mt=8

designed for games on mobile devices [1,13]. Nonetheless, all auditory interaction paradigms for games require much attention, memory skills and the ability to recognize even slightly different sounds. Furthermore, while auditory interfaces that employ spatial sound (e.g. 3D sound) can be successfully used with headphones that isolate the player from the surrounding environment, this may prevent the user from interacting with other players.

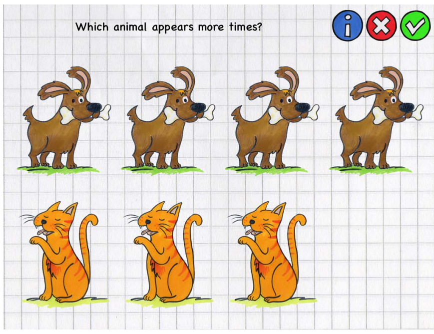
Auditory games have been extended with haptic or tactile feedback in order to reduce the cognitive load required to sight impaired people to construct a mental representation of the scene. Audio-haptic educational games have been proposed both with general purpose haptic devices [4] and with new hardware devices employing vibro-tactile feedback [5,6], or haptic gloves [14] specifically designed to generate tactile stimuli which reinforce audio cues. These solutions proved to be more usable by sight impaired people than auditory interaction paradigms only. Nonetheless, haptic devices are currently still very expensive, most of these devices are available as prototypes only and they are not designed to be used with mobile devices.

3 Design Challenges

During the design and development of *MathMelodies* we faced three main challenges. First, the application has to present exercises that are accessible to visually impaired children. In the preliminary prototype we experimented two main interaction paradigms that we called "sonification-based" and "object-based". With sonification-based interaction the application presents a generic image that can be explored through audio-feedback with a solution similar to the one adopted in [15]. For example, the application can guide the student to identify a triangle by reproducing a sound when the boundary is touched. Vice versa, with the object-based interaction paradigm, the application shows some objects on the screen, each one associated with an audio feedback that represents the object itself. In this case, the audio feedback is independent on the position of the touch within the object. For example, touching the figure of a dog, the application plays a sound of a dog barking. Similarly a digit is read when it is touched. The experimental evaluation has shown that the object-based interaction paradigm is less cognitively demanding for the students, hence resulting more enjoyable for the users and more suitable to represent complex exercises. According to these results, we designed a set of 13 different types of exercises relying on the object-based interaction paradigm. To further simplify the interaction model, we decided to organize the objects into a grid layout that, as we observed in our evaluation, helps reducing the time and mental workload required to explore the entire screen. Another choice driven by the need of simplifying the interaction consisted in the definition of two input techniques: a simplified on-screen keyboard to insert the digits only (e.g., for the addition exercises, see Figure 1(a)) and a multiple choice dialog (e.g., to answer an exercise like the one shown in Figure 1(b)). Finally, we observed that the interaction with the exercises without any preliminary explanation is not intuitive for some children.



(a) Addition exercise with simplified keyboard



(b) Counting exercise

Fig. 1. Two exercises of *MathMelodies*

Also, for some exercises, the eyes-free exploration of the screen can be time consuming. To address these two problems, we decided to add a short explanation that is read when a new type of exercise is presented.

The second design challenge is to stimulate children to play the exercises several times hence taking benefit from reinforcement learning. To address this challenge, we designed the exercises to have up to 6 difficulty levels. For example, in the "easy" addition exercise the child is asked to add two single-digit numbers, while at an harder level (designed for 3rd grade students) the aim is to add three numbers, each one with up to three digits as in Figure 1(a). For the same reason, the exercises are defined in terms of their type and difficulty level and not according to their actual content that is randomly generated each time the exercise is presented to the student.

Another important aspect to stimulate children to play the same exercise several times is to entertain them. We pursued this objective by presenting, in most of the exercises, what we call "audio-icons": amusing drawings, each one associated with an easy-to-recognize and funny sound. Also, the application gives a reward to the child in the form of a short piece of music when a correct answer is provided. As a future work we also intend to create a more sophisticated reward mechanism that takes into account the number of wrong answers the child provided before giving the right one. For example, zero mistakes can be rewarded with 3 "golden stars".

The last design challenge is to immerse the educational activities in an accessible entertaining environment that also links the exercises together and motivates children to keep on playing. We addressed this challenge with a tale, divided into 6 chapters, organized in increasing difficulty levels (two chapters for each grade). Each chapter is further divided into "pages", each one comprising a background image, some text (read by a speech synthesizer) and some "audio-icons" (see Figure 2). Pages are intertwined with the exercises and there are about 30 exercises in each chapter.

(a) A page with a piano audio-icon (b) A page with a frog audio-icon

Fig. 2. Two pages of *MathMelodies* story

Overall, the tale and the audio-icons have also the objective of triggering children's interest. This is similar to the approach adopted in most textbooks that heavily rely on colorful images. The difference is clearly that in *MathMelodies* this solution works for visually impaired children too.

4 Implementation of *MathMelodies*

During the app implementation we had to face a number of technical issues and here we describe two of them. The first issue deals with the large amount of app content, i.e., the story text, images (backgrounds and icons), and audio (sounds and music). Indeed, it is clearly impractical to define the app by hard-coding the content into the program. Instead, we defined a format for the "content file" that describes, for example, the structure of each chapter, each page, etc. A "content engine" in *MathMelodies* reads this file and presents the content to the user, in the form of exercises, pages, etc... Thanks to this approach, it is possible to define the app content independently from the app implementation.

The second issue is related to the implementation of the object-based interaction paradigm that is built on top of the system accessibility tools. On iOS devices, there are two sets of tools that render the system accessible to visually impaired users. One set is designed for low-visioned users and includes the "zoom" screen magnifier, font size adjustment and color inversion. While some ad-hoc gestures are defined to use the zoom functions, the overall interaction paradigm is analogous to the one for sighted users. The second set of tools is globally called "VoiceOver" and defines a totally different interaction paradigm. The overall idea is that, when the user taps on a graphical object (e.g., a button), VoiceOver gives it the focus and describes it both with a speech synthesizer and an external Braille display (if connected). To activate a focused object (e.g., to press a button), the user double taps anywhere on the screen. In addition to this basic behavior, VoiceOver has several additional gestures to make the interaction more efficient.

In order to enhance the app usability for visually impaired users that rely on residual sight, we used large fonts and high contrast between the front objects (i.e., text or pictures) and the background image. Although we did not evaluate this solution with a sufficiently large number of low-visioned users, we expect the app to be accessible to most low-visioned students by using the default accessibility tools. For what concerns blind users or low-visioned users that cannot totally rely on residual sight, some issues arose in the implementation of the object-based interaction paradigm. Indeed, the simplest solution to implement this paradigm would be to fully rely on VoiceOver (i.e., not implementing any custom behavior for app accessibility). This approach would make it possible to develop an app that is totally consistent with the system-wide interaction paradigm. However, this solution suffers from a major drawback, as it is not suitable to address all design challenges. For example, without defining any custom behavior it is not possible to develop the audio icons that reproduce the associated sound upon getting the focus. Other features that call for a custom behavior are multi-tap exploration and automatic reading of pages. Clearly, to achieve a deeper customization of the interaction paradigm a larger coding effort is required and it is quite involved to mimic VoiceOver standard behavior as well as to guarantee the consistency with the system-wide interaction paradigm. For example, the current version of *MathMelodies* (1.0) uses some custom objects in the story view: to enable the automatic reading of a page, story text is "hidden" to VoiceOver and "played" automatically with iOS 7's integrated text-to-speech synthesiser. We chose this approach because we wanted the app to be of immediate use also to users that are still not acquainted to standard VoiceOver gestures. Our preliminary tests, presented in Section 5, validated this approach. However, after app publication we received feedback that led us to reconsider our choice. Indeed, with this solution the text is not shown on external Braille displays. To address this issues we are now working on a new version of *MathMelodies* that minimizes the use of objects with custom behavior.

5 Experimental Evaluation

During the whole design and development process we took benefit from the feedback obtained from one of the designers who is blind and experienced in education for blind persons. In addition, we organized three evaluation sessions.

The first session was organized with four teachers expert in education for blind students[3]. The evaluation was divided in two steps. In the former, we presented a list of the exercises derived from Italian educational directives and integrated with workbooks and online resources. For each exercise we asked the experts to evaluate the importance of the exercise in the education of a blind person and to rate how difficult it is to practice it with existing solutions. In the second step of the evaluation we presented the preliminary prototype implementing sonification-based and object-based interaction paradigms. All four experts

[3] From the center for the blind people in Brescia, Italy.

independently agreed on the fact that object-based paradigm would be quicker to learn and also more adaptable to a larger variety of exercises.

The second session was conducted as a test with three blind children. After a short training with the prototype, we asked each child to solve three exercises with object-based interaction and one exercise with sonification-based interaction. All students have been able to complete and correctly answer exercise 1 (counting) and 2 (position in a table). Vice versa, one student has not been able to complete (and hence to provide an answer to) exercise 3, a spelling exercise, and exercise 4 consisting in recognizing a triangle by a sonification-based interaction. Overall, all students reported that the object-based interaction is easier to understand and two of them also highlighted that it is funnier.

The third evaluation session was conducted with three blind children in primary school and with two sighted children in primary school. All children were required to complete all the exercises in the first chapter consisting in counting exercises, sums, etc. All blind children were enthusiast while using the application. Two out of three reported that they were entertained and engaged especially by the sounds used (e.g. the call of animals and the rewarding melodies). All of them experienced some difficulties in the early exploration of the tables, and needed some help by a sighted supervisor. However, after at most 2 minutes of supervised training, all children got familiar with the application and were able to solve the exercises autonomously and, most of the times, providing a correct answer at the first attempt. The two sighted children enjoyed the application as well. One of the two children experienced some difficulties, at the beginning, in understanding how to answer. This was partially due to the fact that the child didn't pay much attention to the exercise explanation. After explaining how to answer, no more help was needed. To solve this problem we intend to create introductory exercises in which the focus is not on the exercise itself rather on how to use the application.

6 Conclusions and Future Work

To the best of our knowledge, *MathMelodies* is the first app for math learning on mobile devices that is specifically designed to be accessible to visually impaired children. In this paper we describe the main challenges that we had to face in the app design and implementation as well as the results of the experimental evaluations that shows how *MathMelodies* is actually accessible and entertaining.

Currently, the app is freely available on the AppStore and it has been downloaded 700 times in the first two months after the English version has been released. Since the app publication we received feedback from about 10 people, in most of the cases teachers for blind students. This feedback has a high value for us and is driving the design of the next version of *MathMelodies*.

As a future work we intend to take an even larger advantage from the app distribution to the public and we intend to automatically collect usage data and to use them to evaluate the app itself. In this perspective, 700 users are about 100 times as much as we could expect to involve in the evaluation conducted with the physical presence of the users.

Another future improvement consists in developing a collaborative system that allows the teachers to directly participate in the development of the app content. This crowdsourcing system can drastically reduce the development costs of the next versions of *MathMelodies* and ease the scalability of this solution.

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