LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

INSTITUTE OF INFORMATICS
HUMAN-CENTERED UBIQUITOUS MEDIA

Enhancing Analog Game Design with Digital Evaluation and Feedback

A Smartphone-based Approach

Master Thesis

Verena Pues
v.pues@campus.lmu.de

Time allowed for completion: 09.05.2023 - 07.11.2023
Supervisor: Florian Lang, M.Sc.
Examiner: Prof. Dr. Albrecht Schmidt

‘Enhancing Analog Game Design with Digital Evaluation and Feedback’
6th November 2023

Typesetting: PDF-$\LaTeX\,2_\varepsilon$

Abstract

Given the importance of games in human development, contemporary research in human-computer interaction explores the use of tangible user interfaces (TUIs) within the context of play-based learning. TUIs bridge the physical and digital world, enriching educational experiences by allowing for the physical exploration and manipulation of digital information. Despite their potential, existing TUIs are often specialized and require rather complex technical setups, hindering their propagation in classroom environments. Close collaboration with educators in the design process, more flexible concepts, and empowering users to adapt TUIs to their specific needs are essential steps to address these limitations. A qualitative user study involving interviews with ten educational experts yielded valuable insights that offer HCI researchers a deeper understanding of necessary prerequisites and desirable features for crafting TUIs tailored to educational settings. These insights have directly informed the development of the Playmake prototype, a versatile system integrating tactile interactions of a TUI with a cross-platform mobile application for game creation and automated feedback, showcasing practical applications of these findings. A diverse set of learning applications created with Playmake demonstrates its potential for enhancing interactive and personalized classroom education by empowering teachers and students in authoring custom tangible games.

Zusammenfassung

Die enge Verbindung zwischen Wahrnehmung und Erkenntnisgewinn betont die Notwendigkeit haptischer Erfahrungen im Lernprozess. Dieser Fakt und die wichtige Bedeutung von Spielen für die menschliche Entwicklung sind Gründe, warum aktuelle Forschung im Bereich Mensch-Computer-Interaktion den Einsatz von Tangible User Interfaces (TUIs), greifbaren Nutzerschnittstellen, mit Bezug auf deren Tauglichkeit für spielerische Lernenanwendungen hin untersucht. TUIs bilden eine Brücke zwischen der physischen und digitalen Welt, indem sie den Umgang mit digitalen Inhalten durch direkte Manipulation physischer Objekte ermöglichen. Trotz ihres Potenzials sind sie im schulischen Umfeld noch nicht verbreitet, da bestehende TUIs meist für nur eine einzige Anwendung optimiert sind und häufig ein komplexes teschnisches Setup benötigen. Eine enge Zusammenarbeit mit Pädagogen im Design-Prozess, flexiblere Konzepte und die Befähigung der Nutzer, TUIs an ihre spezifischen Anforderungen anzupassen, sind entscheidende Schritte, um die Praxistauglichkeit von TUIs zu erhöhen. Im Rahmen einer qualitativen Nutzerstudie wurden zehn Experten aus verschiedenen Bildungssektoren interviewt. Die Ergebnisse liefern Forschenden ein tieferes Verständnis für notwendige Voraussetzungen und wünschenswerte Funktionen von TUIs im schulischen Kontext. Geleitet von diesen aufschlussreichen Einblicken, wurde Playmake entwickelt. Der Prototyp kombiniert die haptische Interaktion von TUIs mit einer plattformunabhängigen, mobilen Anwendung zur Spielentwicklung und zeigt, wie die Erkenntnisse aus den Interviews praktische Anwendung finden können. Eine beispielhafte Auswahl an Lernspielen, die mit Playmake erstellt wurden, unterstreichen das Potenzial des Konzepts, den Unterricht interaktiv und abwechslungsreich zu bereichern.

Contents

Introduction

Games are crucial for human development, contributing to mental, emotional, and social growth [88], and can serve as a mechanism for learning [19]. As the close connection between perception and cognition emphasizes the importance of haptic experiences in the learning process [76], current human-computer interaction (HCI) research investigates the utilization of tangible user interfaces (TUIs) in the context of play-based learning applications. TUIs bridge the physical and digital worlds, benefiting learning with natural interactions [54] and motor cognitive skill development [10] through direct physical manipulation. Furthermore, they promote "self-exploration, self-correction, and self-regulated learning" [68]. While research suggests TUIs can benefit learning, their adoption in classrooms remains limited [112].

Most of those TUIs are targeted at very specific tasks, such as interactive storytelling for exploring emotions [130], learning shapes and pronunciation of Hangul characters (Korean language) [56], or investigating colors and structures found in everyday objects with a TUI drawing tool [103]. Many TUIs rely on heavy tabletop installations, complex camera setups, or highly specialized technical solutions. Those technological factors are impractical for everyday classroom usage or limit the use of those tools to a few use cases. Close collaboration between TUI researchers and educators is crucial to address this gap in research. Involving teachers, students, and domain experts in the design process and empowering users to customize TUIs is vital for meeting diverse student needs, covering the different subject areas in current curricula, and yielding positive learning outcomes.

Our work aimed to gain broad insights into the usage of games and technology in current classrooms and elaborate the requirements of a TUI to build customizable educational games for classroom usage. By utilizing existing hardware such as smartphones and tablets, we erase the need for technological or programming knowledge. We conducted a qualitative user study involving ten experts from different educational sectors in semi-structured interviews to deeply understand teachers' daily experiences and work routines and to discuss our research objective.

The results show that games are integral to contemporary teaching methods, enhancing the learning experience and fostering motivation. Our concept was well received as the teachers aim to customize and infuse creativity into their lessons to cater to their students' individual needs. Personalized feedback, flexibility, broad device compatibility, and pre-made templates let a customizable TUI complement classroom education in open teaching sessions or individual support and allow for the co-creation of educational games with students.

The insights and feedback guided the development of the Playmake prototype. This compact, multi-purpose system integrates the haptic interaction of a TUI with a cross-platform mobile application to empower teachers as experts in their respective subject areas to author tangible games. The prototype comprises a cardboard box featuring a transparent playing surface where physical game elements of any shape, marked with fiducial markers, can be placed. A smartphone or tablet utilizes its camera to monitor the game's progress and provides players with audio and visual feedback.

The outcomes of the interviews validate the significance of the Playmake concept and supply HCI researchers with in-depth insights, necessary prerequisites, and desirable characteristics for developing TUIs tailored to classroom environments. The resulting prototype establishes the groundwork for ongoing advancements to enrich personalized educational experiences and empower users to create custom interactive tangible games.

Related Work

Our research delves into the intersection of games, learning, and TUIs. To cover the related background in literature, we discuss how games can be harnessed for educational purposes and explore the concept of game-based learning and its terminology. Moreover, we give an overview of TUIs' potential to benefit learning by combining haptic interactions with digital data. Finally, we emphasize the importance and opportunities of empowering teachers and students to modify TUI behavior, as our work contributes towards a step in the direction of interactive and personalized education.

2.1 Games and Learning

Games are a constitutional part of children's life and contribute to their mental, emotional and social development [88]. Among humans and animals alike, play is an essential developmental activity and games as part of human culture can serve as mechanisms for learning [19]. While playing, participants experience a state of flow [24] that enhances their concentration and triggers moments of happiness, thereby motivating them to continue playing - a phenomenon that can be harnessed for knowledge transfer [28, 58].

2.1.1 Game-based Learning, Serious Games and Gamification

Game-based learning is a fundamental concept in which educational content is conveyed through the format of a game [53]. While all games require some form of learning, even if that learning is not applicable or valuable beyond the game environment [19], the idea behind game-based learning is to harness the learning potential of entertainment games and apply it to formal educational purposes [64]. A further distinction can be made between board game simulations, which are simple, hands-on games that cultivate fundamental understanding, and digital game-based learning, which is generally more complex, employing audiovisual effects to enhance attention and gaming motivation [53].

The boundaries between (digital) game-based learning and serious games, another popular term in this realm, are too blurred to establish a clear distinction [28, 64]. Serious games serve a purpose beyond mere entertainment [19, 28] and are primarily designed with an educational background [28] and serious intentions [64]. They are utilized in various fields such as military, government, education, and healthcare [122]. For example, they are employed to train heart surgeons in the sequences of complex surgeries using virtual operating room simulations [104].

What can be clearly distinguished, however, is game-based learning and the widely used term gamification [19]. Game-based learning involves the use of entire games, typically within a larger educational context, whereas gamification utilizes individual game design elements to achieve positive effects in non-game-related processes [19, 121]. Making game-based learning and gamification two substantially distinct approaches [19].

2.1.2 The Challenge of Balancing Play and Learning

While the idea of effortlessly acquiring knowledge through play may be appealing, it cannot be assumed that merging gaming and educational content will invariably yield positive learning outcomes. If we consider play as a free and voluntary activity [22, 48], this use of play for the sake of learning contradicts its essence [64]. Incorporating educational content into games represents a delicate balance between desired implicit and explicit learning. Explicit learning can potentially disrupt the flow of gameplay and, consequently, the effectiveness of the learning process [64].

Several established learning theories can provide insights into the mechanisms that can contribute to the facilitation of learning through games. Based on other literature [80, 113, 132] Becker [18] defined five categories of learning theories that underpin educational game design: behaviorism, humanism, cognitivism, constructivism and social learning. Behaviorist theories primarily focus on external motivation through rewards and punishments, whereas humanism takes a holistic approach, emphasizing self-actualization [18]. Cognitivism explores how we learn by examining information processing and meaning-making and constructivism involves learners constructing knowledge through their ideas and experiences [18]. Social learning highlights the role of communities in the learning process [18]. Kiili's experiential gaming model [58] emphasizes the importance of integrating those educational theories and game design artifice to create educational games that are both meaningful and engaging. Markova et al. see cognitivism and constructivism as most applicable considering tangible technology [75].

Research findings, such as those elaborated by Eckhardt et al. [28], who compared the learning outcomes of game-based learning to those of traditional frontal teaching, confirm the notion that serious games can have a positive impact on learning. In their comparative study, the serious game outperformed traditional teaching in all examined categories (learning outcomes, motivation, enjoyment and satisfaction) [28]. However, the applicability of these results to game-based learning in general is limited.

Concluding, the substantial investment and the ongoing expansion of the use of games for learning in education suggest that they are achieving sufficient success to justify their continued utilization [19]. However, when creating educational games, it is essential to build upon educational theories to understand how we learn and employ a well-developed game design to achieve the optimal balance between gameplay satisfaction and learning outcomes [18, 58]. This includes considerations such as maintaining game balance, aligning with the player's skill level, crafting a compelling storyline, and ensuring suitable graphics and sounds. All that while avoiding the risk of overloading the player's working memory with an abundance of rich multimedia elements [58].

2.2 Tangible User Interfaces

Game-based learning leverages the engaging nature of games to deliver educational content, often in the form of digital information. TUIs bring a new dimension to this synergy, bridging physical and digital worlds. They benefit learning processes with natural interactions that encourage hands-on exploration [54] and facilitate motor cognitive skills [10]. To unlock the full potential of TUIs as educational tools, it is crucial to lower technical burdens and enable teachers to customize the device's functionality [6].

2.2.1 Promise of a Natural Form of Interaction

Evolution has equipped humans with rich senses and sophisticated skills through diverse interaction with our multi-modal environment [52]. However, we do not make use of them when interacting with the digital world, where the graphical user interface (GUI) has become the standard [51], "sitting in front of, and staring at, a single glowing screen" [131]. However, flat displays cannot capture the essence of real-world objects [107]. Real objects possess affordances, which denote the possibilities for action and constraints, that restrict possible actions [85]. Used in combination, as a result of thorough design decisions, they can implicitly guide user behaviour [47].

The idea behind TUIs is to combine the benefits of digital technology with the richness of the physical world [52]. Augmenting physical objects to seamlessly manipulate and represent digital information and thereby leveraging users' familiarity and skills from the non-digital world [54, 107], TUIs have the potential to enhance the way people interact with and make use of digital data [111]. By building upon existing knowledge, the cognitive effort needed to operate a TUI decreases [54]. Applications for TUIs range from simulation and information visualization, over entertainment and music to social communication and rehabilitation purposes [86, 111]. The most dominant application areas for TUIs are learning, collaboration and problem solving [111, 112].

2.2.2 Tangible Learning

TUIs offer innovative ways for children to play and learn [77], by lowering the cognitive burden and providing students with hands-on interactive experiences [68]. Perception is closely intertwined with cognition, underscoring the significance of haptic experiences in the learning process [76]. Given that TUIs engage multiple senses, this favorable aspect applies here as well [135].

Outside the classroom, children have always engaged in play with physical items like building blocks, effortlessly acquiring a wide range of skills in the process [86]. More than a century ago, pioneers like Froebel [33] and Montessori [82] recognized the educational potential of hands-on materials and sensory experiences for children. Multiple findings from the fields of psychology and education have demonstrated that the use of tangible objects for tackling problem-solving tasks outperformed the use of more abstract presentations for children of varying age groups, suggesting real benefits for learning from tangible interfaces [86].

TUIs promise great potential to enhance learning experiences [10, 51, 68, 75, 134] by facilitating natural interactions that are accessible to a wide variety of learners [10, 68, 134]. They encourage exploration, while simplifying abstract ideas through concrete, tangible representations [10, 134]. The profiting spectrum of learners ranges from preschool to university [68] and people with special needs [111]. As TUIs provide more degrees of freedom for exploring the effects in the digital realm by direct manipulation, compared to more traditional interfaces, they potentially offer more divers opportunities to translate those experiences into knowledge [10, 86].

Educational interface designs should minimize the cognitive burden on learners regarding tasks unrelated to the core educational contents to enable learners to focus their resources on understanding those [86]. TUIs can achieve this goal with their familiar, natural form of interaction [134] and the facilitation of tangible thinking, which involves using the environment to aid cognition [111]. A related theory is projection, an essential concept, that simplifies thinking by using external resources in the environment [59], such as visualizing possible chess moves by hovering a piece over the board [29].

Due to their great potential, tangible learning has received growing attention in recent years. Tangible interaction has been explored for various different learning domains, such as literacy and storytelling [9, 62, 102, 123, 130], foreign languages [56], history [119, 126], art [101, 103], programming [23, 78, 106, 133] (in combination with music [87, 105]) and math [7, 66, 108, 109]. Research has identified that TUIs have a positive impact on various aspects of learning [68, 69]. Studies revealed that learners were more active or engaged when utilizing TUIs [69]. Additionally, research has indicated that TUIs are user-friendly for beginners, facilitate cognitive processes, and foster communication and collaboration [68]. However, it should be noted that the significance of these findings is constrained, as many studies employed small sample sizes and did not conduct long-term investigations [68, 69, 75].

2.2.3 Future Directions: Empowering Users

Although TUIs hold potential for complementing educational activities in a positive way, they have not yet found widespread adoption in classrooms and often remain in a prototypical state [112]. In the realm of tangible learning, it is predominantly researchers from the HCI community who define and develop applications. These applications, while innovative, do not always meet educational requirements. Teachers expressed concerns about unclear learning activity goals and the preference for "hip" technology over learning outcomes [69].

To address these issues, TUI researchers should collaborate with teachers to gain insights into real classroom settings and students' needs [69, 68]. This can be achieved by involving teachers and students in the design process right from the start [62]. However, the influence of teachers should not end there. To fully harness TUIs' potential as educational tools, it is essential to empower teachers, the primary experts in their field, to customize the device's behaviour [6]. Embracing adaptability in TUI design holds significant promise for addressing the diverse and evolving needs of students and specific curricula.

Tackling this opportunity, Andrao et al. present SMARTER 2.0 [6]. The tangible device supports teachers in designing their own games, modalities and applications through the system's integration with SENSATION, an end-user development environment for trigger-action programming [6, 25]. The system comprises a plywood box measuring 26x11cm, RFID readers, a speaker, and an RGB LED. The slots for tangible tiles are uniform, enhancing flexibility for different games and subjects [6]. The developers of SMARTER introduced language primitives for custom math games, allowing teachers to create rules in the format: "DO action(s) WHEN event WHILE state(s)" [6].

Mendes and Romão took another approach by creating an interactive tool that enables not only the teacher but also the students to build their own educational games [79]. This concept aligns with a learning-by-teaching approach, wherein children take on the role of the instructor. With the Tangible Games (T-Games) authoring tool, rather than employing a conventional computer, children engage with physical items on a tabletop to represent objects and actions in their games [79]. Children must prepare their game's materials, which requires in-depth research on the learning topics [79]. The game design process resulted in highly motivated children engaging deeply with the learning materials [79]. Both examples show how empowering teachers and students to modify system behavior helps better tap into TUIs' educational potential.

Background and Motivation

Games have proven to be valuable tools for enhancing learning experiences. Tangible interactions offer a unique and rich set of interaction possibilities compared to purely digital or analog solutions, as they combine the strengths of both worlds. Literature shows how combining a playful approach with tangible interaction unlocks the potential for making education more engaging.

However, designing (tangible) games for educational purposes in a way that benefits the learning process and outcomes is a challenging endeavor. It is, therefore, necessary to involve educators in the design process. In our research project BrailleBuddy [62], we describe the design process of a TUI for practicing early Braille literacy. This project serves as an example of effectively integrating educators into the design process within the context of university research projects.

As the literature on TUIs for learning suggests focusing more on the teacher's perspective [68, 69], we aim to take a step further by empowering educators from all kinds of subjects to create their own tangible games. While there is widespread research on tangible interaction focusing on particular use cases, only a few researchers target the authoring of custom applications by users.

We highly consider the technological and cost factors to fit the classroom context. TUIs often rely on large, immobile tabletop setups, complex camera configurations, or highly customized technical solutions. Eliminating the need for self-built electronics and heavy setups reduces costs and enables individuals without technical backgrounds to replicate the system. This approach seeks to make integrating our system into classrooms as seamless as possible, aligning with the actual requirements of educational institutions.

To achieve this goal, we propose employing conventional mobile devices such as smartphones as the sole technical component. As a proof of concept, we have successfully replicated BrailleBuddy's functionalities using the Google Pixel 6 smartphone [91]. For a better understanding of our research background, we present our prior work on BrailleBuddy and its reconstruction in the upcoming sections.

3.1 Case Study: BrailleBuddy

Learning Braille, a tactile font for reading and writing, is essential for navigating everyday life and the academic success of individuals who are blind or have severe visual impairments. In our work on the project BrailleBuddy [62], we explored the opportunities to support early learning of Braille with tangible computing.

Special education teachers and parents of visually impaired children rely on analog materials like tactile books [120], Braille-labeled everyday objects [63] or toys [45], and other store-bought [13, 12] or self-made [74] tangible materials to assist Braille learning. In addition to these more traditional tools, multiple tangible learning interfaces have been developed to improve abstract thinking and tactile senses [3, 70, 89] and to learn Braille characters [8, 32, 34, 55] or numbers [83]. Many digital solutions use a rather complex technical setup or enlarged Braille characters, which destroy the characteristic textural features students essentially rely on at the early stages of the Braille learning process [63]. To contribute to the existing research work, we aimed for a portable prototype that is easy to set up, uses standard-size Braille characters, and facilitates self-directed exploration of Braille by a child without adult assistance.

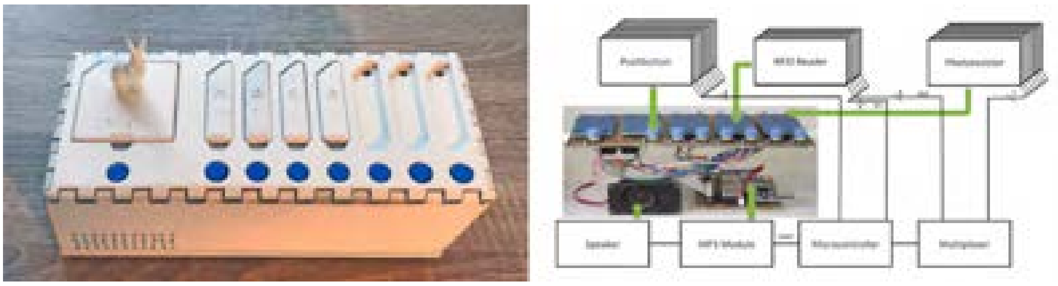

Figure 3.1 BrailleBuddy [62] is a compact portable TUI that facilitates children's self-directed exploration of Braille, a tactile font used by visually impaired people. The user can place 3D-printed platelets into recessed areas to trigger actions and receive auditory feedback. Large platelets are used to start a specific game. In the shown example, the user is prompted to spell „hare“ using Braille letter platelets. The platelets are recognized using near-field communication. On the left, you can see BrailleBuddy's internal electronic components and a schematic illustration of how they are connected.

To achieve this goal, we followed a user-centered inclusive design process, implementing feedback from low-vision research experts and special education students and teachers at several stages of the development process. A total of six design iterations resulted in BrailleBuddy, a self-contained tangible device consisting of a wooden case with several recessed areas on its lid into which 3D-printed Braille platelets can be placed to solve games and receive auditory feedback. BrailleBuddy's electronic components include an ESP32 microcontroller, a multiplexer, a MP3 module and a speaker. Five RFID readers and seven light sensors recognize the corresponding tags attached to the Braille platelets and determine their exact location in the eight recessed areas. Below each area is a push button that can be used to repeat instructions or audio feedback. Figure 3.1 shows our final prototype and its internal electronic setup.

We evaluated BrailleBuddy at a special education school with eleven first to third-grade students with severe visual impairments and their teacher to gain insights from both perspectives. During the study, we gathered qualitative feedback on three game modes (Word Copy, Word Riddle, and Word Scramble) with rising difficulty levels. The study results indicate that BrailleBuddy has the potential to effectively complement Braille learning in an extracurricular fashion, as the participating children enjoyed playing the games and could do so in an independent manner.

The positive reactions to BrailleBuddy from both students and teachers have motivated us to pursue working on it further. In replacing the custom-built electronics with a conventional smartphone, we see potential for building a more robust and flexible TUI for multi-purpose use cases.

3.2 Smartphone-based Approach: Proof of Concept

To validate our idea, we rebuilt BrailleBuddy, replacing its electronic components with a Google Pixel 6 smartphone [91]. As the device works with Google's Android operating system, we developed a native Android App in Java. We placed the smartphone inside the prototype's case and integrated transparent acrylic glass into the lid to monitor the game state from below, comparable to larger tabletop solutions [83]. The rebuilt box is displayed in Figure 3.2.

Figure 3.2 BrailleBuddy's original lid consisted of two thin wooden plates. In the new prototype the lower plate was replaced with a see-through acrylic glass layer [91]. This change enables the smartphone's camera to monitor the game state from below when placed at the bottom of the box.

A similar solution was developed by Almukadi et al. [4], who used a medium-sized transparent box as a playing field where young children could place letter blocks to create words. A camera inside the box analyzed the game state. Therefore, they used fiducial markers on the bottom of the blocks and the open source framework reacTIVision [2]. Visual feedback was given via a computer display. We see potential in optimizing this approach with means to a more comfortable work height.

However, reducing the box height also means a smaller distance between the camera and the area to monitor. This leads to challenges regarding maximizing the camera's field of view. Furthermore, we decided to use a closed opaque case (except the storage areas on the lid) to hide the camera and focus the user's attention on the playing field. This choice results in little to no external light, making it challenging for the camera to detect game elements.

To achieve an angle of view that allows the smartphone's camera to capture the relevant area, we raised BrailleBuddy's case by 38mm. To control the camera in our app, we used the CameraX API [26]. We assessed the front and ultra wide-angle cameras of the Google Pixel 6 to determine their appropriateness for our needs.

Monitoring the lid with the front camera required an additional 210° clip-on fish-eye lens. This method offers two significant advantages: nearly all mobile devices have a front camera, and the light from the upward-facing screen can illuminate the box from the inside. Since a well-lit room cannot be taken for granted, especially with blind users, internal illumination is a big plus. However, the image quality drops drastically toward the edges of the fish-eye lens, which increases the challenge of accurately recognizing game elements.

Alternatively, we used the rear camera of the Google Pixel 6, which comes with an ultra-wide-angle lens. This approach results in a better image quality and eliminates the need to attach an additional lens to the smartphone. Verifying the proper lens alignment can be quite difficult for children or users with significant visual impairments. However, the illumination issue stays unresolved, as using the flashlight led to strong reflections on the acrylic glass.

To track the state of the playing field, our application takes and analyzes two photos per second. The images are cropped at the bounding box of each area of interest (AOI), creating one crop per card slot and button position to optimize the recognition by removing distracting and irrelevant image elements. The AOI positions are stored in a text file, created in an initial setup process, requiring the user to replace the playing field lid with an extra setup lid that marks the AOIs with text.

We used Google's ML Kit's Text Recognition API [43] to recognize and analyze the setup lid and the game elements marked with text on their bottom. A critical requirement for BrailleBuddy was to keep the Braille character platelets as narrow as possible to preserve compound words' characteristics. The combination of relatively poor image quality and printing 2D codes, such as QR- or barcodes small enough to fit the platelets, resulted in the loss of the crucial details of the codes. That is why we chose to rely on text recognition, as letters are easier to distinguish. However, the image quality, compromised either by the additional clip-on lens or poor lighting conditions, also affected this method. So, we further stabilized the text recognition by maintaining a list of known words and comparing the recognized text to the list using the Levenshtein distance. The Levenshtein distance is a measure of similarity, defined as the smallest number of single-character mutations (insertions, deletions, or substitutions) required to transform one string into the other [67, 84].

The original BrailleBuddy prototype had physical push buttons to repeat the audio feedback, lowering the cognitive load. The most promising approach to integrating buttons into our camera vision system was to use the tips of rubber thimbles as a replacement, see Figure 3.3. Their elasticity caused them to return to their prior shape after being pressed in. We glued printed letters inside the rubber dome, which are hidden in an unpressed state and are visible to the camera when pressed onto the acrylic glass. Unfortunately, the glue changed the material's flexibility, and the buttons no longer spring back into shape.

In conclusion, we rebuild the basic functionality of the initial BrailleBuddy prototype, such as recognizing game elements, assigning them to the correct position on the playing field, and giving audio feedback via the smartphone speakers accordingly, with a native Android app. While we did not find a satisfactory solution for keeping the button functionality, the results are sufficient to provide a solid foundation for future work.

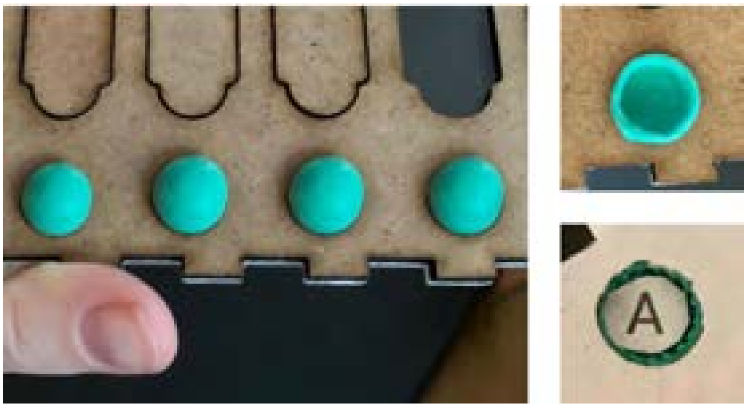

Figure 3.3 The images illustrate our approach to substitute the traditional push buttons of the original BrailleBuddy prototype with tips of rubber thimbles [91]. When the thimble button is pressed, the letter stuck within the dome becomes visible to the camera positioned inside the box.

Exploring Opportunities

This chapter introduces the concept of Playmake, an adaptable TUI designed to enable users to create their own tangible educational games. The concept is an evolution of BrailleBuddy's replication, without custom-built electronics, which laid the foundation for our work (compare Sections 3.1 and 3.2). Our objective is to discuss the potential of Playmake and its possible adaption in classroom scenarios with experts from different educational backgrounds. An overview of the contributing experts is given in Table 4.1. We conducted semi-structured interviews and employed qualitative data analysis to extract insights that influenced the development of a functional prototype.

Table 4.1 We conducted semi-structured interviews with experts from different educational sectors, namely primary and secondary schools, and from the field of special education. The ten contributing experts from overall seven different schools are listed in rows one to ten, including eight active teachers, a former teacher, and a university student with practical teaching experience. Furthermore, we introduced and discussed our concept with the students of an 8th-grade class.

ID	Job Title	Age	Gender	School Type (ID)	Specialization
P01	teacher	35	male	secondary school (A)	english, sports, movement arts (elective), school counselor
P02	teacher	43	male	secondary school (A)	latin, spanish, ancient greek, computer science
P03	teacher	57	male	secondary school (B)	math, physics, computer science
P04	former teacher	72	male	secondary school (C)	german, history, social studies
P05	teacher	38	female	primary school (D)	all subjects (grade 1 to 4)
P06	teacher	32	female	primary school (E)	all subjects (grade 1 to 4), latin, sports
P07	teacher	28	female	primary school (F)	all subjects (grade 1 to 4)
P08	teacher	28	female	primary school (F)	all subjects (grade 1 to 4)
P09	special education teacher	27	female	special school (G)	general education, mental development
P10	university student	23	female	special school (H) [1]	general education, learning disabilities and autism spectrum disorder
P11	8th-grade students	-	-	secondary school (A)	-

[1] School H does not refer to one specific school but encompasses the multiple institutions where P10 has gained practical teaching experience.

4.1 Methodology

To gain comprehensive insights into how games and technology are used in school settings, we conducted a qualitative study involving ten experts from different educational sectors. This methodology was chosen to ensure a deep understanding of the subject gathered from diverse perspectives. We interviewed three active and one former secondary school teacher, four primary school teachers, and one special education teacher representing seven different schools. One of our experts is a university student, with practical experience across multiple special education institutions. All participants live in Germany, with nine residing in Bavaria (BY) and P03 in North Rhine Westphalia (NRW).

Our interview covered three main areas of inquiry:

- Participants' daily roles and responsibilities
- Their experiences and perspectives on the use of games for educational purposes
- Feedback and suggestions related to our conceptual idea

The semi-structured interviews allowed for spontaneous discussions and follow-up questions, ensuring that we captured in-depth responses from the participants. The interview duration ranged from 18 to 105 minutes, with an average time of 35 minutes. One interview was held at a school, a second one at the teacher's home, and all the remaining interviews were conducted via telephone. Each interview was recorded, transcribed, and prepared for analysis. Additionally, we had the opportunity to present our research to an 8th-grade class and discuss the concept's potential with the students.

We employed an iterative coding approach using the qualitative data analysis software Atlas.ti. Two researchers collaborated to analyze the transcribed interviews to identify and categorize critical themes, patterns, and insights emerging from the data. This rigorous coding process facilitated the organization and interpretation of the interview data, ensuring that we derived meaningful conclusions from the collected information.

4.2 Playmake: First Concept Idea

To optimize the interview process and encourage informed responses, a pre-interview document was sent to each participant together with the interview invitation. This document provided a comprehensive overview of the research project, including its motivation and the conceptual framework. The document was designed to familiarize participants with the study's objectives and details of the planned prototype and is summarized in the following paragraphs.

TUIs offer a unique approach to enhancing learning with natural interaction and an engaging experience. Our concept empowers its users to customize a modular TUI for their purposes without prior technical knowledge or programming experience. The Playmake system aims to provide educators and learners with a straightforward and cost-effective way to create their own interactive learning games by relying on a conventional smartphone instead of complex technical setups and custom-built electronics.

Playmake comes in the shape of a cardboard box with a transparent playing field embedded in the lid. Figure 4.1 shows the first version of the prototype. Compared to BrailleBuddy, the playing area is significantly larger, measuring approximately 22x14.5 cm, providing users with more space to implement their game ideas. The smartphone is attached to the side wall to maximize the camera's viewport by increasing the distance between the playing area and the camera. From this position, the camera captures a mirror that reflects the playing field, see Figure 4.2. The smartphone runs the Playmake application, which recognizes game elements, evaluates the game status, and provides audio feedback like sound effects, explanations, or melodies.

To create a game using Playmake, users start by crafting a cardboard layout for the playing field. This layout defines where game elements can be placed on the field. Next, the layout is captured with the app. Users can then group, associate, and define relationships among the areas for game elements, which determine the interpretation of game states. This flexible approach allows for the implementation of diverse rules and game ideas. Game elements, such as cards or figures, can be entirely customized by the user using hand-drawn or printed game cards, building blocks, or even materials gathered from nature.

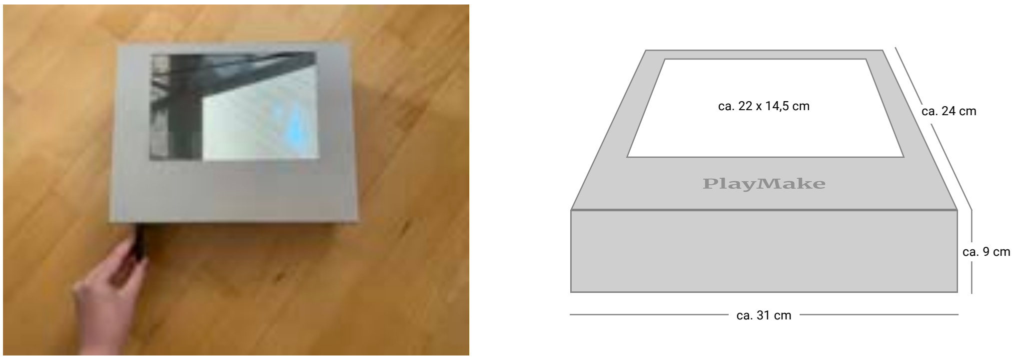

Figure 4.1 The left image shows the top view of our first iteration of the Playmake prototype. From the side, the user can slide a smartphone into the box. When positioned, the smartphone's camera observes the transparent playing field via a mirror. On the left, we illustrate the dimensions of the cardboard box: 31x24x9 cm (LxWxH). As this is only the first version of the prototype, those numbers serve as approximations.

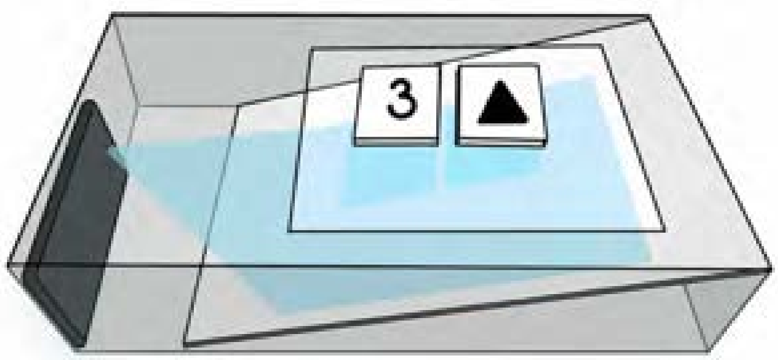

Figure 4.2 The internal setup of Playmake consists of the smartphone positioned on the box's sidewall and a diagonal mirror that reflects the transparent playing field. When game elements are placed on top of the box, they can be recognized by the camera.

4.3 Findings

This section presents the core insights derived from in-depth semi-structured interviews with ten experts from different educational backgrounds and a discussion with 8th-grade students. These findings encapsulate diverse perspectives on using digital media and educational games in the classroom and on the conceptual framework of Playmake.

4.3.1 Technological Equipment in Schools

Since our concept is based on using a mobile device, we wanted to find out from the teachers what technical equipment they have available at the schools. Tablets, specifically Apple iPads, are available at all the participants' schools, but the number of devices varies. From our interview findings, we could derive six categories of how those devices are distributed at the schools. Table 4.1 gives a compact overview.

iPad Suitcases. A common system is to provide so-called iPad suitcases (schools A, B, F and H). These sets can be borrowed and then used in different classes. School A has additional tablet devices for their all-day care premises. Since there are not enough devices for all classes, the iPad suitcase approach involves a certain amount of prior planning and arrangement. P05 told us that her school (D) has so few tablets that she almost wholly forgoes their use, although she would like to use them regularly.

Class and Service Devices. Schools A and G equip their teachers with their own service devices (tablets). Additionally, School G provides each class with its own iPad, which makes two devices per class (including the teacher's service device).

Tablet Class. Schools A and B both have so-called tablet classes in which every student is equipped with a tablet. The devices are either provided by the school or are private devices of the students. P02 has equipped an entire room according to his technical requirements, the so-called Latin Lab, with a tablet for each student and a large screen. The secondary school teachers P01, P02, and P03, report that using students' personal devices (tablets and smartphones) is a regular occurrence. This also applies to non-tablet classes.

Rental Devices. P03 sees a trend towards co-funding private devices for students by the schools. School A has a pool of rental devices for students with less financial prospects.

Other Equipment. School A has its own school cloud through which files can be managed and shared. However, the school's internal Wi-Fi is not reliable (P02). Schools A and B have 3D printers available that could be used to produce complex custom game elements for Playmake. School F has digital whiteboards that allow more interactive lesson formats and make resource-sharing between teachers straightforward.

Table 4.2 Tablets were the most frequently mentioned technical devices used in the classroom. These devices are managed and utilized differently across the schools, from which five concept categories could be derived. The listing of a school means that a teacher mentioned the concept. It does not necessarily imply that unlisted schools do not follow this concept.

Concept	Schools	Description
iPad Suitcases	A, B, F, H	sets of iPads are shared among classes
Service Devices	A, G	the school provides their teachers with tablets
Class Device	G	one tablet available per class
Tablet Class	A, B	each student of a class has a tablet for usage in class
Rental Devices	A	students with less financial backgrounds can borrow a device from the school

4.3.2 Use of Digital Media in Class

Not only the technical equipment of the schools is of interest to our work, but also the significance their use has in the classroom and what advantages and disadvantages come along with it. Hence, we asked the teachers about their perspectives on using digital media in the school.

P10 observed that students perceive the use of technical devices as something special. P01 states that using smartphones and tablets is also a motivating factor for his students. Especially in the primary school sector, however, he believes it is important that digital media adds genuine educational value and not only serves as a motivator due to being a technical device. P03 also emphasizes the role of devices as complementary tools.

"The digital device itself should not stay in focus,
but rather its application and educational relevance."
- P03[2]

P02 sees one clear advantage: digital technology saves work and resources, e.g., worksheets and homework can be distributed and managed via the school cloud. Another advantage mentioned is the possibility to adapt tasks more precisely to the individual needs of different students (P10) and that students can receive differentiated feedback directly (P01). However, addressing data protection concerns is crucial when working with digital applications. For instance, applications must ensure that no personal data is stored by implementing alternative login options like codes or pseudonyms (P01).

P03 reports on uncertainties that can be burdensome for both students and teachers, such as the lack of uniform rules for using various tools like the internet and artificial intelligence (AI), as well as fair approaches for assessment in the context of these tools and the extensive possibilities for exchange. In addition to these challenges, the digital world has other risks, such as misinformation and addiction. While the internet provides us with easy access to valuable knowledge on the one hand, it is crucial to raise awareness and provide education on navigating the sheer bulk of information on the other hand, emphasizing the importance of critical thinking and source evaluation to avoid misinformation (P04). P02 observed outside of the classroom that applications using gamification elements as addictive mechanisms to promote in-app purchases are prevalent among students.

Those dangers and the fact that dealing with digital media is an integral part of everyday life, even for young children, make using digital media in schools unavoidable (P07, P08, P10). It is essential to educate children about handling media, discuss the advantages and disadvantages, point out potential dangers, and establish rules early on (P07, P08).

In summary, digital media saves work and resources, can be motivating, plays a vital role in students' everyday lives, adapts to students' individual requirements, and gives direct feedback. But it should not be used exclusively (P02, P07). Analog work such as writing on paper, sketching, or crafting trains many abilities, such as motor skills, concentration, and conscientiousness (P01, P03 - P05, P07). In conclusion, the appropriate use of various media, both digital and analog, tailored to the specific use case is a good combination for examining learning content from different perspectives.

"The more divers the media formats, the better." - P02[3]

---

[2] Original quote: "Nicht das digitale Gerät an sich steht im Vordergrund, sondern eben die Anwendung und der Bezug zum Unterricht und der pädagogische Einsatz." (P03)

[3] Original quote: "Je mehr verschiedene Medien, desto besser." (P02)

4.3.3 General Use of Games in the Classroom

Using games in the classroom is a prevalent and valuable practice among the interviewed educators. All interview partners, but P04, use games regularly in their teaching. P04, whose active career as a teacher took place in the 1970s, reported that a game-based approach to learning content was not in high demand at that time, and that is why he did not use games in the classroom. However, he also tried to present content in an engaging way, e.g., by weaving facts into stories to make the larger context comprehensible for his students.

We learned from the other participants about the occasions on which they integrate games into their lessons. Games are used to introduce and elaborate new topics (P05, P07) or to consolidate and repeat already known learning content (P05, P07, P09). The playful contact with topics in the classroom offers additional perspectives to the content (P05, P09). By confronting the students in different situations, information chunks are better linked and more accessible to recall afterward (P02). Knowledge that is proactively applied or independently developed is better anchored (P04, P07, P08). The emotional involvement in the game also increases the relevance of the learning content (P03). P02 calls this approach *"learning with all the senses"*[4].

Playful contact with information is particularly suitable for children (P01). Different types of games can appeal to students with diverging learning types, e.g., competitive game characteristics appeal to children who like to compete (P06). In contrast, other children prefer to play alone and immerse themselves in the game (P06). The playful approach lowers the hurdle to enter the learning process (P01). It can be especially helpful for students with learning difficulties who are frustrated because their learning efforts do not seem to be as successful (P01, P06, P10).

"In the context of play, children's interests converge to some extent, as all children enjoy playing." - P01[5]

Moreover, the benefits of using games extend beyond knowledge acquisition and methodological skills. Games promote the students' frustration tolerance (P10) as well as emotional and social bonds in the classroom (P02, P08, P09) and train communication and interaction (P02, P08, P09). Perceptual abilities also increase (P10), and creative thinking is strengthened by linking different skills and introducing one's ideas (P09). In addition, games provide an important balance to focused work: They serve as relief and relaxation between work sessions, as mobilization and rhythmization, and tend to lighten the mood in the class (P05, P06, P09, P10).

Increased motivation was mentioned frequently as an added value of using games in the classroom (P01, P03, P06, P07, P09). They represent short-term goals that students are much more aware of achieving than finishing a unit in the curriculum (P01). Direct positive feedback serves as an obvious reward and thus helps to maintain motivation (P01), allowing students to engage with a topic longer and more deeply (P09). P06 uses games as an incentive for students to work diligently by allowing them to play games once they finish their tasks.

The teachers pointed out that it is crucial for learning games to add value to the lesson by meeting the subject matters as neatly as possible and testing the entire range of

[4] Original quote: "Lernen mit allen Sinnen" (P02)
[5] Original quote: "Im Spiel vereinen sich die Kinder-Interessen so ein bisschen, also dass einfach alle Kinder gerne spielen." (P01)

competencies (P02, P06). The levels of the tasks should be adequately challenging and cover different degrees of difficulty (P02).

In conclusion, integrating games in the classroom is a versatile and effective way to complement teaching. It benefits the learning outcomes and promotes emotional engagement, social interaction, and student motivation. The key to success lays in creating games that are closely aligned with the curriculum and that challenge students appropriately.

4.3.4 Game Types Used in Class

Our objective is to derive insights from the current utilization of games to identify the specific modalities of gameplay that could benefit from our concept. Furthermore, we aim to discern the essential attributes that a prototype must possess to enable the creation of classroom-appropriate games. That is why we are not only interested in the purposes and occasions for which teachers integrate games into their teaching; we also want to know which types of games are actually used in class.

In the classroom, both analog and digital games are utilized. Traditional analog *parlor games* foster emotional and social skills (P08, P09) or promote attention and the ability to respond quickly (P10). In addition, *movement games* that stimulate both the body and the mind were popular among the teachers (P03, P05, P08, P09). Many of the mentioned games *involve the entire class*, either collaborating or competing with each other (P03, P05, P06, P08, P09). A competitive element can be introduced by collecting points (P01) or time-based challenges (P06). Memory games (P09, P10) and learning picture cards for various purposes (P06, P07) can be used both in analog (P06, P09, P10) and digital formats (P07).

In the digital realm, various *digital learning games and apps* were mentioned (P02, P05, P06, P08, P09), e.g., digital supplementary materials from different educational publishers (P05, P07, P10). P09 uses game apps that train attention with eye control, especially since more complex tasks are challenging for her students with special needs. In mathematics, augmented reality features [38] help visualize mathematical concepts, and online tutorials and exercises provide students with additional training opportunities (P01). P02 uses different digital applications to teach the basics of programming.

Other solutions enable teachers *to create their own games or content.* This includes different online platforms (P02, P09) and solutions that allow customizing quiz-like games (P02, P03, P09), e.g., "Kahoot!" [57] (P03), as well as the digital whiteboard software "myViewBoard" [129] (P07, P08), which allows the creation of various games like jigsaw puzzles, dominos, or math games (P07). P03 particularly appreciates Kahoot! [57] as it comes with a vast selection of pre-created content and because he receives immediate feedback on individual students' progress and can identify which tasks are challenging or easy for his class. P01 creates custom games from PowerPoint slides and observed that their interactivity and feedback motivate students more than plain worksheets (P01).

A digest of concrete games, applications, and platforms mentioned by the participants is given in Table 4.3. In Appendix A.1, each item is explained briefly for better comprehensibility. The participants employ a combination of analog and digital games to enhance the learning experience, often to actively engage the entire class. Digital tools offer educators a convenient way to generate and share custom-made multimedia content, including educational games. The mentioned game types provide an insight but should not be considered a complete list. However, the spontaneously mentioned games during the interviews offer a good overview.

Table 4.3 This table lists all concrete digital (d) or analog (a) games, applications, and platforms mentioned by the participants during the interviews and assigns them to categories.

Game/Solution	Cited by	d/a	Type
Desert Island Game [50]	P08	a	Word Guessing Game, Whole Class Activity
Dobble [27]	P10	a	Parlor Game, Card Game
Ecken-Rechnen [118]	P03	a	Math Game, Movement Game
Hangman	P03	a	Word Guessing Game, Whole Class Activity
Kniffel [116] (Yahtzee)	P09	a	Parlor Game, Dice Game
Menschen-Memory	P03	a	Whole Class Activity
Ping Pong	P05	a	Whole Class Activity
Rechen-Bingo [81]	P05, P08	a	Math Game, Whole Class Activity
Rechen-Fußball	P03, P05, P08	a	Math Game, Whole Class Activity
Saboteur [114]	P09	a	Parlor Game, Card Game
Tafel-Fußball [128]	P09	a	Whole Class Activity
Zwerg-Riese	P05	a	Movement Game, Whole Class Activity
Anton App [11]	P05, P08, P10	d	Learning Games App
Bitsboard [46]	P09	d	Content Creation Platform
Cargo-Bot [65]	P02	d	Learning Games App (Computer Science)
Geogebra [35, 38]	P01	d	Learning Platform (Math)
H5P [44]	P02	d	Content Creation Platform
Kahoot! [57]	P03	d	Quiz Creation Platform, Whole Class Activity
LearningApps.org [49]	P02, P09	d	Game Creation Platform
Marbotic [72]	P09	d	Tangible Learning Games App
mathegym.de [5]	P01	d	Learning Platform (Math)
myViewBoard [129]	P07, P08	d	Content Creation Platform, Whole Class Activity
Plickers [90]	P02, P09	d	Quiz Creation Platform, Whole Class Activity
Quizlet Live [97]	P02	d	Quiz Creation Platform, Whole Class Activity
Robot Karol [98]	P02	d	Learning Games App (Computer Science)
Safe Cracker (PowerPoint)	P01	d	Content Creation, Whole Class Activity

4.3.5 Playmake: Game Ideas and Inspiration

We explicitly asked the participants for their game ideas tailored for Playmake. The following paragraphs describe game ideas or specific use cases the teachers came up with. We grouped them into subject areas: *math*, *history*, *biology*, *literacy*, *foreign languages*, *general knowledge*, *music*, and *others*. While *math, history, literacy*, and *foreign languages* included ideas for secondary school, the other topics focused on primary school knowledge only.

Math. Mentioned topics in the field of mathematics for the secondary school included fractions (P01), function graphs (P01), geometry(P06), and set theory (P09). A concrete idea for implementing fractions was the association of visual representations (e.g., divided circles) with numerical representations concerning the reduction of fractions (P01). Another suggestion was to utilize Playmake's transparent surface to draw and evaluate function graphs, highlighting where the answer diverges from the correct solution (P01). While P09 could envision the concept's use for complex mathematical operations, P03 raised the point that there are already many reasonable existing solutions for abstract tasks. He saw the tactile advantage of our concept, particularly for younger children, e.g., when exploring number spaces (P03). For specific learning styles, touching concrete objects and feeling the corners and edges can aid understanding in primary school geometry (P06). This could be combined with a playful learning approach using Playmake (P06). Additional mathematical topics in primary school, such as general arithmetic tasks (P07), multiplication tables (P05), and sorting exercises (P07) were mentioned.

History and Biology. P10 could envision that the multimedia aspects of Playmake could enhance history lessons through storytelling and sound effects. For instance, it could make historical settings like a medieval castle come to life (P10). By using videos, one could also depict interviews with eyewitnesses from historical periods, such as the era of National Socialism, making history more vivid and engaging (P10). One of the students (P11) could envision Playmake being used in biology classes. One game idea she came up with was arranging body parts.

Literacy and Foreign Languages. Several suggestions emerged on the topic of early literacy (P05, P07, P09), such as word association games including word-to-picture (P07), word to initial sound (P07), word to word-type or Montessori word-type symbols (P05). Other ideas were combining syllables to build terms or breaking words into syllables (P07). Games related to words' origins and semantic shifts (P10) are more related to more advanced literacy. The use of audio was seen as advantageous in vocabulary training for foreign languages (P06, P07) and for promoting German as a second language (P10) because it allows for the direct inclusion of correct pronunciation. However, the students (P11) considered vocabulary training with Playmake possibly more time-consuming than traditional repetition.

General Knowledge[6]. Another application idea for audio is the matching game "Which animal did you hear?" where animals could be associated with their typical sounds (P01). P03 liked the idea of using everyday objects from nature to create a game for matching bushes to fruits (P07) or leaves to trees. Nutrition is also a suitable topic, such as assigning food items to various categories like fruits and vegetables or local and exotic fruits (P05).

Music and Others. Game ideas for music subjects were associating instruments with their names or sounds (P08) or placing musical notes to create a melody (P06). P09 suggested matching realistic images with symbols to train abstraction skills and symbol comprehension. P08 could envision students creating a board game where quiz questions must be answered on some fields. Other ideas included matching games on various topics (P01), jigsaw puzzles (P01, P08), and the incorporation of escape game elements (P01). For further inspiration for educational games, teachers recommended researching primary school blogs online (P06 - P08), such as Eduki [39] and others [1, 20, 21, 99, 100, 110, 125].

We also asked if the teachers know of comparable solutions to Playmake. The concept of different game sets with evaluation by the system reminded P02 of LÜK boxes [40]. LÜK boxes are educational tools consisting of a box, exercise cards, and answer tiles. Students solve tasks on the cards by positioning the answer tiles in the box. To check their answers, the box is flipped, and the underside of the tiles is examined. If the tiles are in the correct position, the box displays an image or color for self-assessment. P09 mentioned Marbotic [72], which uses wooden letters and numbers that can be placed on a tablet running a dedicated mobile app and combines physical and digital tools to enhance the learning experience.

---

[6] In Germany, elementary school includes a subject known as "Sachkunde" or "Heimat- und Sachkunde." This subject covers interdisciplinary topics like health, sustainability, social sciences, natural sciences, geography, history, and technology. To simplify, in the context of this thesis, we refer to it as "general knowledge" because there is no direct equivalent in the English-speaking realm, to the best of our knowledge.

4.3.6 Playmake: Application Possibilities

Once we had gathered game ideas, we also wanted to know how these games could be integrated into the classroom environment. Seven participants can imagine using the concept in their work with the students (P01, P05 - P10). P02 could only imagine its use if the audio feedback is designed as discreetly as possible. There should be no annoying background noise ("ringing and robotic voices" (P02)[7]) when using several devices in one room. P03 found it challenging to develop concrete use cases for his teaching at secondary school but could well imagine the concept for use at primary schools. P04 expressed concern that the concept has a quiz-like nature and thus would be too insubstantial to use in the classroom.

Playmake could be incorporated into partner- (P02) or group work (P07) or as part of independent work phases (P03, P07). P06 could imagine offering Playmake to reward students who have completed their tasks or homework. P06, P07, P09, and P10 see potential in using our concept as part of so-called "Lerntheken" or "Freiarbeitsstationen" [60, 61]. Both concepts are forms of a method called open teaching, which describes a teaching phase in which the students work independently through different work assignments and materials to elaborate on a topic or to repeat what they have already learned. Another potential use case scenario would be individual support lessons, where a teacher deals intensively with one student (P06, P07, P09).

P05 and P08 see a lot of potential in involving the students in creating games. In doing so, the children would engage intensively with the learning content without recognizing it as work (P05). The pride in developing their own game would be highly motivating for the students (P05, P08). Moreover, designing a game concept itself is a valuable exercise (P05). P08 also sees advantages for the teacher: Instead of the teacher having to prepare games, the children create their own reusable games (P08). P06 suggests to involve the entire class in the creation of a single game to harness the students' combined potential, as she is concerned that some groups of students may be overwhelmed by such a task. But overall, P06 finds it more realistic for the teacher to prepare the games.

"Involving them in the game design process
would be a mega highlight for my students." - P01[8]

Using Playmake in a home environment is also conceivable (P01, P04 - P06, P07). In the elementary school age group, there would be the advantage that it can be assumed that all parents have a smartphone, which may only be the case for some students (P06).

4.3.7 Playmake: Target Group

The participants see the target age group for Playmake starting from kindergarten (P03) or primary school (P01 - P03, P05, P07, P10, P11). P07 envisions using Playmake throughout the whole primary school level, primarily in the first and second grades, and with more complex tasks or topics in the third and fourth grades. P06, on the other hand, can imagine using it starting from the third or fourth grade and only after the students are well-acquainted with the device. P08 also sees the primary application in the third or fourth grade because

[7] Whole quote: "...,so that the entire atmosphere is not dominated by ringing and robotic voices." Original quote: "..., dass nicht die ganze Atmosphäre von so Geklingele und Roboterstimmen da beherrscht wird." (P02)

[8] Original quote: "Das [Miteinbeziehen in den Design-Prozess] wäre für die [Schüler] ja ein Mega-Highlight!" (P05)

particular reading and writing skills should be given when children create their own games. P06, P09, and P10 also mentioned the application of Playmake in special education.

P01 could also envision the use of Playmake not only in elementary schools but also in secondary schools. There, primarily in the 5th and 6th grades. For higher grades, it depends on how complex the tasks can be and how far the difficulty level can be extended (P01 - P03). Potential applications for Playmake in secondary school could be support for addressing deficiencies in fundamental skills for struggling students (P01) or for enhancing learning in history or foreign language subjects (P10).

4.3.8 Playmake: Requirements and Feature Requests

During the interviews, we aimed to learn from the teachers about the requirements for the system to be suitable for classroom use. Additionally, we wanted to harness their creativity and explore what special features would make Playmake even more appealing to them. The results are as follows:

Playmake should...

- come with templates and pre-made games
- have appropriate game board dimensions
- provide differentiated, unambiguous feedback
- give the option to personalize feedback
- incorporate the device display
- analyze student performance and report the results to the teacher
- allow for interconnectivity of devices
- incorporate AI features
- provide offline capability
- be made of affordable, durable, and lightweight materials
- allow for do-it-yourself (DIY) construction
- provide extensive device compatibility, supporting both smartphones and tablets

Templates and pre-made games. Blank cards and printing templates for Playmake would simplify the game creation process (P01, P07, P09). In addition to the option of custom game development, having pre-made games included with Playmake would be beneficial. This would save time and effort (P02, P06, P07, P10) and help users recognize the potential capabilities of Playmake, enabling them to implement their ideas (P01, P08, P10). Furthermore, pre-made game sets could contribute to a more successful product launch by lowering barriers to try it out, and teachers would immediately see a clear connection and added value for their teaching (P03). For applications intended for classroom use, providing a comprehensive guide and overview of the functionalities (P08) and concrete examples and field reports is a best practice (P03, P10).

Difficulty and Game board dimensions Primarily for use in secondary schools, the games should not be too easy, and Playmake's game creation should allow for complex tasks (P01 - P04). P02 suggested that a larger game board would help increase the complexity of the games. Regarding the format, P04 recommended using the shape of a DIN A4 sheet, as it is well-suited for conducting thought processes.

Differentiated and unambiguous feedback. The feedback from the device should be as differentiated as possible, taking into account intermediate steps and providing hints at various levels, ranging from simple tips to guiding towards the solution (P01, P10). This enhances the learning effect (P01) and avoids frustration by giving students the opportunity to improve (P07) by enabling them to understand how they can enhance their performance (P08, P10). This would allow for independent use by children (P08). P05 suggested that there should be the option to provide additional information about individual elements in case students want more details. When including the students in the creation process, feedback options should be kept simple (P05), clear and unambiguous (P07).

Personalized feedback. Furthermore, it was mentioned that it would be advantageous if the audio feedback could be personalized to match the students' interests (P01, P09). For example, using animal sounds for a young target group (P01) or cool sound effects like applause from an audience could enhance motivation (P09). Also, adapting the language of a game to the age group is an important factor, as traditional games used in special education often come from the elementary school level and can be too childish for teenagers going through puberty (P09).

Incorporation of the display. As mentioned in Section 4.3.6 on potential application possibilities, P02 expressed concerns about audio feedback and the resulting level of noise in the classroom. The suggestion arose to use the smartphone screen in addition to audio feedback to have the option to reduce or eliminate sounds when necessary (P02). Furthermore, the screen could guide through the steps of a game (P03), visualize the order of play for multiple players (P02), and display scores (P02, P03). P04 and P09 also find linking auditory information with visual elements beneficial.

Analysis and reports on student performance. Another popular feature idea was to connect Playmake with a diagnostic tool for teachers, which evaluates the games and provides individual feedback on the status of each student, including which tasks were easy or difficult (P01, P03, P09). However, it is essential to note that no personal information should be stored to ensure data privacy (P01).

Interconnectivity, artificial intelligence and offline capability. Other feature requests included connecting the boxes with each other to incorporate the progress of other students into the game (P03), which could also be displayed at the classroom wall using a projector (P02), as well as integrating a conversational AI (P04). Furthermore, the application should work offline, as the Wi-Fi connection in the school environment is not reliable (P02).

Usage of affordable, durable, and lightweight materials. We not only received feedback on the functionalities but also regarding the construction properties. P07 pointed out that the system should not be too expensive because the schools' budget is limited. To save further costs besides using already existing technology, we could publish a DIY construction manual that allows teachers to build the Playmake case themselves (P03). The material should be selected to ensure the system's durability and resistance to damage, even when handled by children (P07, P10). Additionally, the cases should not be too large or heavy so they can be stored in the school and easily transported between classrooms (P06, P07). This also involves considering how materials for different games are stored and organized to prevent them from getting mixed up (P07).

Extensive device compatibility. The majority of participants recommended considering that Apple iPads should be the preferred technical device for development, as they are well-established in schools (P03, P04, P06 - P10) and provide a familiar user experience (P10). P06 speculated that there might be more opportunities to use smartphones in secondary schools than in primary schools, where few students own a smartphone, and using teachers' private devices is problematic (P06, P09). P01 and P02 confirmed this speculation, as their students always have functioning smartphones with them. P02 would, therefore, prefer using smartphones over organizing iPad suitcases, which involves more effort. P10 recommends supporting both tablets and smartphones.

Overall, Playmake should be technically reliable (P07) and user-friendly (P06, P07, P10) with a manageable learning curve (P10). Visuals and text should be easily discernible (P07), and created games should have a save feature (P05). Feedback should be provided promptly without annoying delays (P02, P10).

4.3.9 Playmake: General Feedback

In addition to specific game or application ideas, requirements, and feature requests, we also received more general feedback on the concept. This feedback is summarized below.

P02 praised the idea of using existing hardware, thus being environmentally friendly by saving resources. The board game-like nature and the direct manipulation of physical objects give the concept a unique quality and multidimensionality compared to a conventional tablet application (P02, P10). The tactile interaction may be easier for young students than a purely digital solution (P07). For example, in the early stages of learning, haptic aids like using bead chains can support understanding number spaces (P03). Haptic elements also assist certain learning styles (P06, P11) and students who struggle with learning (P06). P08 stated that providing audio aligns with the preference of young students to prefer hearing instructions rather than reading.

Another positive aspect highlighted by the participants is the openness of the concept, which makes it applicable to all subject areas, and the use of different materials (P03, P05, P09) as well as the possibility to create custom games (P01, P03, P05). All active teachers and the university student (P01 - P03, P05 - P10) have reported that they have already prepared custom games for their classes. One reason for this is the lack of funding for other options (P09). Another reason is that existing solutions rarely match the individual needs of students perfectly (P06, P07, P09, P10), including elements such as incorporating characters from the used textbooks (P06), the correct target vocabulary (P06, P09), and suitable types of tasks (P06).

While there is a willingness to create their own materials, this also comes with a significant increase in time and effort. Some of our participants (P02, P03, P06, P07) expressed concerns about how much time and work creating games for Playmake could involve. P07 noted that there are already many reasonable existing solutions for various scenarios and that creating games in multiple versions would be necessary for use in class. P06 pointed out the relatively high amount of work required to develop the game compared to the actual time it would be used. P02 and P03 suspected that most of the work would involve inventorying game elements, such as labeling, importing, and configuring codes. Regarding the nature of the codes attached to the game elements, they should not allow for apparent conclusions about the elements' affiliation, as this could be exploited by the students (P06).

In conclusion, the openness of the concept, allowing for the creation of a diversity of games, and the board game-like nature and tactile interaction are well received. The game creation process should be as effortlessly as possible to integrate into teachers' daily routines. A focus on cost-effectiveness, durability, and user-friendliness will guide the further development of our prototype, and compatibility with the widely used Apple iPads is a key consideration.

Development Process

The starting point of our software was the native Android app running on a Google Pixel 6 smartphone, described in Section 3.2. We re-engineered the entire app during this work and introduced game creation functionalities. The interview results had significant implications for our approach to identifying game elements. Through optimizing this process, we also identified opportunities to enhance the overall analysis of the playing field. Furthermore, we transitioned away from the native solution and opted for a cross-platform approach to ensure compatibility with a wide range of devices, particularly Apple iPads.

5.1 Tagging Game Elements

To use the camera image to analyze the game board, game elements must be made identifiable. We have pursued several approaches for tagging elements, which are described in detail below.

Text and Numerical Codes. We employed Google's ML Kit's Text Recognition API [43] in the original application to identify game elements (compare Section 3.2). This approach required a predefined record of known words to compensate for recognition errors using the Levenshtein distance. The text on the elements reflected their meaning. P06 noted that players could exploit the text on the bottom of the game elements to deduce solutions. As an alternative, we utilized numerical codes for marking game elements. However, digits were often misinterpreted as letters, making it impossible to decipher the actual code. While the ML Kit exhibited high reliability under good image quality conditions, we needed another solution for our specific purposes.

Geometric Shape-based Codes. Due to the demanding lighting situation within the box and the resulting limited image quality, we needed codes based on easily distinguishable elements. Consequently, we opted to generate custom codes using combinations of geometric shapes (triangle, circle, and square). Each code consists of six forms, with at least one triangle, reducing the number of possible codes from 729 to 665. We leveraged the tip of the triangle to determine the code's orientation and the order of the elements. To expand the pool of potential codes, we attempted to work with the colors red, green, and blue. However, we encountered challenges in reliably distinguishing these colors under low-light conditions. To recognize the geometric shapes, we employed edge detection methods that examine adjacent pixels for sudden changes in pixel intensity, characterizing edges. We used OpenCV [124], an open-source computer vision and machine learning library renowned for its optimized algorithms across various applications to detect our codes. OpenCV offers support for multiple programming languages and platforms. As our native app was developed in Java, we integrated the OpenCV Java library into our project at this stage. Additional interfaces are available for C++, Python, and MATLAB. While one can distinguish perfect shapes based on the number of corners (three corners for a triangle, four for a square, and otherwise a circle), the contours extracted from the photographs did not allow such straightforward identification. Therefore, we differentiated the shapes based on the number of points in the outline and the centroid, representing the object's center of gravity. Shapes with more than 16 points were interpreted as circles. Shapes with the centroid above or below the center were interpreted as triangles and the rest as squares. Each shape was assigned a corresponding number to generate a code that is easy to read and store (triangle = 3, circle = 0, square = 4). An example is illustrated in Figure 5.1.

Although this solution generally worked reliably, there was some vulnerability, particularly in areas distant from the camera. The imprecise focus in these regions caused the corners of squares to blur, making them challenging to distinguish from circles. Precise detection of the game elements is essential for a smooth and frustration-free gaming experience. Reducing the size of the playing area was not a feasible option, as participants P02 and P04 desired a specific size to enable the implementation of more complex games. Consequently, we revisited the search for an alternative method for tagging our elements.

April Tags. In our preliminary work, we had previously assessed the suitability of QR and barcodes, see Section 3.2. However, the inadequate image quality blurred the fine details of these codes. Nevertheless, we decided to give fiducial markers a second chance, as they are designed for quick and precise recognition. We opted for AprilTags due to the work by Basiratzadeh et al. [17], who compared various types of fiducial markers in their research and found that AprilTags delivered the best results for their smartphone-based measurements. AprilTag [16] is a versatile visual fiducial system for multiple tasks, including augmented reality, robotics, and camera calibration. It enables to obtain precise 3D position and orientation data from printable targets. The library is implemented in C, has no external dependencies, and is well-suited for real-time applications, even on cell phone-grade processors. It offers different code families tailored to various use cases and the ability to generate custom code families. We selected the tag36h11 family, which comprises 587 different codes. Images of all generated AprilTag 3 families are available in a Git repository [15] for reuse. The repository also provides a Python script for converting PNG files into scalable SVGs. For our application, we scaled the tags to 13x13mm. We retained a white border to enhance recognizability, resulting in an overall tag size of 16x16mm, perfectly matching the width of BrailleBuddy's narrow letter cards [62]. With appropriate lighting inside the box, elaborated in Chapter 6, the tags are recognized flawlessly, providing an efficient solution for our purpose.

Figure 5.1 The image illustrates the evolution of our game element tagging approach throughout the development process. Initially, players could exploit the codes presented in textual form (left) to deduce solutions. In response, we explored alternative solutions: we began generating custom codes using combinations of geometric shapes (middle) and utilized edge detection for analysis. Ultimately, the most reliable approach proved to be using AprilTags (right).

5.2 Playing Field Analysis

The analysis of the gaming field comprises several consecutive steps, including identifying the field's boundaries, image rectification to correct the mirror angle, recognition of playing cards, and analysis of their codes. To streamline the last two steps, we integrated AprilTags.

For the continuous monitoring of the playing field, we primarily considered two options: utilizing the image stream provided by the camera or capturing a photograph at regular intervals. When employing the image stream on the Google Pixel 6, we received images in the YUV420 format. While the ML Kit could handle the stream seamlessly, we needed to convert the image to RGB format for further processing. Unfortunately, the conversion process, which involved iterating over every pixel of the image, proved insufficiently performant. Furthermore, the image quality of the stream was reduced compared to the approach of taking photographs. Consequently, we opted for the latter method, which involved capturing an image and awaiting the analysis results before taking the next shot.

In an initial attempt, we employed edge detection with OpenCV to locate the borders of the playing area. To enhance the reliability of gaming field recognition, considering changing backgrounds are visible through the transparent surface, we stored a reference image of the distorted gaming field shape in grayscale in the app's resource folder. We generated a reference contour from this image that our program could use to compare with the identified edges from the photograph. Before utilizing AprilTags, we followed a similar approach with the playing cards. We enclosed the geometric shape codes within rectangles to differentiate the codes from other clutter contours. The position of the playing cards could then be matched with a previously captured gaming field layout, facilitating rule evaluation.

While edge detection generally worked, and is used in our application to initially scan user created game layouts, it had yet to reach a level sufficient for recognizing the gaming field from within the box. Given our previous success with AprilTags on our gaming elements, we decided to use them for defining the gaming field borders. Considering the challenging angle introduced by the mirror, we employed larger 24x24mm sized tags for the edges to improve their recognizability. The AprilTag detection automatically gave us the x and y positions of the tags' corner points. By affixing tags to the corners of the playing field, we could directly utilize these points to define the borders, as illustrated in the right picture in Figure 5.2.

Figure 5.2 The left image shows the initial attempt to use edge detection to find the game layout borders and the game element codes. To simplify the process, we utilized AprilTags to achieve both goals, as depicted in the right image.

5.3 From Native App to Cross-Platform Solution

Our interviews show that Apple iPads were schools' most widely used devices, so our application needed to support them, which is not the case with our native Android application. Considering the potential use of students' private smartphones, we aimed to encompass a wide range of devices. Consequently, we re-implement the app using Flutter [41] and Dart [42], Flutter's primary programming language. Flutter is an open-source framework developed by Google, designed for creating multi-platform applications (mobile, web, desktop, and embedded devices) with a consistent user experience across various platforms, all from a single codebase [41]. Additionally, we integrated C and C++ code for OpenCV and AprilTag detection.

Before transitioning to Flutter, we utilized the CameraX API [26] for camera access. This functionality was replaced with the Flutter camera plugin [31] from pub.dev, the official package manager for Flutter and Dart packages. Unfortunately, at the time of this work, no package was available for integrating powerful edge detection into a Flutter application [37]. Consequently, we followed Gerken's example of accessing OpenCV methods from a Flutter app by including native implementations as a local plugin [36, 37]. Therefore, we re-implemented our edge detection and rectification features in C++.

Furthermore, we integrated code from the AprilTag's Git repository [14] into our local plugin to leverage their detection system. Their original implementation employed multiple threads to expedite the detection process. This approach conflicted with Flutter's thread management, resulting in app crashes, so we adapted the code to operate solely on the main thread.

We give a schematic overview of the local plugin in Figure 5.3. The resulting application and its features are described in Chapter 6, which outlines the final state of the prototype.

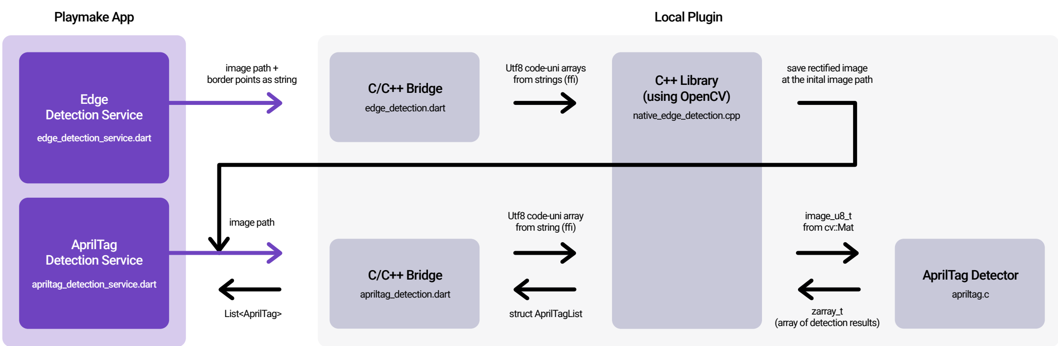

Figure 5.3 The graphic illustrates Playmake's analysis process of the playing field. The Playmake app passes the path of the taken picture to a bridge that converts the string into a C-compatible format. Utilizing OpenCV methods in our C++ library, we read the image file, rectify it by creating a perspective matrix from the positional information given by four AprilTags attached to the borders of the playing field, and update the file at the given path. The file structure is inspired by Gerken's simple-edge-detection plugin [36, 37]. The path is then forwarded from our app's AprilTag service down to the C implementation of the AprilTag detector. The detection results are formatted and returned to the service, where the AptilTag positions are passed to the gameplay activity for further processing.

Playmake Prototype

The following sections introduce the current state of the Playmake prototype, an application that blends traditional board game-like elements with automated feedback. The associated app comes with basic features to create, edit, and play custom educational games. Leveraging computer vision, Playmake provides a versatile game development and gameplay platform. We describe the prototype's components, external features, as well as the game creation and gameplay processes, which serve as a foundation for further research and development.

6.1 Components and Exterior Appearance

Our interview findings emphasize the high demand for integrating visual information and feedback using the device display. To achieve this, we had to rethink the positioning of the smartphone in our setup: we placed it on top of the box instead of inside to make the display visible to the user, as shown in Figure 6.1.

The best results for capturing the playing area were achieved using the rear camera and two mirrors, as illustrated in Figure 6.2. Our participants advised us to choose materials that are robust enough for use by children and lightweight for easy transportation. Therefore, we experimented with reflective film applied to cardboard as a substitute for heavier, potentially fragile mirrors. However, this solution was susceptible to dents, which complicated tag detection. Consequently, we kept regular mirrors. We consciously decided not to use the wide-angle camera of the Google Pixel 6, as only some of our target devices are equipped with such.

The dimensions of the playing field captured with the described setup are 16x21cm. We chose a tempered glass tablet screen protector as a cost-effective and lightweight solution for the transparent material of the playing area. Around the playing surface, the height of the box is only 10cm to allow comfortable playing when placed on a table.

By removing the smartphone from the inside of the box, we can no longer utilize the display's light to illuminate the playing area. We attempted to use the camera flash as an alternative, but the smartphone overheated within a few minutes. While this may be a device-specific issue, we wanted to avoid damaging the devices or posing a safety risk during prolonged use. Without internal illumination, the entire system highly depends on external lighting. To ensure the reliability of our prototype in various environments, we integrated a small, battery-powered bicycle lamp to control the light conditions. We designed a joist for this lamp on the long side of the case, allowing users to easily mount it or remove it for recharging.

Figure 6.1 The Playmake prototype consists of a cardboard box with a see-through playing field embedded in the lid. Exchangable custom game layouts with slots for designated game elements can be placed on the transparent layer. The setup is suitable for smartphones and tablets.

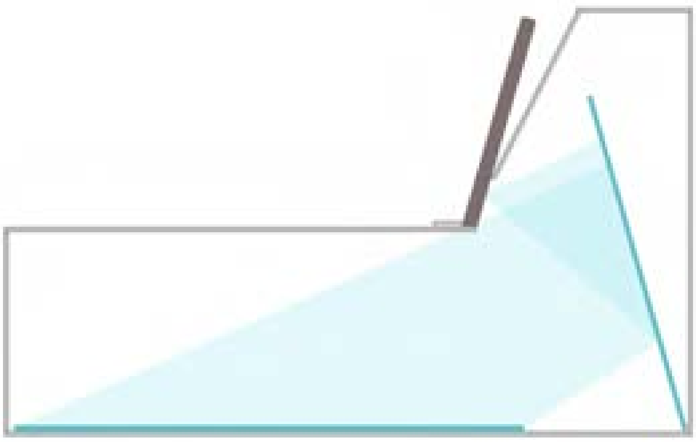

Figure 6.2 While the device's display faces the user, the rear camera observes the gameplay through two mirrors inside the box. A slanted mirror directs the camera's view onto the reflection of the playing field on a larger mirror positioned beneath the transparent surface.

6.2 Game Creation Activity

After starting the companion application for Playmake, the user can select an existing game from a list of all stored games or create a new game by clicking the floating action button in the lower right corner. The user is guided through the game creation process in four steps. All information the user provides is stored in an SQLite database. Figure 6.3 shows screenshots of the game creation activity.

In the first step, the user can define a name for the game and optionally describe it in more detail. The second step is to determine the playing area's layout. Therefore, a new layout can be created by crafting a custom design from cardboard or comparable material and scanning it with the app using the camera button below the layout gallery. The slots in the layout design can have any shape and are not limited to squares. With OpenCV's edge detection, the app recognizes the border of the layout and the slots for game elements. The recognized contours are then rectified using a perspective matrix. The resulting contours are stored as a string in the database, and an illustration of the rectified layout is stored with the dimensions of 996x1307 pixels. This image is then available for selection in the layout gallery. Alternatively, the app lets users choose between three predefined layouts and all prior captured custom layouts in the gallery.

In the third step, the user can define relations between the layout slots. These relations define the rules of the game. The editor displays the layout illustration. By selecting multiple slots, the user can either group slots or assign a relation between two slots or a slot and a group. Possible relations include $=, \neq, >, \geq, < \textit{and} \leq$. After selecting a relation, the user has the option to create reactions in the form of audio, image, a combination of both, or video that are played or displayed when a relation is fulfilled or not.

The last step is to create an inventory of game elements. Therefore, the code of each game element in the form of an AprilTag is scanned with the camera. The user can then assign a value to this tag. This value is used during gameplay to validate the prior recorded relations. Furthermore, the user can define reactions triggered when the element is placed or removed. The game creation process is complete when all tags relevant to the user's game are processed. The game can be edited at any time in the future to, for instance, include more tags.

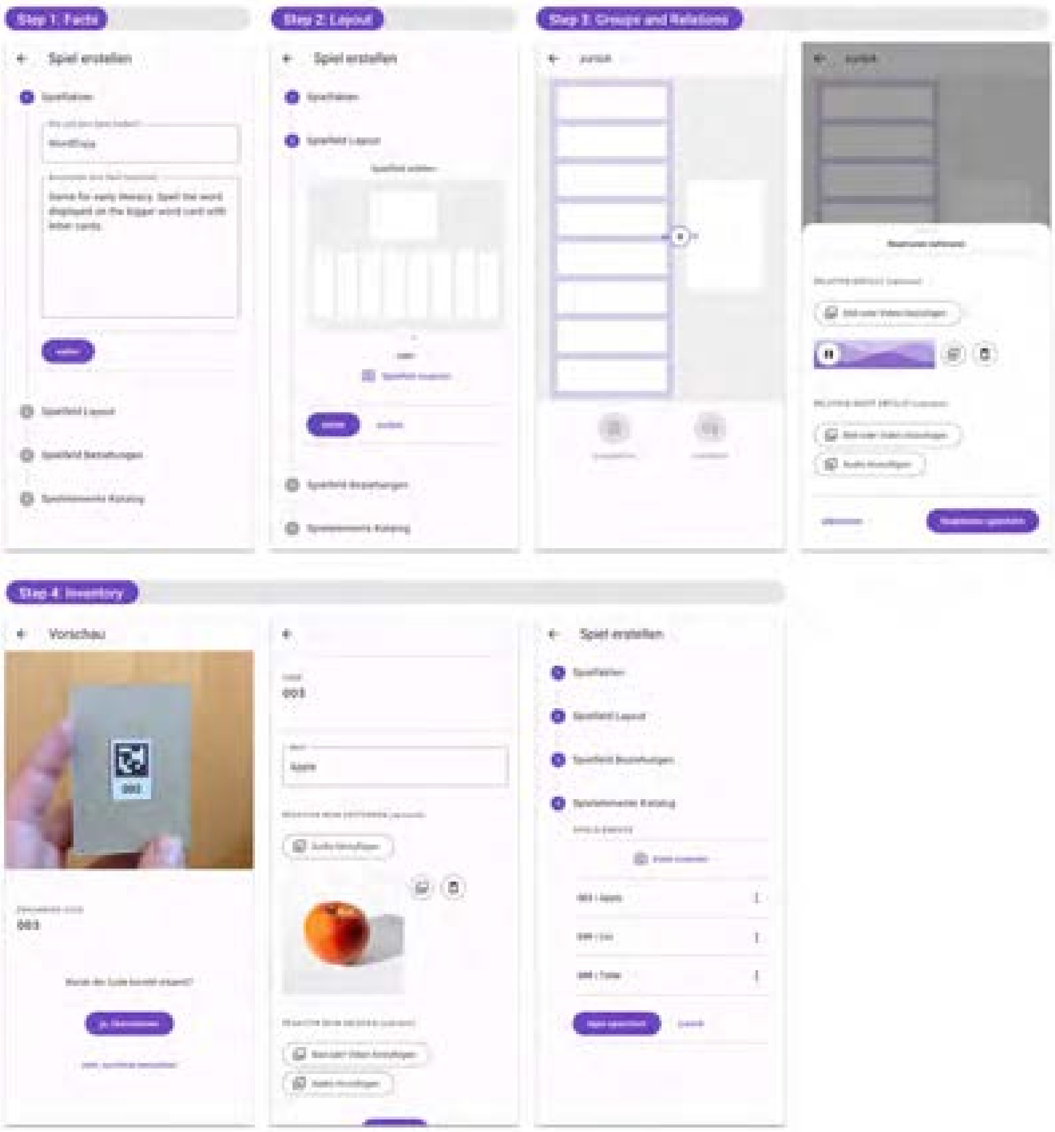

Figure 6.3 The seven screenshots depict excerpts from the game creation process. The first two screens illustrate how game facts and the playing field structure are defined. The layout is either chosen from the gallery or scanned with the camera. Subsequently, the layout's fields can be optionally grouped, and relationships between these fields are established, as depicted in the following two screenshots. The relations define the game's objectives. The second row of images displays excerpts from the inventory creation process. AprilTags are captured and assigned to values. Reactions in the form of audio, image, or video files are defined for game elements, which are played or displayed during the gameplay.

6.3 Gameplay Activity

On the entry screen, the user can select a game from the list for editing, deleting, or starting the game. When the gameplay is initiated, all relevant data for the selected game is loaded from the database, including layout contours, relations, reactions and the game element inventory. The display provides a camera preview to assist the user in correctly positioning the smartphone or tablet to capture all four border tags of the playing area.

Subsequently, the user is required to capture an image, which is utilized to detect and temporarily store the x and y positions of the corners. These positions are then employed throughout the gameplay to crop and rectify the playing area, simplifying the identification and assignment of game elements. The corrected image is resized to the exact dimensions of the predefined game layout during the rectification process. This allows direct mapping of the positions of elements to the slots of the underlying layout. Once the user confirms the accuracy of the field recognition, the game loop is started. Two googly eyes appear on the screen, observing the playing field. Meanwhile, the camera continuously captures images to monitor the status of the playing area. Each image is processed using the predetermined corner points and is then examined for AprilTags.

When a tag is removed, or a new tag is detected, its assigned removal or placement reaction, if available, is executed. Afterward, the corresponding slot in the playing field layout is determined to evaluate the relations, which are stored within the layout (compare step 3 in Section 6.2). To assess the relations, the values of the tags on the connected slots are compared. Then, the appropriate reaction, specified by the user for success or failure, is triggered. In the absence of a visual reaction (image or video), the default response is a change in the expression of the eyes on the screen to either happy or sad, as shown in Figure 6.4.

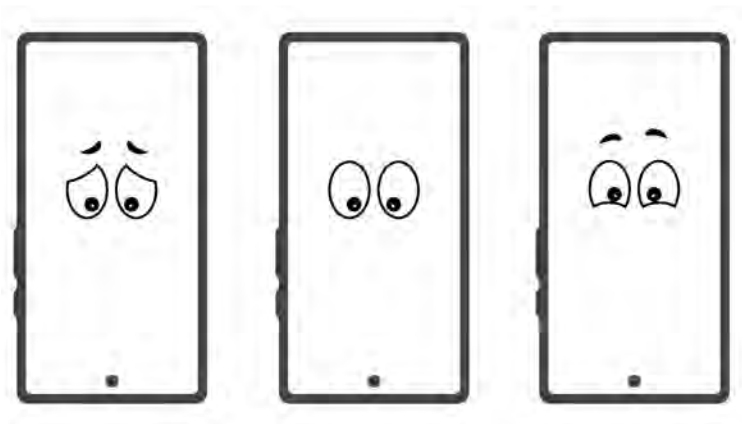

Figure 6.4 When a relation is evaluated, and the game creator has not defined a visual reaction, Playmake reacts by changing its facial expression. It monitors the game's progress with a neutral face (middle). Depending on whether a relation was fulfilled or not, the eyes change from neutral to either sad (left) or happy (right).

6.4 Proof of Concept Applications

Based on the expert interviews we designed and implemented different games to highlight our current prototype's capabilities. They include two math games: *GeoShape Puzzle*, focusing on early geometry, and *Fraction Master*, dealing with mathematical fractions, a topic that is typically taught at the beginning of secondary school. *Spell Carousel* is a game that challenges players with collaborative spelling tasks. *Autumn Adventure Puzzle* is an example of engaging students in the game creation process, while *Living History* is used as a resource to prepare history presentations based on eyewitness interviews.

GeoShape Puzzle

This game can be played either individually or in small groups. Each group has number cards, a collection of wooden geometric shapes hidden inside a bag, and a Playmake device. The materials are shown in Figure 6.5. One of the players selects a body from the bag, and the group must then discuss the object's characteristics. The object is passed among the players, who must collectively determine the number of corners, edges, and surfaces of the geometric shape. Once they believe they have found the correct solution, the object is placed on the Playmake surface, and audio feedback is provided, revealing the name of the geometric shape, e.g., cube, cylinder, cone, or pyramid.

Subsequently, the players must place number cards corresponding to the count of corners, edges, and surfaces, receiving feedback accordingly. In the event of an error, the object is returned to the bag to be discussed in another game round. If the group's answers are all correct, the object can be set aside. The game's objective is to empty the bag by correctly identifying and categorizing all the geometric shapes.

Figure 6.5 The materials for the game GeoShape Puzzle [94] include wooden geometric shapes and number cards. On the playing surface, the pyramid has been correctly matched with the number of its surfaces, edges, and corners, and Playmake responds with a happy face.

Fraction Master

Student groups are equipped with a Playmake and a hour glass. Each group is subdivided into smaller teams, each with an identical set of cards displaying mathematical fractions inside a bag. These sets are color-coded to distinguish which cards belong to each team. Additionally, there is a distinct set of fraction cards to start a game round in another bag. Figure 6.6 gives an overview of the game elements.

At the start of the game, each team draws one game round fraction from the bag. The team with the largest fraction initiates the game by placing their fraction card on the designated slot on the Playmake. The remaining drawn cards are returned to their bag. The game round's objective is to identify five fractions smaller than the game round fraction and arrange them in the correct sequence on the playing field. This may involve changing the positions of previously placed cards during the game. The player who is currently taking their turn must draw a card from their team's bag and the hour glass is started. Before time runs out, the player must decide whether to place the card on the playing field, set it aside, or place it back into the bag if unsure. Cards placed aside cannot be used in the same game round.

Playmake displays a decimal and visual representation of the fraction to provide additional assistance whenever a card is placed. If a team successfully fills all five slots in the correct order, they win the round and retain the initial fraction card. If a card is placed incorrectly, the opposing team automatically wins the round, and a new game round card is drawn. All other fraction cards are returned to the teams. The team with the most fractions collected by the end of the game, either after a designated time set by the teacher or when no cards remain in the bag, emerges as the overall winner.

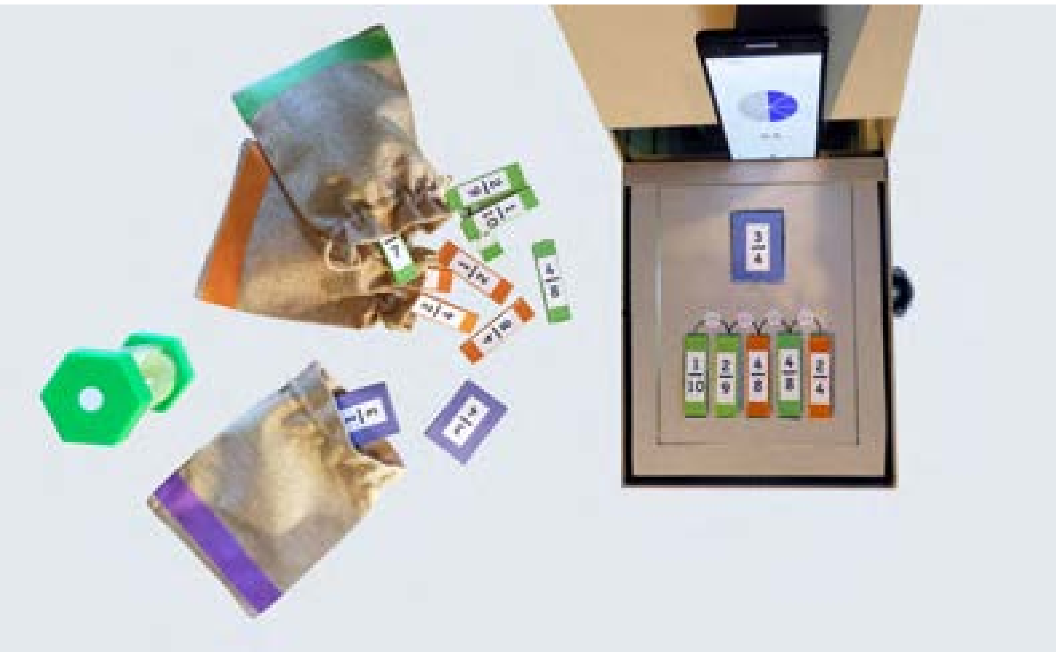

Figure 6.6 For the game Fraction Master [93], the players are assigned to two teams. One team plays with the green fraction cards, the other with the orange cards. The game's objective is to collect more purple fraction cards than the opponent team by sorting fractions.

Spell Carousel

This game can be played alone or in a small group. In addition to Playmake, you will need letter cards in a small bag, word puzzle cards, and a carousel plate attached to Playmake. The puzzle cards show an image representing a word, with dashes indicating the number of letters in the word. These cards are shuffled and placed face down in a stack. The top five cards are used to fill the seats of the carousel. One position of the carousel hovers over a visible area for Playmake's camera and the puzzle at that spot must be solved before the carousel can be spun further. The setup is depicted in Figure 6.7. The game's goal is to make a full rotation with the carousel. To achieve this goal, players need to solve word puzzles collaboratively.

In turn, players draw letters from the bag and can discuss with the group whether the drawn letter is part of the sought-after word and, if so, at which position it belongs. The letter can then be placed in one of the designated slots on Playmake, or the player can choose to pass if they believe the letter is not present in the word. Discarded letters can be put aside and returned to the bag for the next puzzle later on. When a letter is placed on Playmake, the system provides appropriate feedback, letting the player know whether their move was correct. Now, the next player can draw a letter. When a word is completely solved, the carousel on the Playmake screen turns, accompanied by happy music, and the physical carousel can be rotated to the next position.

Figure 6.7 For the game Spell Carousel [96], we have constructed a rotating cardboard disc on which cards with illustrated images are placed. The goal is to spell the associated words. After a word is solved, the carousel can be spun one position further.

Autumn Adventure Puzzle

This game serves as an example of what co-creating games for Playmake with students could look like. Part of the game creation process is an expedition to a nearby forest. The students are encouraged to collect fruits and leaves from different trees. Back in the classroom, the collected items are discussed with the entire class. For the next step, it is advisable to prepare additional resources to engage all students.

The class is divided into several groups. Each group is provided with game card templates and fruit-leaf pairs of different trees. Each student is tasked with creating game cards for a tree. The fruit should be attached to one game card, while the other card should feature a drawing of the tree's leaves, focusing on its distinctive characteristics. The children can reference the actual leaf and other provided materials. The final task is to write a short note about their favorite information regarding the tree and its fruit. Therefore, they can use acquired knowledge from the expedition and group discussion or research child-friendly websites or other age-appropriate sources.

For the next lesson, the teacher prepares the Playmake app using the resources created by the students. Figure 6.8 gives an example of how such a game could look like. The children can then play their own games on a Playmake device, recalling the learning contents. The game layout consists of two slots. The leaf cards are placed face-down on the table, similar to a memory game. One of the fruit cards is placed in one of the slots, and the information about the tree, selected by the student who worked on that tree, is played as feedback.

The students take turns flipping over leaf cards. When they believe they have uncovered the matching leaf for the fruit on the game surface, they place it in the other slot for verification. If the combination is correct, the current player keeps the card. The leaf card is returned to the table if the combination is incorrect. The goal is to collect more leaf-fruit combinations than the other players.

While this game is designed to be created in the fall, when trees typically drop their fruits, alternative versions can be implemented in different seasons, such as matching leaves to tree names.

Figure 6.8 The left image depicts Playmake's setup for the game Autumn Adventure Puzzle [92]. This memory-like game aims to find matching pairs of tree fruits and leaves. When a fruit is placed, the animation of a friendly bear gives additional information, as shown on the right.

Living History

In this educational game, students are tasked with conducting interviews with World War II eyewitnesses and summarizing their insights for the class. The objective is not only to extract factual information but also to reflect on the emotional impact of these conversations. The class is divided into smaller groups, each assigned a Playmake and a set of pre-arranged questions. For each Playmake, reactions from a different eyewitness are provided, including Holocaust survivors and Wehrmacht soldiers. Within their respective groups, students engage in discussions to determine the sequence and selection of questions to be posed. When a question is placed on the Playmake surface, it triggers a video recording featuring the corresponding eyewitness's response, as visualized in Figure6.9.

Figure 6.9 A potential interview partner for Living History [95] is Else Baker, who was deported to Auschwitz at the age of eight. Through the efforts of her adoptive father, she was rescued. Various question cards can trigger response videos. The original interview was conducted by the German newspaper FAZ [30].

Discussion and Future Work

We created Playmake, a fundamental prototype of a compact, multi-purpose TUI accompanied by a cross-platform mobile application. This integrated system empowers teachers, as the experts in their respective subject areas, to author educational tangible games. The prototype's development is based on interviews with ten experts from different educational fields, namely primary and secondary school education and special education. Furthermore, we discussed the concept with with students of an 8th-grade class. We gained comprehensive insights and perspectives on the use of games and technology in the classroom, and used these findings to evaluate the concept's suitability to complement classroom education and gather requirements for such a TUI.

The results show that including games in teaching is a common practice to enhance the learning experience. Leveraging the playful aspects of gaming in an educational context can be instrumental in promoting student engagement and social skills while fostering meaningful learning interactions. The games used range from traditional parlor games to various digital learning games and apps. While digital solutions allow to adapt tasks more precisely to the individual needs of different students, tactile interaction highly benefits specific types of learners. Playmake's board game-like nature with direct physical manipulation in combination with personalized feedback was well received by our participants.

Utilizing existing hardware promotes familiarity and reduces costs, which is particularly important given budget constraints in many schools. So, it is essential to support devices already available in the classroom, including students' private mobile devices, and especially Apple iPads. While the quality of technical equipment varies across schools, Apple iPads are commonly used. Since our app is implemented with the cross-platform solution Flutter, it can be used on both smartphones and tablets with different operating systems. Cost-effectiveness is not limited to technology but also extends to other materials used. Additionally, providing do-it-yourself (DIY) instructions can lower acquisition costs.

Playmake as a product should offer a variety of pre-made educational games for different subjects and grade levels. These games can serve as templates and examples for teachers and students to create and share custom content. For this purpose, collaboration with educational publishers should be considered to meet different curricula requirements and provide teachers with direct added value for their teaching. Furthermore, cooperation with seminars for prospective teachers during their teaching internship to develop game ideas could lead to beneficial outcomes (P06). This way, we can ensure that the games and activities created with Playmake have real-world relevance and engage students in meaningful learning experiences. Providing an educational guide or manual for teachers is advantageous. It should include tips on using Playmake effectively in the classroom, examples of best practices, and potential game ideas.

Teachers aim to infuse creativity into their lessons to cater to their students' specific needs. Preparing custom games is a regular part of preparing teaching lessons, as pre-existing solutions rarely match the students' individual needs ideally. That is why the educators positively highlighted the versatility of Playmake and the possibility of creating custom games. The concept's flexibility makes it applicable across various subject areas and adaptable to suit individual requirements. Furthermore, encouraging active student involvement in the game creation process holds significant promise: they immerse themselves deeply in the educational material, and the sense of accomplishment in developing their own game can be a highly motivating factor. Possible game ideas for Playmake ranged from math, history, biology, literacy, foreign languages, general knowledge, and music, proving the concept's versatility.

While there is a willingness among the participants to create their own materials, they had concerns about the effort involved in creating games for Playmake. To achieve a straightforward game creation process and to lower the efforts involved, Playmake should provide teachers and students with some helpful resources, which include templates, pre-made assets, and the option to collaborate on game creation by sharing games. In the context of game creation, the user interface that navigates through the steps of the creation process plays a significant role. It should be user-friendly for students and teachers and have a manageable learning curve. Pre-made games could make the process more transparent and demonstrate the potential of Playmake's capabilities.

While audio feedback can be engaging, ensuring it does not disrupt the classroom environment is essential. Using smartphones or tablets allows for adjusting volume or headphone usage out of the box. Integrating visual cues on the device's display, implemented through image and video reactions, provides more versatile feedback forms. Incorporating visual game instructions and explanations or tips in future work will leverage the potential of the screen further. While our proof of concept games already demonstrate the versatility of the prototype, features like high scores, lives or timers, and integral multiplayer modes would invite competitive elements and allow for more complex games with less constructional effort than in our example games. Playmake should additionally offer evaluation tools that will enable teachers to track individual student progress and the effectiveness of the games. This can aid in tailoring their lessons to the needs of their students. Given the sensitivity of handling student's data, it is crucial to prioritize data privacy and security. Playmake does not store any personal information.

Seven out of ten participants can imagine using Playmake in the classroom, especially in open teaching sessions or for individual support. This indicates that Playmake is suitable for integration into educational settings. While there was consent for usage in primary school, the potential target age group can range from kindergarten to secondary school. An essential step for further development is testing the existing interface's usability and effectiveness, followed by multiple iterations for continuous optimization. Evaluating the prototype in different school settings is necessary to decide whether it is flexible enough to adapt to different age groups and learning levels and define additional features to achieve this goal. The testing should include the creation of new games as well as the usage of these games in classroom environments and involve teachers and students alike since both are potential users of Playmake.

Conclusion

By consulting experts from various educational sectors, we have gathered comprehensive insights into the use of games and technology in the classroom and identified multiple requirements for developing a multi-purpose TUI for creating and playing custom educational games. It should provide extensive device compatibility, differentiated and personalized audio-visual feedback, and be made of affordable, durable materials that allow for DIY construction. We integrated the most essential features into our first functional prototype of Playmake and its mobile, cross-platform application. Multiple example applications demonstrate the feasibility of our technical setup.

Despite literature on TUIs for learning suggests a greater emphasis on the teacher's perspective, only a few authors have focused on users authoring custom applications. The design of our integrated system fills this research gap by empowering teachers and students to create custom tangible applications. Enabling teachers to develop or customize games ensures they align closely with the curriculum and challenge students appropriately. Automated feedback helps students to engage with learning content in a playful and self-directed manner. The mix of digital and analog materials provides several ways to engage students in the game-creation process from a young age.

Overall, our interview findings confirm the potential and relevance of the Playmake concept in educational settings, with a focus on primary school and special education. The resulting prototype lays the foundation for further user studies and development, enhancing interactive and personalized education.

Bibliography

References

1 Grundschullotchen - schule, material und mehr. https://www.grundschullottchen.de/. Accessed: 19 October 2023.

2 reactivision 1.5.1 - a toolkit for tangible multi-touch surfaces. https://reactivision.sourceforge.net/. Accessed: 17 October 2023.

3 Marian Adusei and Doyoung Lee. 'clicks' appcessory for visually impaired children. *Conference on Human Factors in Computing Systems - Proceedings*, Part F127655:19–25, 5 2017. URL: http://dx.doi.org/10.1145/3027063.3049275, doi:10.1145/3027063.3049275.

4 Wafa Almukadi and Guy A. Boy. Enhancing collaboration and facilitating children's learning using tuis: A human-centered design approach. In Panayiotis Zaphiris and Andri Ioannou, editors, *Learning and Collaboration Technologies*, pages 105–114, Cham, 2016. Springer International Publishing. doi:10.1007/978-3-319-39483-1_10.

5 Rainer Ammel. Mathegym - die lernplattform für gymnasium und realschule. online Übungen für mathe + latein + englisch + chemie + physik. Website. Retrieved October 15, 2023 from https://mathegym.de/.

6 Margherita Andrao, Alessandro Cappelletti, Giuseppe Desolda, Francesco Greco, Barabara Treccani, and Massimo Zancanaro. Smarter than before: Empowering teachers to program a modular iot educational device. In *Workshops, Work in Progress, Demos and Doctoral Consortium at IS-EUD*, 2023.

7 Margherita Andrao, Giuseppe Desolda, Francesco Greco, Ren Manfredi, Barbara Treccani, and Massimo Zancanaro. Smarter: An iot learning game to teach math. In *Proceedings of the 2022 International Conference on Advanced Visual Interfaces*, AVI 2022, New York, NY, USA, 2022. Association for Computing Machinery. doi:10.1145/3531073.3534467.

8 J. Andrés Sandoval-Bringas, Mónica A. Carreño-León, Israel Durán Encinas, Alejandro Leyva Carrillo, Italia Estrada Cota, and Rafael Cosio Castro. Using tangible interfaces for teaching braille. In *2020 3rd International Conference of Inclusive Technology and Education (CONTIE)*, pages 128–132, 2020. doi:10.1109/CONTIE51334.2020.00032.

9 Alissa N. Antle, Min Fan, and Emily S. Cramer. Phonoblocks: A tangible system for supporting dyslexic children learning to read. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, page 533–538, New York, NY, USA, 2015. Association for Computing Machinery. doi:10.1145/2677199.2687897.

10 Alissa N Antle and Alyssa F Wise. Getting down to details: Using theories of cognition and learning to inform tangible user interface design. *Interacting with Computers*, 25(1):1–20, 2013.

11 Anton. Anton - lerne einfach mit spaß für die schule! https://anton.app/de/. Accessed: 15 October 2023.

12 APH. Pop-a-cell. https://www.aph.org/product/pop-a-cell-4-pack/, 2022. Accessed: 15 October 2023.

13 APH. Swing cell compact. https://www.aph.org/product/swing-cell-compact/, 2022. Accessed: 15 October 2023.

14 AprilRobotics. apriltag. https://github.com/AprilRobotics/apriltag. Accessed: 28 October 2023.

15 AprilRobotics. apriltag-imgs. https://github.com/AprilRobotics/apriltag-imgs. Accessed: 28 October 2023.

16 APRIL Robotics Laboratory at the University of Michigan. Apriltag. https://april.eecs.umich.edu/software/apriltag. Accessed: 28 October 2023.

17 Shahin Basiratzadeh, Edward Lemaire, Masoud Dorrikhteh, and Natalie Baddour. Fiducial marker approach for biomechanical smartphone-based measurements. pages 1–4, 04 2019. doi:10.1109/BIOSMART.2019.8734237.

18 Katrin Becker. Digital game-based learning: learning with games. *Choosing and Using Digital Games in the Classroom: A Practical Guide*, pages 25–61, 2017.

19 Katrin Becker. What is it about games? *Choosing and Using Digital Games in the Classroom: A Practical Guide*, pages 3–23, 2017.

20 Kerstin Breuer. Materialwiese - material und tipps für die grundschule. https://materialwiese.de/. Accessed: 19 October 2023.

21 Carina Busch. Grundschultante - material, ideen und tipps aus dem grundschulleben. https://diegrundschultante.blogspot.com/. Accessed: 19 October 2023.

22 Roger Caillois. *Man, play, and games*. University of Illinois press, 2001.

23 Marleny Luque Carbajal and M. Cecília C. Baranauskas. Analyzing the socioenactive dimensions of creative learning environments with preschool children. In *Proceedings of the 19th Brazilian Symposium on Human Factors in Computing Systems*, IHC '20, New York, NY, USA, 2020. Association for Computing Machinery. doi:10.1145/3424953.3426510.

24 M Csikszentmihalyi. Flow. the psychology of optimal experience. new york (harperperennial) 1990. 1990.

25 Giuseppe Desolda, Francesco Greco, Francisco Guarnieri, Nicole Mariz, and Massimo Zancanaro. Sensation: an authoring tool to support event–state paradigm in end-user development. In *Human-Computer Interaction–INTERACT 2021: 18th IFIP TC 13 International Conference, Bari, Italy, August 30–September 3, 2021, Proceedings, Part II 18*, pages 373–382. Springer, 2021.

26 Android Developers. Camerax overview, 2023. Accessed: 17 October 2023. URL: https://developer.android.com/training/camerax.

27 Dobble. Dobble classic. https://www.dobblegame.com/de/die-spiele/dobble-classic/. Accessed: 15 October 2023.

28 Linda Eckardt, Steffen Körber, Eva Johanna Becht, Alexandra Plath, Sharaf Al Falah, and Susanne Robra-Bissantz. Fuhren serious games zu lernerfolg? – ein vergleich zum frontalunterricht. 2017. doi:10.1007/978-3-658-16742-4_11.

29 Augusto Esteves, Elise van den Hoven, and Ian Oakley. Physical games or digital games? comparing support for mental projection in tangible and virtual representations of a problem-solving task. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, TEI '13, page 167–174, New York, NY, USA, 2013. Association for Computing Machinery. doi:10.1145/2460625.2460651.

30 F.A.Z. Auschwitz-Überlebende else baker über ihre zeit als kind im kz | langfassung, 2023.

31 flutter.dev. camera 0.10.5+5. https://pub.dev/packages/camera. Accessed: 28 October 2023.

32 Patric Galera Forcelini, Laura Sánchez García, and Ermelindo Paulo Breviglieri Schultz. Braille technology beyond the financial barriers: A braille literacy platform to effectively combat braille literacy crisis. In *Proceedings of the 8th International Conference on Software Development and Technologies for Enhancing Accessibility and Fighting Info-Exclusion*, DSAI 2018, page 41–46, New York, NY, USA, 2018. Association for Computing Machinery. doi:10.1145/3218585.3218590.

33 Friedrich Fröbel. Die menschenerziehung [on the education of man]. *Keilhau/Leipzig, Germany: Wienbrach*, 1826.

34 Vinitha Gadiraju, Annika Muehlbradt, and Shaun K. Kane. Brailleblocks: Computational braille toys for collaborative learning. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–12, New York, NY, USA, 2020. Association for Computing Machinery. doi:10.1145/3313831.3376295.

35 GeoGebra. Geogebra zum lernen und unterrichten mit mathematik. Website. Retrieved October 15, 2023 from `https://www.geogebra.org/?lang=de`.

36 Marc Gerken. flutter-simple-edge-detection. `https://github.com/flutter-clutter/flutter-simple-edge-detection`. Accessed: 28 October 2023.

37 Marc Gerken. Implementing edge detection in flutter. `https://www.flutterclutter.dev/flutter/tutorials/implementing-edge-detection-in-flutter/2020/1509/`. Accessed: 28 October 2023.

38 GeoGebra Team German. Augmented reality. Website. Retrieved October 18, 2023 from `https://www.geogebra.org/m/agpb7bq7`.

39 Lehrerkolleg LK GmbH. eduki - inspiration für deinen unterricht. `https://eduki.com/de`. Accessed: 19 October 2023.

40 Lehrerkolleg LK GmbH. LÜk ist das lernspiel. `https://www.westermann.de/eltern-und-schuelerinnen/grundschule/luek/`. Accessed: 19 October 2023.

41 Google. Build apps for any screen. `https://flutter.dev/`. Accessed: 28 October 2023.

42 Google. Paint your ui to life. `https://dart.dev/`. Accessed: 28 October 2023.

43 Google. Text recognition v2, 2023. Accessed: 17 October 2023. URL: `https://developers.google.com/ml-kit/vision/text-recognition/v2`.

44 H5P Group. Reate, share and reuse interactive html5 content in your browser. Website. Retrieved October 15, 2023 from `https://h5p.org/`.

45 LEGO Group. Lego braille bricks. `https://www.legobraillebricks.com/`, 2020. Accessed: 15 October 2023.

46 happymooseapps. Bitsboard. Website. Retrieved October 15, 2023 from `http://bitsboard.com/`.

47 Eva Hornecker. Beyond affordance: Tangibles' hybrid nature. TEI '12, page 175–182, New York, NY, USA, 2012. Association for Computing Machinery. `doi:10.1145/2148131.2148168`.

48 Johan Huizinga, Hans Nachod, and Andreas Flitner. *Homo ludens: vom Ursprung der Kultur im Spiel*. Rowohlt-Taschenbuch-Verlag, 2009.

49 Verein LearningApps interaktive Lernbausteine. Was ist learningapps.org? Website. Retrieved October 15, 2023 from `https://learningapps.org/impressum.php`.

50 Sara Ipatenco. Play this trending desert island game with your students! `https://www.boredteachers.com/post/desert-island`. Accessed: 18 October 2023.

51 Hiroshi Ishii. The tangible user interface and its evolution. *Communications of the ACM*, 51(6):32–36, 2008.

52 Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*, pages 234–241, 1997.

53 Axel Jacob and Frank Teuteberg. Game-based learning, serious games, business games und gamification – lernförderliche anwendungsszenarien, gewonnene erkenntnisse und handlungsempfehlungen. 2017. `doi:0.1007/978-3-658-16742-4_8`.

54 Robert JK Jacob, Audrey Girouard, Leanne M Hirshfield, Michael S Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. Reality-based interaction: a framework for post-wimp interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 201–210, 2008. `doi:https://doi.org/10.1145/1357054.1357089`.

55 Rabia Jafri. Electronic braille blocks: A tangible interface-based application for teaching braille letter recognition to very young blind children. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 8548 LNCS:551–558, 2014. URL: `https://link.springer.com/chapter/10.1007/978-3-319-08599-9_81`, `doi:10.1007/978-3-319-08599-9_81`.

56 Azusa Kadomura, Koji Tsukada, Tetsuaki Baba, and Kumiko Kushiyama. Hangul gangul: Interactive toy for hangul learning. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, TEI '12, page 323–324, New York, NY, USA, 2012. Association for Computing Machinery. `doi:10.1145/2148131.2148203`.

57 Kahoot! All you need to make learning awesome this back-to-school. Website. Retrieved October 15, 2023 from `https://kahoot.com/schools/`.

58 Kristian Kiili. Digital game-based learning: Towards an experiential gaming model. *The Internet and Higher Education*, 8:13–24, 03 2005. `doi:10.1016/j.iheduc.2004.12.001`.

59 David Kirsh. Projection, problem space and anchoring. 2009.

60 Bettina Kroker. Unterrichtsmethode: Lerntheke. `https://www.betzold.de/blog/lerntheke/`, 2019. Accessed: 8 October 2023.

61 Bettina Kroker. Unterrichtsmethoden: Das stationenlernen. `https://www.betzold.de/blog/stationenlernen/`, 2020. Accessed: 8 October 2023.

62 Florian Lang, Verena Pues, Albrecht Schmidt, and Tonja-Katrin Machulla. Braillebuddy: A tangible user interface to support children with visual impairment in learning braille. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, CHI '23, New York, NY, USA, 2023. Association for Computing Machinery. `doi:10.1145/3544548.3580844`.

63 Markus Lang, Ursula Hofer, and Friederike Beyer. *Didaktik des Unterrichts mit blinden und hochgradig sehbehinderten Schülerinnen und Schülern.* Kohlhammer, Stuttgart, 2010. ISBN: 978-3-170-20151-4.

64 Son Le and Peter Weber. Game-based learning-spielend lernen? 2011.

65 Two Lives Left. Cargo-bot. Website. Retrieved October 18, 2023 from `https://apps.apple.com/ch/app/cargo-bot/id519690804`.

66 Zeina Atrash Leong and Michael S. Horn. Representing equality: A tangible balance beam for early algebra education. In *Proceedings of the 10th International Conference on Interaction Design and Children*, IDC '11, page 173–176, New York, NY, USA, 2011. Association for Computing Machinery. `doi:10.1145/1999030.1999054`.

67 Vladimir I. Levenshtein. Binary codes capable of correcting deletions, insertions, and reversals. *Soviet physics. Doklady*, 10:707–710, 1965.

68 Yanhong Li, Meng Liang, Julian Preissing, Nadine Bachl, Michelle Melina Dutoit, Thomas Weber, Sven Mayer, and Heinrich Hussmann. A meta-analysis of tangible learning studies from the tei conference. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '22, New York, NY, USA, 2022. Association for Computing Machinery. `doi:10.1145/3490149.3501313`.

69 Meng Liang, Yanhong Li, Thomas Weber, and Heinrich Hussmann. Tangible interaction for children's creative learning: A review. In *Proceedings of the 13th Conference on Creativity and Cognition*, C&C '21, New York, NY, USA, 2021. Association for Computing Machinery. `doi:10.1145/3450741.3465262`.

70 Maria D. Lozano, Victor M. R. Penichet, Barbara Leporini, and Anil Fernando. Tangible user interfaces to ease the learning process of visually-impaired children. In *Proceedings of the 32nd International BCS Human Computer Interaction Conference*, HCI '18, Swindon, GBR, 2018. BCS Learning & Development Ltd. `doi:10.14236/ewic/HCI2018.87`.

71 Marbotic. Marbotic learn to read and count. `https://apps.apple.com/us/app/marbotic-learn-to-read-count/id1583225997`. Accessed: 19 October 2023.

72 Marbotic. We help kids learn to read and count. easy! `https://marbotic.com/`. Accessed: 19 October 2023.

73 Marbotic. Marbotic app. `https://www.youtube.com/watch?v=qzgP0FVijZY&t`, note = Accessed: 18 October 2023, 2022.

74 Kasey Markoski. Diy braille cell. https://www.youtube.com/watch?v=I7bBkj3dGVY, 2020. Accessed: 15 October 2023.

75 Milena S Markova, Stephanie Wilson, and Simone Stumpf. Tangible user interfaces for learning. *International Journal of Technology Enhanced Learning*, 4(3-4):139–155, 2012.

76 Paul Marshall. Do tangible interfaces enhance learning? In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*, TEI '07, page 163–170, New York, NY, USA, 2007. Association for Computing Machinery. doi:10.1145/1226969.1227004.

77 Paul Marshall, Sara Price, and Yvonne Rogers. Conceptualising tangibles to support learning. In *Proceedings of the 2003 Conference on Interaction Design and Children*, IDC '03, page 101–109, New York, NY, USA, 2003. Association for Computing Machinery. doi:10.1145/953536.953551.

78 Aditya Mehrotra, Christian Giang, Noé Duruz, Julien Dedelley, Andrea Mussati, Melissa Skweres, and Francesco Mondada. Introducing a paper-based programming language for computing education in classrooms. In *Proceedings of the 2020 ACM Conference on Innovation and Technology in Computer Science Education*, ITiCSE '20, page 180–186, New York, NY, USA, 2020. Association for Computing Machinery. doi:10.1145/3341525.3387402.

79 Laetitia Mendes and Teresa Romão. Children as teachers: A tangible approach. ACE '11, New York, NY, USA, 2011. Association for Computing Machinery. doi:10.1145/2071423.2071438.

80 S.B. Merriam and R.S. Caffarella. *Learning in adulthood: A comprehensive guide (2nd ed.).* San Francisco, CA: Jossey-Bass Publishers, 1999.

81 Mittelschulliebe. Vorlagen für mathe-bingo. https://eduki.com/de/material/88985/vorlagen-fuer-mathe-bingo. Accessed: 18 October 2023.

82 Maria Montessori. The montessori method. *New York: Frederick Stokes Co.*, 1912.

83 Abir Benabid Najjar, Asma Alhussayen, and Rabia Jafri. Usability engineering of a tangible user interface application for visually impaired children. *Human-centric Computing and Information Sciences*, 11, 2021. doi:10.22967/HCIS.2021.11.014.

84 Gonzalo Navarro. A guided tour to approximate string matching. *ACM Comput. Surv.*, 33(1):31–88, mar 2001. doi:10.1145/375360.375365.

85 Donald A Norman. *The psychology of everyday things.* Basic books, 1988.

86 Claire O'Malley and Danae Stanton Fraser. Literature review in learning with tangible technologies. 2004.

87 Huaishu Peng. Algo.rhythm: Computational thinking through tangible music device. TEI '12, page 401–402, New York, NY, USA, 2012. Association for Computing Machinery. doi:10.1145/2148131.2148234.

88 Sonja Petrovska, Despina Sivevska, and Oliver Cackov. Role of the game in the development of preschool child. *Procedia-Social and Behavioral Sciences*, 92:880–884, 2013. doi:10.1016/j.sbspro.2013.08.770.

89 Ana Cristina Pires, Sebastian Marichal, Fernando Gonzalez-Perilli, Ewelina Bakala, Bruno Fleischer, Gustavo Sansone, and Tiago Guerreiro. A tangible math game for visually impaired children. In *Proceedings of the 21st International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '19, page 670–672, New York, NY, USA, 2019. Association for Computing Machinery. doi:10.1145/3308561.3354596.

90 Plickers. Formative assessment has never been faster.formative assessment has never been faster. Website. Retrieved October 15, 2023 from https://get.plickers.com/.

91 Verena Pues. Braillebuddy goes android. https://verenapues.com/public-docs/BrailleBuddy-goes-Android.pdf. Accessed: 17 October 2023.

92 Verena Pues. Playmake - autumn adventure puzzle. https://youtu.be/S8hX7TyzF5Y?si=M09GesNTm3uJb9jP, note = Accessed: 06 November 2023, 2023.

93 Verena Pues. Playmake - fraction master. https://youtu.be/7Hs2okTgLU8?si=hVi0YH4ISFvNZamR, note = Accessed: 06 November 2023, 2023.

94 Verena Pues. Playmake - geoshape puzzle. https://youtu.be/1S2JfXtXN1Q?si=hxbdmDsxaw12tJ9B, note = Accessed: 06 November 2023, 2023.

95 Verena Pues. Playmake - living history. https://youtu.be/hpTqcYtfVOU?si=wx3WcuTX_WRdJRfX, note = Accessed: 06 November 2023, 2023.

96 Verena Pues. Playmake - spell carousel. https://youtu.be/I4oI7I5LZUQ?si=h_kzXtIHegADXl1Y, note = Accessed: 06 November 2023, 2023.

97 Inc. Quizlet. Quizlet live - das schnelle lernspiel für den unterricht, das die schüler lieben und spaß macht. Website. Retrieved October 15, 2023 from https://quizlet.com/de/features/live.

98 CHIP Redaktion. Robot karol. Website. Retrieved October 18, 2023 from https://www.chip.de/downloads/Robot-Karol_77435228.html.

99 Gisela Reinsch and Laurin Reinsch. Lernstübchen grundschule. https://lernstuebchen-grundschule.de/. Accessed: 19 October 2023.

100 Daniela Rembold. Herzlich willkommen auf dem ideenreise-blog. https://ideenreise-blog.de/. Accessed: 19 October 2023.

101 Yvonne Rogers, Michael Scaife, Silvia Gabrielli, Hilary Smith, and Eric Harris. A conceptual framework for mixed reality environments: Designing novel learning activities for young children. *Presence: Teleoperators and Virtual Environments*, 11:677–686, 12 2002. doi:10.1162/105474602321050776.

102 Kimiko Ryokai and Justine Cassell. Storymat: A play space for collaborative storytelling. In *CHI '99 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '99, page 272–273, New York, NY, USA, 1999. Association for Computing Machinery. doi:10.1145/632716.632883.

103 Kimiko Ryokai, Stefan Marti, and Hiroshi Ishii. I/o brush: Drawing with everyday objects as ink. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '04, page 303–310, New York, NY, USA, 2004. Association for Computing Machinery. doi:10.1145/985692.985731.

104 Hamed Sabri, Brent Cowan, Bill Kapralos, Fuad Moussa, Sayra Cristanchoi, and Adam Dubrowski. Off-pump coronary artery bypass surgery procedure training meets serious games. In *2010 IEEE International Symposium on Haptic Audio Visual Environments and Games*, pages 1–5. IEEE, 2010. doi:10.1109/HAVE.2010.5623995.

105 Alpay Sabuncuoglu. Tangible music programming blocks for visually impaired children. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '20, page 423–429, New York, NY, USA, 2020. Association for Computing Machinery. doi:10.1145/3374920.3374939.

106 Theodosios Sapounidis and Stavros Demetriadis. Educational robots driven by tangible programming languages: A review on the field. In Dimitris Alimisis, Michele Moro, and Emanuele Menegatti, editors, *Educational Robotics in the Makers Era*, pages 205–214, Cham, 2017. Springer International Publishing.

107 Magdalena Schmid, Sonja Rümelin, and Hendrik Richter. Empowering materiality: inspiring the design of tangible interactions. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, pages 91–98, 2013. doi:https://doi.org/10.1145/2460625.2460639.

108 Bertrand Schneider and Paulo Blikstein. Flipping the flipped classroom: A study of the effectiveness of video lectures versus constructivist exploration using tangible user interfaces. *IEEE transactions on learning technologies*, 9(1):5–17, 2015. doi:10.1109/TLT.2015.2448093.

109 Eric Schweikardt, Nwanua Elumeze, Mike Eisenberg, and Mark D Gross. A tangible construction kit for exploring graph theory. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, TEI '09, page 373–376, New York, NY, USA, 2009. Association for Computing Machinery. doi:10.1145/1517664.1517739.

110 Susanne Schäfer. Zaubereinmaleins. https://www.zaubereinmaleins.de/startseite/home..../. Accessed: 19 October 2023.

111 Orit Shaer, Eva Hornecker, et al. Tangible user interfaces: past, present, and future directions. *Foundations and Trends® in Human–Computer Interaction*, 3(1–2):4–137, 2010. doi:http://dx.doi.org/10.1561/1100000026.

112 Orit Shaer and Robert J.K. Jacob. A specification paradigm for the design and implementation of tangible user interfaces. *ACM Trans. Comput.-Hum. Interact.*, 16(4), nov 2009. doi:10.1145/1614390.1614395.

113 Ang Chee Siang and Radha Krishna Rao. Theories of learning: a computer game perspective. In *Fifth International Symposium on Multimedia Software Engineering, 2003. Proceedings.*, pages 239–245. IEEE, 2003. doi:10.1109/MMSE.2003.1254447.

114 Amigo Spiele. Saboteur. https://www.amigo-spiele.de/saboteur_4900_1122. Accessed: 15 October 2023.

115 Amigo Spiele. Amigo erklärt ‚saboteur'. https://www.youtube.com/watch?v=QN3AAigrbmI, note = Accessed: 18 October 2023, 2013.

116 Schmidt Spiele. Kniffel. https://www.schmidtspiele.de/details/produkt/kniffel-wuerfelspiel-klassiker.html. Accessed: 15 October 2023.

117 Schmidt Spiele. Kniffel: Clever knobeln - mit köpfchen. spielanleitung. https://www.schmidtspiele.de/files/Produkte/4/49030%20-%20Kniffel/49203_49030_Kniffel_DE.pdf. Accessed: 18 October 2023.

118 Spielfundus. Ecken rechnen! http://www.spielfundus.de/spiele/lernspiele/eckenrechnen.htm.

119 D. Stanton, C. O'Malley, K. Huing, M. Fraser, and S. Benford. *Situating Historical Events Through Mixed Reality*, pages 293–302. Springer Netherlands, Dordrecht, 2003. doi:10.1007/978-94-017-0195-2_37.

120 Fleur Star, Jemma Westing, and Charlotte Oliver. *Animals: Knowledge you can touch*. DK Children, 2016. ISBN: 978-1-4654-3611-5.

121 Stefan Stieglitz. Enterprise gamification–vorgehen und anwendung. *Gamification und serious games: Grundlagen, Vorgehen und Anwendungen*, pages 3–13, 2017.

122 Tarja Susi, Mikael Johannesson, and Per Backlund. Serious games: An overview. 2007.

123 Cristina Sylla. Designing a long term study evaluating a physical interface for preschoolers. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, TEI '13, page 363–364, New York, NY, USA, 2013. Association for Computing Machinery. doi:10.1145/2460625.2460695.

124 OpenCV Team. About. https://opencv.org/about/. Accessed: 28 October 2023.

125 Nicole Trapp. Frau locke - grundschultante. https://fraulocke-grundschultante.de/. Accessed: 19 October 2023.

126 Iliana Triantafyllidou, Athina-Maria Chatzitsakiroglou, Stergiani Georgiadou, and George Palaigeorgiou. Fingertrips on tangible augmented 3d maps for learning history. In Michael E. Auer and Thrasyvoulos Tsiatsos, editors, *Interactive Mobile Communication Technologies and Learning*, pages 465–476, Cham, 2018. Springer International Publishing.

127 SPIELREGELN TV. Dobble (alle 5 spielvarianten) - spielregeln tv (spielanleitung deutsch) - asmodee. https://www.youtube.com/watch?v=Ua64cVpx7VY, note = Accessed: 18 October 2023, 2021.

128 Grundschul Universum. Tafelfußball. https://grundschul-universum.de/tafelfussball/, March 2021. Accessed: 15 October 2023.

129 ViewSonic. myviewboard - eine visuelle lernplattform. Website. Retrieved October 15, 2023 from `https://myviewboard.com/`.

130 Torben Wallbaum, Swamy Ananthanarayan, Shadan Sadeghian Borojeni, Wilko Heuten, and Susanne Boll. Towards a tangible storytelling kit for exploring emotions with children. In *Proceedings of the on Thematic Workshops of ACM Multimedia 2017*, Thematic Workshops '17, page 10–16, New York, NY, USA, 2017. Association for Computing Machinery. `doi:10.1145/3126686.3126702`.

131 Pierre Wellner, Wendy Mackay, and Rich Gold. Back to the real world. *Communications of the ACM*, 36(7):24–26, 1993. `doi:https://doi.org/10.1145/159544.159555`.

132 W-H. Wu, H-C. Hsiao, P-L. Wu, C-H. Lin, and S-H. Huang. Investigating the learning-theory foundations of game-based learning: a meta-analysisjcal. *Journal of Computer Assisted Learning*, 2011. `doi:10.1111/j.1365-2729.2011.00437.x`.

133 Peta Wyeth and Helen C. Purchase. Tangible programming elements for young children. In *CHI '02 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '02, page 774–775, New York, NY, USA, 2002. Association for Computing Machinery. `doi:10.1145/506443.506591`.

134 Diana Xu. Tangible user interface for children-an overview. In *Proc. of the UCLAN Department of Computing Conference*. Citeseer, 2005.

135 Oren Zuckerman, Saeed Arida, and Mitchel Resnick. Extending tangible interfaces for education: Digital montessori-inspired manipulatives. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '05, page 859–868, New York, NY, USA, 2005. Association for Computing Machinery. `doi:10.1145/1054972.1055093`.

Appendix

A.1 List of Games and Applications Used in Class

In the following we present a list of concrete games, applications and platforms that were mentioned during our expert interviews. Each game is briefly described, using explanations provided by the interviewed teachers and, if necessary, supplemented with additional online research.

A.1.1 Analog Games

Desert Island Game ("Was ich alles mitnehme auf eine einsame Insel")
The Desert Island Game [50] trains abstract thinking and is a fun and educational activity for students. The teacher starts by choosing a rule that dictates what items students can bring to a desert island. For example, the rule could be that all items must begin with a specific letter or contain „ie“ (represents a long vowel sound in German). Students then take turns suggesting items that adhere to the rule. The teacher adds the items that match the rule to a list. Once all students have had a turn, the class can discuss the rule and why the chosen items fit it.

Dobble
Dobble is a card game that functions as an observation and reaction game [27, 127]. It offers five different game variations. The game comprises numerous circular cards, each of which displays eight symbols. No matter which cards you compare, there is always precisely one symbol that matches on both cards. The objective of each round is to be the first to spot the symbol that matches on two cards. The player who accomplishes this goal either receives a card or is allowed to discard a card, depending on the game variation being played.

Ecken Rechnen ("Corner Calculation")
In this game, which combines math and movement, players start in different corners of the classroom and move to the next corner upon solving a math problem correctly, with the winner returning to their starting position first [118].

Hangman
Hangman is a word-guessing game where one player thinks of a word and keeps it secret, representing it with dashes or underscores. The other players take turns guessing letters they think are part of the word. For each correct guess, the letters are revealed in their corresponding positions. A hangman figure is drawn for each incorrect guess, typically starting with the head, body, arms, and legs. The game continues until the word is guessed correctly (win) or the hangman figure is completed (loss). The game challenges players' word knowledge and can be played with subject-specific terms (P03).

Kniffel (Yahtzee)
Kniffel is a turn-based dice game [116, 117]. Players have three attempts to form specific combinations from the five rolled dice in each turn. These combinations and their point values are recorded on a score sheet. The player with the most points wins the game.

Menschen-Memory ("People Memory")
Two students leave the classroom while the others are paired up (e.g., German and English vocabulary pairs). The two students then return and must find the pairs, much like a traditional memory game (P03).

Ping Pong
Ping Pong is a versatile game, where students recite the alphabet or other enumerable contents one after another. When the enumeration ends student says "Ping Pong!" (P05).

Rechen-Bingo ("Math-Bingo")
Math Bingo [81] is a calculation game that works similarly to the original Bingo. Students work on mathematical problems and enter the solutions into the Bingo grids. Subsequently, the teacher gradually calls out the answers, which the students compare to their solutions. The first student to have three correct answers in a row shouts, "Bingo!".

Rechen-Fußball ("Calculation-Soccer")
Rechen-Fußball ("Calculation-Soccer") is a possible variation of Tafel-Fußball ("Chalkboard-Soccer"), using math related tasks. For more information refer to the Tafel-Fußball ("Chalkboard-Soccer") section below.

Saboteur
Saboteur [114, 115] is a card game that divides players into two teams. In this game, players take on the roles of either gold miners or saboteurs. The objective for the gold miners is to locate and secure the gold treasure, while the saboteurs win if they manage to thwart this endeavor. Players do not know the roles of their fellow players. This dynamic introduces an exciting element of social interaction, as players must deduce who is aligned with their team. Players must skillfully bluff and plan their moves to conceal their true intentions. The game is also playable in large groups.

Tafel-Fußball ("Chalkboard-Soccer")
The teacher draws a playing field on the chalkboard. A ball is illustrated in the center of the board (alternatively, a magnet can be used). On both sides of the chalkboard, a goal is placed. The class is divided into two teams, and all students are assigned jersey numbers. The teacher then presents tasks that all students initially worked on silently. After a short time, the teacher calls out a jersey number. The students from both teams with the mentioned number must then give the answer. The first student to provide the correct answer earns a point for their team, and the ball moves toward the opposing goal [128].

Zwerg-Riese ("Dwarf-Giant")
This game is suitable for refreshing knowledge and, at the same time, physically activating the students. The teacher gives a statement: if it is true, students stand tall like giants; if it is false, they crouch like dwarfs (P05).

A.1.2 Digital Games, Applications and Platforms

Anton App
The Anton App [11] is an educational platform for students in Germany, offering a wide range of digital learning materials and resources. It provides access to interactive lessons, exercises, and educational content for various subjects and grade levels. The app's content aligns with the German curriculum, making it a valuable resource for students and teachers. With a school license, teachers can manage their students within the app, customize assignments, and receive reports on students' learning progress.

Bitsboard
Bitsboard [46], an educational app for mobile devices, enabling users to create or adapt individual multimedia learning content.

Cargo-Bot
Cargo-Bot is a challenging puzzle game app that helps its users to learn programming concepts [65].

Geogebra
Geogebra [35] is an interactive software with mathematical representations and tools. It includes an Augmented Reality feature that allows students to place constructions in their real environment and explore them from various perspectives [38].

H5P
H5P [44] is a platform for creating interactive HTML content, such as fill-in-the-blank exercises or quiz questions in instructional videos, which can be easily integrated into other webpages.

Kahoot!
"Kahoot!" [57] allows educators to create and host custom quizzes, surveys, and discussions for students in a fun and competitive format. Students can participate using their own devices and compete against each other by answering questions in real-time. It comes with a vast selection of pre-existing content. H5P [44] is a platform for creating interactive HTML content, such as fill-in-the-blank exercises or quiz questions in instructional videos, which can be easily integrated into other webpages.

LearningApps.org
"LearningApps.org" [49] is a website that provides multimedia building blocks for creating diverse learning games and offers a large collection of games created by the community.

Marbotic
Marbotic [72, 71, 73] is a multi-sensory educational method designed by kindergarten teachers and early childhood education experts. Inspired by the Montessori Method, it mixes classic wooden toys with fun learning apps dedicated to preschoolers. Each activity has specific educational goals to help young children build foundational literacy and numeracy skills through a blend of physical play and digital interaction.

mathegym.de
The online platform "mathegym.de" [5] is targeted at students from grades five to twelve and offers math tutorials and exercises at various difficulty levels.

myviewboard
Teachers can use a digital whiteboard to plan their lessons and enhance them with multimedia content. The software "myViewBoard" [129] is designed for preparing these materials, such as educational games and includes tools that promote interactive lessons with active student participation.

Plickers
Plickers [90] is an application that comes with physical QR-code-cards that are distributed to the students. The students use these cards to answer questions by holding up the cards. This allows the teacher to scan the codes with a smartphone or tablet and evaluate the answers in real-time.

Quizlet Live
With Quizlet Live [97] students answer the teacher's questions and tasks using mobile devices. Various game modes promote collaboration.

Robot Karol
"Robot Karol" [98] is a programming environment that introduces students to programming fundamentals. Using simple commands, it allows users to control a small Lego robot named „Karol“ in a 3D virtual world. Through a series of straightforward tasks and commands, students quickly grasp the basics of programming, with the robot character adding a fun and engaging element to the learning experience.

Safe Knacker ("Safe Cracker")
"Safe-Knacker", is a game based on PowerPoint, where students must solve tasks to work out the code to crack the safe. This idea can be applied to other game concepts and can be customized with little PowerPoint skills (P01).

Name: Verena Pues

Matrikelnummer: 11899307

Erklärung

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbstständig angefertigt, alle Zitate als solche kenntlich gemacht sowie alle benutzten Quellen und Hilfsmittel angegeben habe.

München, den 06.11.23 .... VPues

Verena Pues