

Developing design principles for 3D tactile books for visually impaired students: A design and development research approach

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Highlights

- A design and development research approach was used to generate evidence-based design principles for 3D tactile books tailored to students with visual impairments.
- Iterative prototyping integrating tactile, auditory, and digital components enhanced usability, accessibility, and multisensory learning experiences.
- Findings indicate that effective 3D tactile book sets should integrate multisensory elements.

Article Info: Research Article

Keywords: 3D tactile books, visual impairment education, multisensory learning

Abstract

This study addresses the limited availability of standardized and pedagogically grounded tactile learning materials for students with visual impairments by focusing on the design of 3D tactile books. The purpose is to develop evidence-based design principles through a design and development research approach. A mixed-method, iterative methodology was employed, structured around the ADDIE model and involving analysis, design, development, and evaluation phases. The study group consisted of teachers of visually impaired students and field experts selected through purposive sampling across different phases. Data were collected using semi-structured interviews and focus group discussions and analyzed through content analysis. Findings indicate that effective 3D tactile books should integrate multisensory elements, ensure durability and usability, align with learner characteristics, and support independent and collaborative learning. The developed prototype, refined through iterative cycles, demonstrated strong usability, motivational impact, and cognitive support potential. The study concludes by proposing comprehensive design principles to guide future development of accessible, scalable, and instructionally effective tactile learning materials.

1. Introduction

Educational services are carried out with the primary aim of enabling individuals to acquire desired behaviors. These services are not limited to individuals with typical development; they also encompass those who experience various types and degrees of disabilities. In order to effectively meet the educational needs of individuals with disabilities, a systematic set of services provided through individualized programs and methods under the supervision of specially trained personnel is defined as special education (Ataman, 2003). Among the types of disabilities considered within the scope of special education, visual impairment holds particular importance, as it profoundly affects individuals' academic, social, and daily living skills from an early age (World Health Organization [WHO], 2019). Indeed, it is estimated that individuals with typical development acquire approximately 85% of the information they gain throughout their lives through the sense of sight (Cavkaytar & Diken, 2012). This clearly demonstrates the significant impact of partial or

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complete loss of vision on learning processes and fundamentally differentiates the education of individuals with visual impairments from that of their peers.

Visual impairment is defined as functional limitations in the visual system, such as irreversible vision loss or constriction of the visual field, that cannot be corrected through glasses, surgical intervention, or medical treatment (American Foundation for the Blind [AFB], 2020). However, visual impairment does not constitute a homogeneous condition; there are significant differences among individuals in terms of visual acuity, visual field, and overall visual functioning (WHO, 2019). Although many individuals are able to use their residual vision to a limited extent, this capacity is often insufficient for academic learning, necessitating reliance on alternative sensory modalities for information acquisition (Shams & Seitz, 2008).

Students with visual impairment (SVIs) require greater guidance and support in acquiring information compared to their peers throughout the educational process. In particular, the learning of abstract concepts constitutes a significant area of difficulty for these students, as such concepts largely rely on visual experiences and cannot be directly observed (Göksu & Çevik, 2004; Zorluoğlu & Sözbilir, 2017). In this context, it is of critical importance for students to adopt multisensory learning approaches—where senses such as touch and hearing are effectively utilized—in order to construct knowledge in a more meaningful and enduring manner (Shams & Seitz, 2008; Yazıcı & Sözbilir, 2020). Multisensory learning is simply defined as the process of learning a new subject using two or more senses. This approach helps students better process new information, relate new information to prior knowledge, understand the relationships between concepts, and therefore remember, or retain, it (Esplendori et al., 2022). Moreover, recent research in multisensory learning indicates that students show higher levels of attention and enhanced knowledge retention when visual, auditory, and tactile stimuli are presented in a structured manner for a specific purpose, rather than presented simply independently (Gori et al., 2022; Sathian & Lacey, 2022). For SVIs, this is not a pedagogical preference. Touch and hearing have to do the integrative work that vision normally handles, which means materials need to be built around those senses from the start (Cuturi et al., 2021; Gori et al., 2021). The design question, in other words, is no longer how to adapt visual materials for tactile use, but how to design materials that work for sensorily diverse learners in the first place.

One framework that fits this orientation is Universal Design for Learning (UDL), developed by Center for Applied Special Technology (CAST, 2024). UDL is based on three principles that guide instructional decisions: multiple means of representation, multiple means of action and expression, and multiple means of engagement (Levey, 2021). UDL is about developing materials that have inclusive flexibility built in from the start, rather than adapting materials after having discovered a need is identified. Moreover, it takes students' individual differences as the initial design principles rather than an exception (Plantin Ewe & Galvin, 2023). Research on inclusivity has shown that environments based on these principles lead to participation and engage more students at the same time (Foxworth et al., 2021; Plantin Ewe & Galvin, 2023). For example, Abrahamson et al. (2018) argue that the main goal should not be to transform visual elements into tangible objects, but rather to redesign learning materials so that visually impaired and sighted students can work together on the same material. Fundelius et al. (2022), in their study they demonstrated that multimodal book sets with concrete objects, Braille alphabet, and sensory cues enhanced students' ability to access storybook reading in early literacy without dividing them into separate groups. For tactile materials aimed at SVIs, UDL is therefore useful as more than an accessibility checklist. It offers a reason to integrate tactile, auditory, and digital channels into one flexible artifact that works across the whole visual-impairment spectrum.

Access to information for SVIs has been significantly facilitated through assistive technologies such as screen reader software, audio description systems, and Braille materials with the advancement of technology (Kelly & Smith, 2011). However, these technologies are often limited to text-based content and may be insufficient in conveying visual information such as the shape, structure, position, and spatial relationships of objects (Lahav & Mioduser, 2008). Literature indicates that technology-based materials enhance students' learning when utilised effectively (Günbaş, 2022). Recent research emphasizes that SVI

should be supported not only academically but also holistically in areas such as orientation and independent mobility, spatial awareness, motor skills, and early tactile literacy (Phutane et al., 2022). These skills are critical for individuals to make sense of the world around them and to maintain independent living, with tactile materials emerging as highly effective tools in fostering such development (Heller et al., 2005). Furthermore, it is noted that these materials enhance students' active participation in lessons, support motivation, and strengthen their perceptions of self-efficacy.

Tactile materials that enable the concretization and transmission of visual information in education encompass various types, including two-dimensional (2D) raised graphics, three-dimensional (3D) models, and real objects. Standard 2D tactile graphics may increase the cognitive load of SVIs and make interpretation more challenging, as they often require complex legends and involve a high level of abstraction (Holloway et al., 2023). To overcome these limitations, teachers frequently prefer to use 3D models and real objects as "stepping stones" before introducing more complex tactile graphics (Phutane et al., 2022).

Tactile books, with their structures incorporating raised elements and varied textures, constitute a highly effective tool for the concretization of abstract information and for the teaching of fundamental concepts, particularly in early childhood. However, the production of these books through traditional methods is time-consuming, costly, and lacks standardization (Archambault et al., 2022). Excessive detail in the design process, insufficient contrast, or improperly placed Braille labels may negatively affect students' learning processes; moreover, the fact that most existing materials are primarily designed for individuals who are totally blind creates issues of accessibility and inclusivity for students with low vision (Dzhurynskyi et al., 2024).

2. Literature

Recent rapid advancements in three-dimensional (3D) printing technologies have created significant opportunities for the production of tactile materials and the design of tactile books. Through 3D printers, abstract concepts can be directly transformed into tangible objects; this, in turn, enhances students' engagement, supports problem-solving skills, and provides teachers with flexibility in material development (Jones, & Mendez, 2021). Current studies in the literature indicate that 3D printing technologies are effective in the teaching of specific academic and spatial skills. For instance, the use of 3D-printed instructional materials such as 3D cell models in science education has been shown to be effective in addressing students' misconceptions (Andić et al., 2024; Coşkunserçe, 2025), while 3D models have demonstrated superiority over traditional 2D maps in understanding the spatial architecture of complex street crossings and multi-level structures (Holloway et al., 2022; Sargsyan et al., 2023). In addition, 3D map icons that do not require complex legends reduce cognitive load and facilitate learning (Holloway et al., 2023). Furthermore, the direct integration of Braille into 3D replicas of cultural heritage artifacts enables the simultaneous presentation of an object's form and its semantic information (Montusiewicz et al., 2022).

3D printing technologies are no longer limited to the production of physical objects; rather, "multimodal" and interactive systems that integrate auditory and technological components have become a prominent focus of recent research. These systems, which provide simultaneous auditory feedback alongside tactile perception, enrich the learning experience and support learner independence by enabling both sighted and visually impaired individuals to collaboratively use the same materials (Raynal et al., 2024; Valente et al., 2024). The pedagogical case for these systems rests on long-standing theories of multimedia learning. Paivio's dual coding theory and Mayer's cognitive theory of multimedia learning describe two related but separate channels for verbal and non-verbal information, and they argue that learning improves when content is presented through both at once, as long as the design does not overload working memory (Albers et al., 2023). For SVIs, the same two-channel logic applies, just with the inputs redistributed. Braille text and audio narration carry the verbal channel, while 3D objects, raised graphics, and high-contrast colored

elements (for students with low vision) carry the non-verbal one. The practical question is therefore not whether to combine these channels, but how to position them on the page and in time so that comprehension goes up and unnecessary cognitive load goes down.

In the development of educational materials, not only the integration of technology but also the participatory design approach - where the target audience is directly involved in the design process - holds critical importance (Lozano, 2022; Tusitala, 2024). The development of tactile books based on feedback from field experts, teachers, and individuals with visual impairment enhances the functionality and usability of these materials. However, for 3D materials to be effective in classroom applications, they must be aligned with pedagogical planning and used in a balanced manner alongside other instructional materials. Tactile materials developed for SVIs need to be addressed through a holistic approach encompassing both design and implementation dimensions in light of these developments. Although technology-supported, multimodal 3D tactile books hold significant potential, it is noteworthy that studies examining their design processes and classroom effectiveness remain limited. The development of genuine tactile books via 3D printing technologies is a recent phenomenon, necessitating practitioners to have strong technological skills in 3D modeling, 3D printing, and digital material design. Therefore, it is a complex problem, and the potential for 3D tactile books to either revolutionize or coexist with current educational approaches remains a topic of academic debate. There is also a theoretical gap to go with the empirical one. Existing studies rarely articulate an explicit theoretical framework that links tactile, auditory, and digital modalities to inclusive design principles such as UDL (Mukhiddinov & Kim (2021; Phutane et al., 2022; Valente et al., 2023). As a result, design decisions tend to be reported as one-off adaptations rather than as applications of a coherent framework (Phutane et al., 2022), which makes design knowledge hard to carry over to new subjects, grade levels, or learner populations. This situation points to a significant gap in the literature.

This present study aims to derive design principles for 3D tactile books for primary school SVIs through a design-and-development research approach. To this end, the perspectives of visual impairment teachers (TVI) and field experts on the use of 3D tactile books in education were gathered and used as the basis for prototype development. The prototype was iteratively refined through successive consultations with field experts and visual impairment teachers, and the finalized version was subjected to comprehensive evaluation by both teachers and experts to formulate evidence-based design principles.

Research Questions

1. What are the recommendations of visual impairment teachers regarding the design of a 3D tactile book to be used in the education of students with visual impairments?
2. How did the design and development process of the 3D tactile book intended for use in the education of students with visual impairments unfold?
3. What are the views of teachers and experts regarding the evaluation of the developed 3D tactile book?

3. Methodology

3.1. Research Model

In order to answer research questions, this study adopts a systematic research methodology used to bridge the gap between educational theory and practice, Design and Development Research (DDR) methodology, which is often used interchangeably with different terms such as design-based research, design experiments, design research, and development research (Wang & Hannafin, 2005). DDR is defined as “a systematic and yet flexible approach aimed to improve educational applications such as programs, processes, and products by doing iterative analyses, design, development, and implementation based on collaboration among researchers and practitioners in real-world settings” (Richey and Klein, 2007; Wang & Hannafin, 2005). DDR stands out as an important research method in the field of instructional technologies because it helps researchers design and validate technology-based instructional interventions and products (Çağıltay and Göktaş, 2013). The rationale for selecting this methodology within the scope of this study is that it aims to make both practical and scientific contributions simultaneously; it seeks to solve complex, real-world

problems while generating design principles or theories that explain how and why the intervention works. The development of genuine tactile books via 3D printing technologies is a recent phenomenon, necessitating practitioners to have strong technological skills in 3D modeling, 3D printing, and digital material design. Therefore, it is a complex problem, and the potential for 3D tactile books to either revolutionize or coexist with current educational approaches remains a topic of academic debate.

DDR studies use a mixed-methods design and involve multiple parties such as designers, researchers, and practitioners with diverse expertise to prioritize the practical effects of the intervention (Anderson & Shattuck, 2012; cited Atay, et al., 2024). This type of research employs design cycles to test and refine solutions, with an emphasis on the design and implementation of novel artifacts that contribute to the advancement of the field of digital innovation. In this research, the design framework was developed through an iterative process, with teachers of visually impaired students serving as real-life practitioners in the classroom and field experts and instructional designers serving secondarily. The design principles of these instructional materials were iteratively improved and structured using the ADDIE model, one of the most frequently used and fundamental instructional design models for product and process development in DDR studies (Reeves, 2006, Richey & Klein, 2007). The ADDIE model -an acronym that stands for Analysis, Design, Development, Implementation, and Evaluation (Putri, & Sofyan, 2020)- provided a methodological framework that guided researchers for identifying design features, development, implementation, and evaluation of the 3D tactile book set (including 3D tactile books, Braille versions of the 3D tactile books, audiovisual materials published on YouTube and a website) for visually impaired students in the 4th grade of elementary school.

3.2. Data Collecting Tools

This research involves multiple data collection processes and tools, in accordance with the nature of DDR. Semi-structured interviews were used in the analysis and implementation & evaluation phases, whereas focus group interviews were used in the design and development phases of the research.

During the analysis phase, to identify learner and teacher needs related to 3D tactile books and to establish initial design principles through the lens of teachers, a semi-structured interview form was used, consisting of 4 open-ended questions. As for the design phase, a focus group interview was conducted to deepen the initial design principles through the lens of field experts. Later, during the development phase, feedback on the design's progress was obtained from members of the design validity committee (field experts) through regular interval sessions. Finally, a semi-structured interview form with five open-ended questions was used to investigate the design's implementation in the classroom by end users (the instructors) and to determine their viewpoints on the evaluation of the final 3D book set. All interviews, except the final evaluation interview, were held in person. To reach a larger sample, the final interview was conducted online using a descriptive video of the 3D book set, which was emailed to participants in advance. Detailed information about the data collecting tools is presented in Table 1.

Table 1.

Data collecting tools according to the DDR Phases

DDR Phases	Data collecting tools
Analysis	Semi-structured interview form 1. In which areas do you find it difficult to help your students achieve learning outcomes? 2. What are your opinions on the use of existing 3D tactile books? 3. What problems do you encounter when using existing 3D tactile books? 4. What are your suggestions for designing a 3D tactile book?

Design	Focus Group Interview 1 1. Which of the reading passages included in the 4th-grade textbook recommended by the Ministry of National Education would be more suitable for inclusion in a 3D tactile book, considering the characteristics of students with visual impairments (SVI)? 2. How should the text of a reading passage intended for a 3D tactile book be organized according to the characteristics of SVI? 3. How should the visual scenario draft (storyboard) of a reading passage intended for a 3D tactile book be designed according to the characteristics of SVI? 4. What should be the design principles to consider during the development process of a 3D tactile book?
Development	Focus Group Interview - 2 1. What are your thoughts on the general design of the 3D tactile book developed for SVI? 2. Are there any features of the 3D tactile book developed for SVI that you find lacking or that you would suggest changing in terms of design? If so, what are they? 3. Do you approve of the final design of the 3D tactile book developed for SVI?
Implementation & Evaluation	Semi-structured Interview 1. How would you evaluate the general features (design, usability, etc.) of the developed 3D tactile book? 2. How would you evaluate the educational features (student characteristics, targeted skills, motivation, etc.) of the developed 3D tactile book? 3. What could be the problems encountered while using the 3D tactile book developed for SVI? 4. What could be the suggested solutions regarding the problems encountered while using the 3D tactile book developed for SVI ? 5. What are the features you suggest changing or improving (if any) in the developed 3D tactile book?

3.3. Sampling or Study Group

In design and development research, researchers, participants, field practitioners, and users involved in the process work collaboratively. Participant selection in these studies varies according to the research objective and the instructional design stages (Richey and Klein, 2007). In this research, different participant groups were used in the analysis, design, development, implementation, and evaluation phases. Purposive sampling methods were employed to determine participants; specifically, the snowball sampling technique was used in phases 1 (analysis) and 4 (implementation & evaluation), while simultaneous convenience sampling and criterion sampling were used in phases 2 (design) and 3 (development).

Phase 1. In order to identify learner and teacher needs related to 3D tactile book set and to establish initial design principles accordingly, the participants of Phase 1 consisted of 20 teachers who were graduates of either a visually impaired education program (n=18) or a primary school teaching program (n=2) and were actively working in schools for the visually impaired at the time of the study. Of the 20 participants, 14 were female, and 6 were male. Regarding educational attainment, 16 held a bachelor's degree, 3 a master's degree, and 1 a doctoral degree. All participants held undergraduate degrees from either Gazi University, Department of Special Education (n=18), Ondokuz Mayıs University, Department of Primary Education (Ö18), or Celal Bayar University, Department of Primary Education (Ö19). The majority specialized in Education of the Visually Impaired, while Ö18 became a special education instructor through a certificate program organized by the Ministry of National Education (MEB), and Ö19 served as a classroom teacher. Among those with postgraduate degrees, Ö6 and Ö11 earned their master's degrees at Gazi University, Ö3 completed a master's degree at Western Michigan University, followed by a doctorate at the University of Arizona, and Ö12 completed a master's degree at Master Reading University.

Phase 2 & Phase 3. The participants in this phase are the members of the design validity committee who played an active role in the design and development process of the primary prototype. The design validity committee consisted of seven members (four male, three female), all affiliated with Dokuz Eylül University, except for one member employed at the Ministry of National Education (MEB). Six of the seven

members held doctoral degrees, while one held an undergraduate degree. The members' areas of expertise varied across several fields, including Computer Education and Instructional Technology (CEIT) (n=3), Special Education (n=1), Classroom Teaching (n=1), Turkish Language Education (n=1), and Education of the Visually Impaired (n=1).

Phase 4. The participants of Phase 4 included 18 participants (seven male, eleven female) drawn from universities and the Ministry of National Education (MEB). In terms of institutional affiliation and role, three participants were faculty members at Antalya AKEV University, Anadolu University, and Ege University respectively, while three others served as research assistants at Gazi University, and one participant was affiliated with the University of Arizona. The remaining eleven participants were teachers employed by MEB. Regarding educational background, seven participants held bachelor's degrees, seven held master's degrees, and two held doctoral degrees. In terms of expertise, the majority specialized in Education of the Visually Impaired (n=11), followed by Special Education (n=4) and Computer Education and Instructional Technology (CEIT) (n=3).

3.4. Data Analysis

Qualitative data obtained from focus group interviews and semi-structured interviews were analyzed using content analysis through the model proposed by Creswell (2007). Content analysis is a qualitative data analysis method that aims to identify concepts and relationships that explain data from a text or a collection of texts (Yıldırım and Şimşek, 2018). As for the familiarization of the data, the audio recordings of focus groups and semi-structured interviews were examined and transcribed separately by the researchers without any changes. Following that, researchers determined a reference transcript for coding for each data gathering method. At this stage, each researcher noted what was considered important and discussed it to reach a consensus before initiating the coding procedure. The transcripts and audio recordings were matched, and the consistency between them was evaluated. After organizing the qualitative data for analysis, the researchers proceeded to code and develop themes. Primarily, the researchers generated initial codes from the transcripts. After eliminating all conflicting and overlapping codes until a consensus was reached on the code list, the researchers proceeded to the next stage, generating the themes and sub-themes. analyzing the other interviews. The remaining interviews were all analyzed by using this six-stage cycle.

Validity and Reliability

During the content analysis of all the obtained qualitative data, assistance was provided by an independent field expert from the Department of CEIT, who is experienced in content analysis. After independently creating sub-themes and categories, the expert compared the researchers' sub-themes and categories with her own. This process continued until consensus was reached on the themes. Inter-coder reliability was calculated using the equation "Reliability = Agreement / (Agreement + Disagreement) x 100" (Miles and Huberman, 1994). A value of .70 obtained from this equation is considered acceptable in many qualitative data analysis studies (Miles and Huberman, 1994). In the analyses conducted within the scope of this study, inter-coder reliability was found to be higher than .70 ($\kappa = .93$), indicating reliable coding. In addition to inter-coder reliability, participant confirmation was used to ensure credibility. In face-to-face interviews, participants were asked at the end whether they had any additional points to add, whether they would make any changes to the points they had previously stated, and whether the interviews in their current form were suitable for data analysis. In online interview forms, participants could view and edit their answers to the interview questions later. In addition, to ensure transferability, the results were presented by including direct quotations from the participants and by adhering to the form in which the researcher obtained the data from the primary source (Yıldırım and Şimşek, 2018).

3.5. Research Procedures

The DDR research process was structured across four iterative phases (as mentioned in 3.1. Research Design): analysis, design, development, implementation, and evaluation. During the analysis phase, semi-structured interviews were conducted with 20 teachers holding degrees in visual impairment education to identify learner and instructor needs related to a 3D tactile book designed for students with visual impairments (SVI). The design decisions derived from this phase were subsequently reviewed with teachers

employed at a school for the visually impaired in İzmir, following which Turkish language course was selected as the target subject area, and fourth-grade primary school students who had already acquired Braille literacy were identified as the target learner population. In the design phase, the development process was guided by a design validity committee comprising field experts and a classroom practitioner specializing in visual impairment education. The committee's feedback informed all major design decisions prior to prototype development. During the development phase, storyboard drawings for the 3D tactile book were prepared and an initial prototype was produced based on the findings of the preceding phases. The emergence of the first prototype initiated a series of iterative design cycles conducted with the active participation of the validity committee. The prototype was revised based on feedback from each cycle and resubmitted for committee review. The finalization of the 3D tactile book was achieved through three successive design cycles. In the implementation and evaluation phase, semi-structured interviews were conducted with experts in special education, and computer education and instructional technology. The interviews aimed to identify practical challenges that might arise during classroom use of the finalized book set, to gather expert-recommended solutions to potential problems, and to obtain design and pedagogical evaluations of the material's classroom applicability. Given that specialists in visual impairment education are relatively few in number and are geographically dispersed, a video introducing the book set and demonstrating its detailed use was produced and shared via YouTube (<https://www.youtube.com/watch?v=uCyRUufFQKI>) prior to the interviews. The video presented both the tactile book and the accompanying website, and expert opinions were subsequently collected through Google Forms.

4. Findings and Discussions

Phase 1: Needs Analysis

Teachers who participated in the interviews reported that they experience the greatest difficulty in teaching abstract concepts to students with visual impairments (*T2: "... Abstract concepts need to be concretized"*). This challenge is followed by content areas that require visual representation (*T5: "... it is difficult to explain to children because it contains too much visual content, especially shapes"*) and independent living skills. Turkish language courses emerge as the most prominent domain of difficulty (*T14: "... poorly described stories in Turkish, grammar rules, and non-tactile activities in art classes"*) when evaluated by subject area. In addition, Mathematics, Science, and Geography are also frequently identified as subjects in which students encounter significant challenges.

Teachers evaluated existing tactile books positively, particularly in terms of engaging multiple sensory modalities (*T19: "Students with visual impairments often have to rely more on their listening (auditory) skills in lessons. However, many students prefer to read and understand through touch. When our verbal descriptions are insufficient for their comprehension, allowing them to feel through touch becomes more enjoyable for them. Therefore, tactile books are beneficial"*), facilitating the concretization of abstract concepts (*T2: "... They help us concretize abstract content"*), and enhancing retention in learning (*T10: "... Tactile books should definitely be included in the education of visually impaired individuals. They are important because they make learning easier and improve retention"*). In addition, teachers identified support for individuals with total visual impairment, usability, and the provision of direct experiential learning as further positive features, each mentioned by at least one participant. The aspect of creating direct experience is particularly noteworthy, as it enables students to establish—even symbolically—contact with objects they would not be able to physically access in real life (e.g., a beehive or geographical landforms).

The most frequently reported complaint regarding existing tactile books was related to usability (*T2: "They should be ergonomic. They should be easy to carry and use. They should not negatively affect human health. ... they are very bulky and quite difficult for children to carry. However, we do not have more practical materials available to use"*). Existing books were evaluated as cumbersome, difficult to transport, and prone to rapid wear and tear. This was followed by concerns regarding limited production (*T8: "Although*

the number of these books and the printers producing them has been increasing, I still think they are insufficient. They could be further developed, and both the quantity and quality of tactile books on the market are inadequate”), insufficient multimedia support (T9: “... not sufficient, especially for graphs and tables. We experience difficulties with texts that include figures. Since activities are visually based, we have trouble benefiting from standard textbooks”), and the lack of up-to-date and comprehensive instructional content (T7: “They are useful, but the publications mostly contain outdated content; books with more examples and broader content should be used”).

Teachers provided recommendations for the planned 3D tactile book across 29 sub-themes, which were grouped under four main themes: stimulus diversity, compliance with material design principles, content diversity, and alignment with learner characteristics. The majority of teachers emphasized that the book should not appeal solely to the sense of touch; rather, auditory elements - and, if possible, olfactory components - should also be integrated into the design (T14: “... I do not think it is appropriate to reduce this solely to tactile elements. Actively incorporating sound could make it more effective. ... Touch is not the only alternative sense to vision; hearing should also be included”). In addition, it was suggested that tactile stimuli should be enriched through the use of varied textures (T7: “I think it should be more distinguishable and understandable, and that different tactile stimuli could be used”). The most emphasized material design principle was fidelity to real-life representations (T10: “If the images or other three-dimensional elements in the book can be designed as close to reality as possible, it would provide the most accurate education”). Reflecting direct criticisms of existing materials, durability (T14: “... using non-deformable raised texts and images would be effective for longer-term use”) and ergonomics (T7: “It should be ergonomic. It should be easy to carry and use”) were also highlighted as priority considerations. Furthermore, it was strongly emphasized that the book should avoid overly complex structures and present content aligned with standard textbooks (T4: “You can start with textbooks, because students in inclusive classrooms cannot learn the same content as their peers since the books remain too abstract for visually impaired students. This way, you can also reach a much larger audience”). Another notable recommendation was the differentiation of the book according to levels of visual impairment (T18: “For students with low vision, color contrast should be considered; for totally blind students, images should be presented in raised form if possible, or otherwise described verbally”). Accordingly, large print and high color contrast were suggested for students with low vision, while Braille text and raised graphics were recommended for students with total visual impairment.

Table 2

Outcomes of Needs Analysis

Design Decisions
It was primarily decided that textbooks - particularly in Turkish, Mathematics, and Science - would serve as the foundational basis for content development.
Additionally, it was determined that concepts with which students cannot establish direct physical contact, such as animals and natural elements, should be included within the scope.
Design Principles
<i>Material Design Principles</i>
Objects and visuals should be designed to closely resemble real-life counterparts.
Proportional scaling should adhere to original dimensions.
The design should remain simple, avoiding unnecessary details.
Complex content should be presented progressively, in line with the principle of sequencing.
Abstract concepts should be transformed into concrete, tangible forms.
Comprehensibility should be prioritized; explanatory texts should be concise and focused.
3D objects and Braille texts should be used in an integrated manner.
Durable, deformation-resistant materials should be utilized.
The design should be ergonomic and easy to carry.
Readability should be ensured.
The material should be producible at low cost.
<i>Content Diversity</i>

The material should address not only the sense of touch but at least two sensory modalities.
 Audio components (e.g., narration, sound effects) should be integrated, while olfactory stimuli may be optionally included.
 Tactile stimuli should be diversified through the use of varied textures.

Alignment with Learner Characteristics

High color contrast and large font sizes should be used for students with low vision.
 Braille text and raised visuals should be provided for students with total visual impairment.
 Content and materials should be adapted according to different age groups.

Phase 2. Design

The design decisions made during the analysis phase were reviewed with teachers working at a school for students with visual impairments in İzmir. Based on these consultations, it was decided that the Turkish language course would be selected as the content focus, and that the study would be conducted with fourth-grade primary school students who had already acquired Braille literacy. Following this decision, the design phase of the book was initiated. The design process was carried out in line with the input of a design validation committee consisting of field experts and a teacher of students with visual impairments as a classroom practitioner. The committee's feedback is presented under three main categories: the selection of reading texts to be included in the tactile book, design decisions regarding how these texts should be adapted according to the characteristics of students with visual impairments, and the material design principles guiding the development of the book.

Selection of Book Texts

The design validation committee recommended that the texts to be included in the 3D tactile book be selected from the compulsory themes in the fourth-grade primary school Turkish textbook (Childhood World, National Struggle and Atatürk, Virtues, and Our National Culture), with a particular emphasis on texts containing abstract concepts. They further emphasized that including different text types would be beneficial both for enhancing students' awareness of text genres and for enabling a more comprehensive evaluation of the study, as reflected in the following statement: E5: "... *Students would gain an understanding of each genre; for example, one informative text, two narrative texts, and one poem.*" In addition, the field expert in primary education suggested that narrative texts should be prioritized for this age group and that text selection criteria should be carefully examined in accordance with the standards outlined in the national curriculum (E5: "... *The criteria for texts to be included in textbooks by the Ministry of National Education are already defined.*"). Based on these considerations, the experts reached a consensus to include four texts representing three different genres (informative, narrative, and poetic) in the tactile book. Under the guidance of the Turkish language education expert, the selected texts were as follows: Friendship (poem) from the theme Childhood World; Müstecip Onbaşı (memoir) from National Struggle and Atatürk; The Stork and the Fox (fable) from Virtues; and The Frog Who Wanted a Voice (story) from Our National Culture.

Adaptation of Texts to Learner Characteristics

Experts in Special Education and Primary Education, along with a teacher of students with visual impairments, emphasized that concretization serves as a fundamental instructional strategy in educational activities conducted with students with visual impairments. Accordingly, they stated that the selected texts should be adapted to learners' specific needs by incorporating contexts that enable the concretization of positional concepts and spatial relationships between objects (E4: "... *for example, concepts of position such as under, above, next to, entering into, or exiting from something. ... We can work on relationships between objects, and if we can capture these within the texts, it means we have concepts that can be represented as tangible objects.*"). In this context, the design validation committee unanimously decided that the texts should be adapted accordingly, that the objects and concepts embedded within these texts

should be designed as 3D representations, and that these elements should subsequently be integrated into a cohesive book structure.

Findings on Design Principles

The design validation committee emphasized that the tactile book should be both durable for tactile use and sufficiently lightweight for students to carry (E3: *"It should be a material that can be given to the student and taken home to study with their family when needed,"* E5: *"Could the material be softer? 3D prints are usually made from very hard materials and may break with repeated touch"*). The primary objective of this design principle is to enable students to use the book not only in school but also in out-of-school learning environments, such as at home with family members. Another factor discussed regarding the physical properties of the book was its size. In order to prevent unfamiliarity for students and to ensure seamless integration into daily school routines, consensus was reached that the tactile book should be designed in dimensions similar to standard textbooks (E5: *"The size of the book will be similar to standard textbooks, right?"*, E6: *"I think it should be"*). Additionally, the primary education expert suggested that the three-dimensional objects associated with the book should be provided in a lightweight, compartmentalized box, which would enhance both durability and usability. Furthermore, to support students' independent access to and use of the tactile book and its 3D components, it was recommended that clear usage instructions be included in Braille within the book (E4: *"They will use it together with Braille instructions... For example, 'The materials for the first page of this book are located in this box. They are in the triangular compartment; you can take them out'"*).

Another notable design recommendation emerging from the design validation committee was the development of a dedicated website for the tactile book and the sharing of the developed 3D models with the public through an open-access digital platform. It was emphasized that making these files accessible online would enable teachers to easily download and utilize them in their own instructional contexts (E1: *"... if you had a website at the end... to introduce the project. Perhaps the models produced here could be shared there and made available to teachers in any school. Those who access it could easily download the files and print them. Because such original materials are very limited in Turkey"*).

During the development of the initial prototype, the design decisions related to content and the design principles guiding the prototype are presented in Table 3.

Table 3

Outcomes of Design Phase

Design Decisions
It was decided to include different text types - namely narrative texts, informative texts, and poetry - in the book. The selection of these texts was carried out in accordance with the criteria outlined in the national curriculum of the Ministry of National Education.
Accordingly, four texts representing different genres were selected for the development of the 3D tactile books: Friendship (poem), The Stork and the Fox (fable), Müstecip Onbaşı (memoir), and The Frog Who Wanted a Voice (story).
Design Principles
<i>Material Design Principles</i>
Materials should be adapted to the specific needs and developmental levels of students with visual impairments (VI).
The materials used in the book should be durable and portable.
Clear and explanatory instructions should be included to support independent use of the book.
The 3D models of characters and objects included in the book, as well as audio narrations of the texts, should be shared with the public within an open-access framework.
A dedicated website should be developed to disseminate digital multimedia elements that support the book.

Phase 3: Development

During the development phase, based on the findings obtained from the analysis and design stages, storyboard drawings for the 3D tactile book were created and the initial prototype was developed. Following the emergence of the first prototype, iterative design cycles were initiated with the active involvement of field experts and the classroom practitioner; the prototype was revised in light of the feedback received and resubmitted to the committee for further evaluation. The process of reaching the final version of the 3D tactile book was completed after three design cycles.

Design Cycle 1: Development of the Initial Prototype

Design Cycle 1 began with the development of the initial prototype. During this process, the researchers collaborated synchronously and ubiquitously with members of the design validation committee through Web 2.0 tools, and the prototype was refined through collective feedback. Storyboards for the initial prototype were prepared digitally using MS PowerPoint, followed by brief consultations with committee members to assess their appropriateness. The storyboards included representative placements of the book cover designs, multimedia elements to be included on each page, and instructional components. After the committee members unanimously approved the storyboards, the modeling phase was initiated. An example of the storyboard is presented in Figure 1.

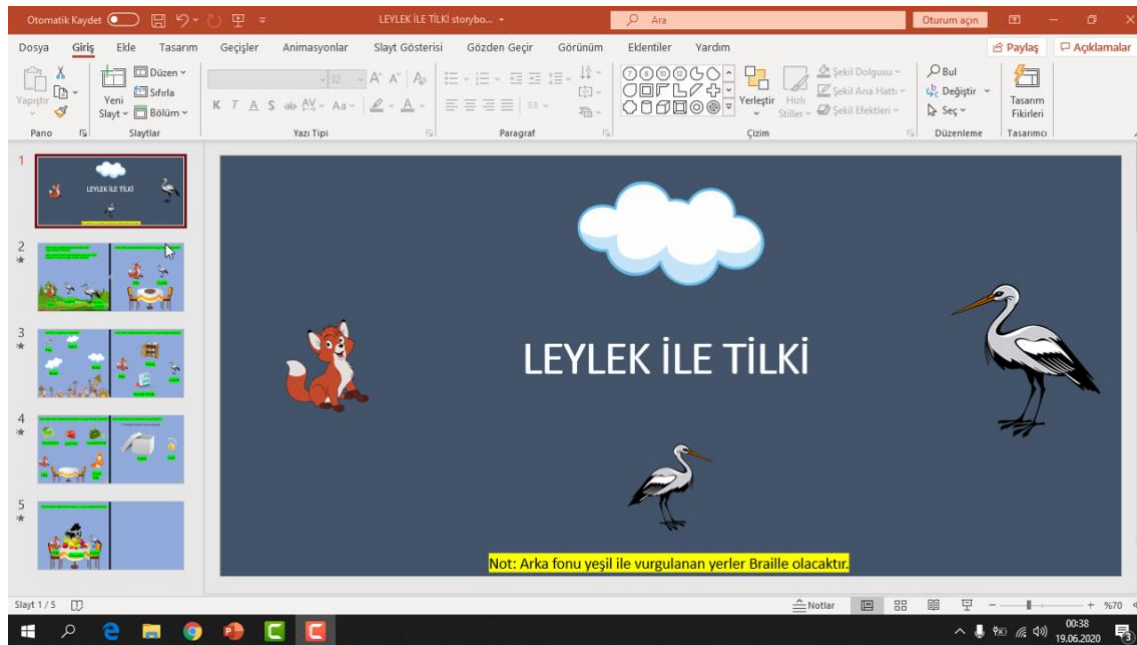


Fig 1. Storyboard for The Stork and the Fox

During the modeling process, Tinkercad and SketchUp software were utilized; while the majority of the designs were created using Tinkercad, finer details were refined with SketchUp (Figures 2, 3, 4, and 5).

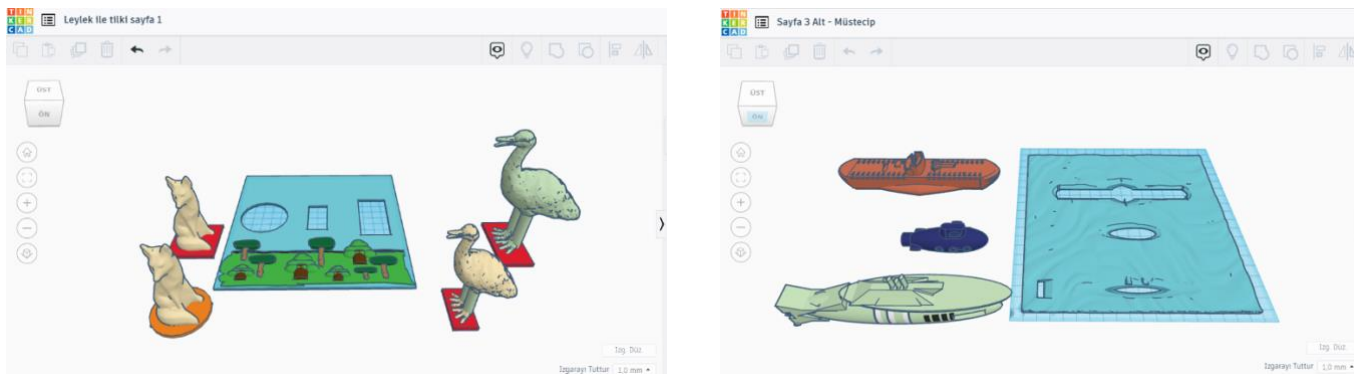
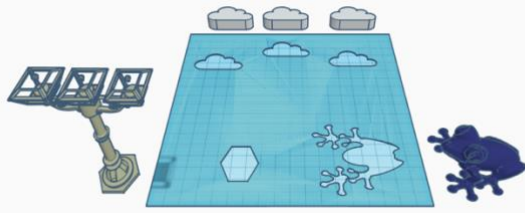
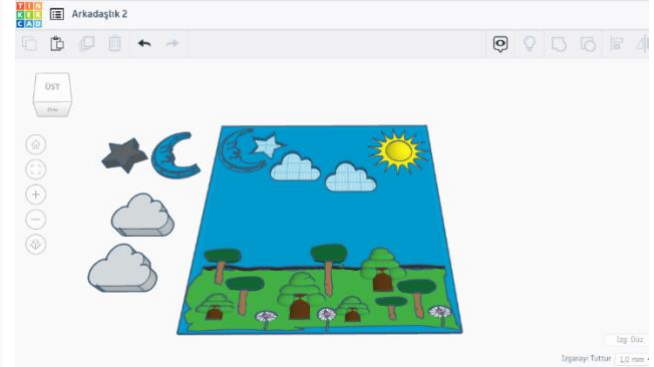
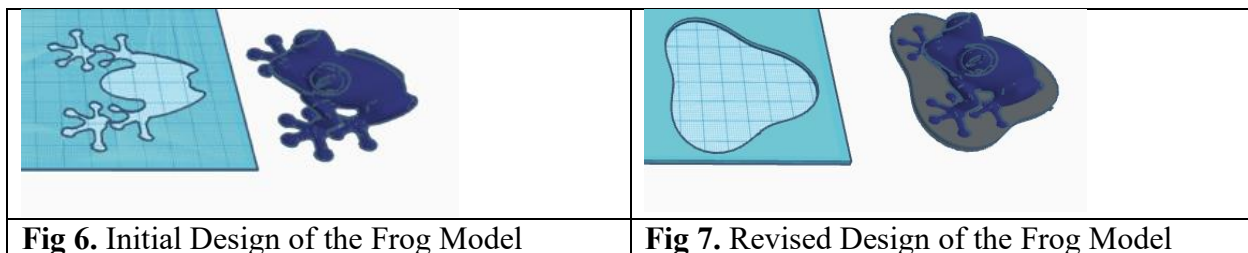


Fig 2. Page 1 Design of The Stork and the Fox Text**Fig 4.** Page 2 Design of The Frog Who Wanted a Voice Text**Fig 3.** Page 3 Design of the Müstecip Onbaşı Text**Fig 5.** Page 2 Design of the Friendship Text

Layout schemes based on the narrative structure were designed by the researchers, while characters and objects were created using pre-existing models selected from the Tinkercad library. During the printing process, Ultimaker 3 and Ender Pro printers were used in conjunction with Cura slicing software; a total of approximately ten filaments (PLA+ and ABS) were consumed. Printing durations varied depending on model complexity: 2.5-dimensional base designs were completed in approximately 18 hours, whereas the 3D stork model required an average of 9 hours. The number of printed components per text was 23, 10, 12, and 10, respectively. The complete and error-free production process took approximately one month for The Stork and the Fox and three weeks for each of the remaining three texts. Throughout the process, frequent production errors caused by filament clogging were encountered.

During the development of the initial prototype, revisions were made based on the researchers' design experiences and the feedback of the design validation committee. The selected models were adapted in terms of size and form to align with the tactile perception characteristics of students with visual impairments. For instance, certain models such as the stork and the frog, which have structurally thin legs and therefore limited tactile base surfaces and increased fragility when printed, were modified by adding geometric base supports (Figure 6 and Figure 7).



After the printing process, 3D objects that contained excessive detail leading to potential confusion for students or that failed to accurately represent real-life counterparts were replaced with simpler and more realistic versions. For instance, certain 3D objects that were not aligned with Turkish cultural context (e.g., a street lamp) were redesigned accordingly (Figure 8). In addition, the primary education expert suggested that presenting the fox in a standing position would facilitate better comprehension for students. Based on this feedback, a standing model of the fox was designed and printed (Figure 9). These revisions aimed to enhance students' ability to interpret the models, improve the durability of the materials, and facilitate the spatial placement of objects on the book surface.

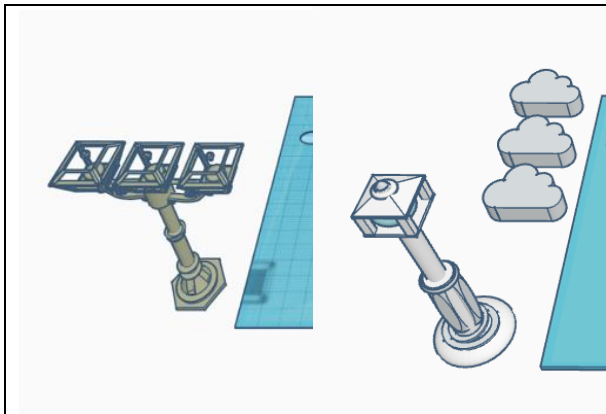


Fig 8. Initial and Revised Designs of the Street Lamp Model



Fig 9. Initial and Revised Designs of the Fox Model

The special education expert involved in the design validation committee emphasized that visual impairment exists along a broad spectrum, with some students being totally blind while others fall into the low vision category. Accordingly, it was suggested that, in order to address a wider range of learners and to make use of color cues for students with low vision, the characters in the developed books should be colored in a manner consistent with real-life representations. This recommendation was approved by the design validation committee, and the prototype was revised accordingly.

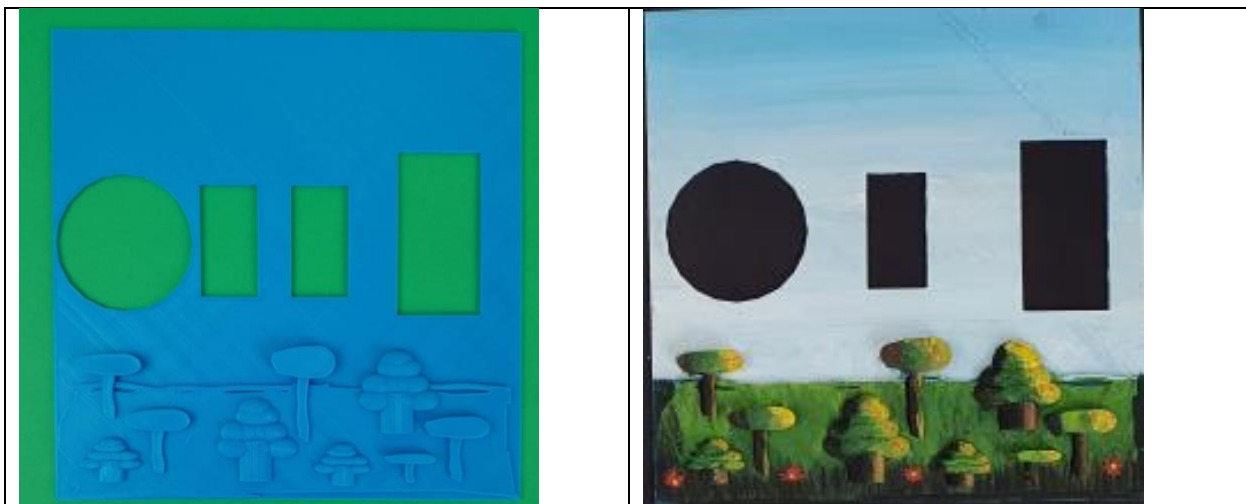


Fig 10. Initial and Revised Designs of a Page Design

In line with the design decisions made during the design phase, a website was developed using a PHP and MySQL-based WordPress infrastructure to support the book content and provide open access. The domain dokunsakitap.com.tr was purchased for two years, and a subdomain was configured to make the platform accessible via dokunsakitap.com.tr. To enhance accessibility, the “One Click Accessibility” plugin was integrated, offering features such as grayscale mode, high contrast, negative contrast, light theme, underlined links, and readable font options. To facilitate easy access to the website, it was proposed to include QR code visuals on the book covers directing users to the platform. Accordingly, users can access the site either by directly entering the URL in a browser or by scanning the QR code using a mobile device camera. Finally, the four selected texts were narrated by a senior student in a Turkish Language Teaching program.

Design Cycle 2

In line with the decisions made during Design Cycle 1, a second prototype was developed and presented to the design validation committee for evaluation. The committee, composed of field experts, expressed generally positive views, emphasizing that the integration of 3D objects, Braille text, and auditory materials constitutes a significant strength in terms of simultaneously addressing multiple sensory channels (E7: *"Fatih has made a great effort; it is a very good method. There are three-dimensional objects, written text, and audio—the child can listen to the story. It is very effective, as it appeals to the learner through three different modalities"*). However, in order to reach the final form of the design, the experts also provided critical recommendations for improvement, particularly regarding physical usability and pedagogical appropriateness.

Physical usability evaluations were addressed within the contexts of portability, structural integrity, and hygiene. The majority of experts indicated that the books present certain limitations in terms of portability; specifically, the large number of 3D components included in the materials may negatively affect both their weight and ease of transport. This situation was noted to pose challenges not only for students in carrying the materials home but also for teachers in terms of storage and organization (E4: *"... transportation is always a problem,"* E5: *"Within the scope of the current project, storing and carrying these materials in a box certainly presents difficulties for teachers..."*). As a potential solution, it was recommended to design a dedicated storage box in which each component has a defined place, and it was agreed that this would be implemented in the next prototype (E7: *"Yes, could it be boxed? For example, the spelling guide came in a wooden box. Although that one was heavy..."*). The design validation committee also emphasized that, given the intensive tactile use by multiple students, deformation or breakage of book pages, Braille text outputs, and 3D objects would be inevitable (E7: *"They constantly touch, press, pull, and open things with their fingers. While trying to understand what something is, they may damage or break it more quickly"*). As solutions, the use of durable materials such as cardboard for book pages, the production of backup copies of Braille texts and 3D objects (E1: *"Sometimes the stork's legs can break even before it reaches the student. Therefore, such delicate materials should be produced with backups—not one stork, but two or three"*), and the use of flexible filaments in 3D printing were recommended (E1: *"There are materials called flexible filaments. These are generally imported and are highly resistant to breakage because they can bend"*). The multi-user nature of the materials also raises concerns regarding hygiene. In this regard, it was suggested that the materials should be designed in a way that allows for easy cleaning after each use (E1: *"After the pandemic, concerns about hygiene have increased. These materials need to be cleaned after use, as they are handled extensively"*).

The most frequently emphasized sub-theme was adaptation, referring to the need to revise materials in accordance with learner characteristics within the theme of pedagogical appropriateness. The design validation committee reached a consensus that adding Braille labels directly onto 3D models—previously considered as a design decision—could negatively affect students' exploratory learning processes. Accordingly, this practice was discontinued (E4: *"If the student is with the teacher, the teacher can already explain which one is the frog. Braille cues can be provided when the student is alone,"* E1: *"In a way, it may also lead to cognitive laziness—'What is this? Oh, it's a frog.' It would be better if they could perceive it through tactile exploration"*). Adjustments were also made regarding the placement of multimedia elements, and a standardized page layout was established by consensus: Braille text on the left page, 3D materials on the upper section of the right page, and Braille instructions on the lower section of the right page (E4: *"It would be more convenient if the instructions and Braille reading points are located at the bottom, closer to the user"*). Additionally, it was noted that the narration speed on the website was perceived as too fast and should be reduced (E5: *"I found the narration generally too fast; I think this should be adjusted as well"*).

Finally, due to the inclusion of multiple design components in 3D tactile books (e.g., videos, storage boxes, 3D prints), it was suggested that a concise parent–teacher guide should be developed to address the use,

maintenance, and storage of the materials (E5: “A general teacher guide could be included, explaining how such materials should be preserved, stored, and used—without being overly long”).

During the development of the second prototype, the design decisions reflecting revisions made in line with the researchers’ design experience and the feedback of the design validation committee are presented in Table 4.

Tablo 4

Design Revisions Based on Cycle 1 Decisions

Design Revisions

The inclusion of Braille labels directly on 3D models was discontinued; instead, the principle of enabling students to independently explore materials through tactile interaction was adopted.

Backup components were produced for fragile and delicate 3D objects, and duplicate copies of Braille texts were generated.

A dedicated protective storage box was designed, with designated compartments for each component.



Rigid and durable cardboard was used for the book cover and pages.



A standardized layout was established in a double-page format, with Braille text placed on the left page, 3D materials positioned in the upper section of the right page, and Braille instructions located in the lower section of the right page.

A parent–teacher guide was prepared in PDF format and uploaded to the website.

To enable adjustment of narration speed, the audio recordings—along with an introductory video of the book—were uploaded to YouTube and made accessible via the homepage of the website.

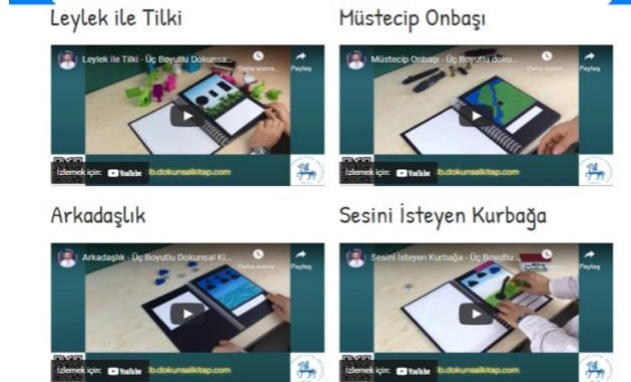
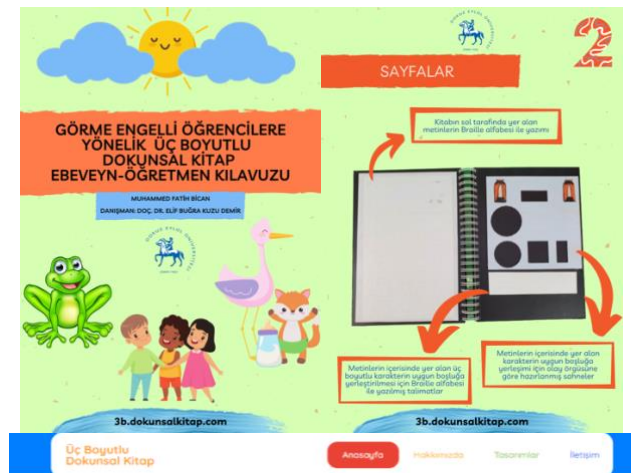
The Stork and the Fox
<https://www.youtube.com/watch?v=z71MkvMOASU>

Müstecip Onbaşı
<https://www.youtube.com/watch?v=2iocgaLHpgo>

Friendship
<https://www.youtube.com/watch?v=6tS5Kcn0GMk>

The Frog Who Wanted a Voice
<https://www.youtube.com/watch?v=bXeDR1j6BuM>

On the “Designs” subpage of the website, downloadable 3D model files of the materials included in the book were provided for use as needed.



Design Cycle 3

In line with the decisions made during Design Cycle 2, a third prototype was developed and presented to the design validation committee for evaluation. Considering the 3D tactile book and its associated components (books for four different texts, 3D models, a parent - teacher guide, and additional Braille outputs), the prototype evolved into a comprehensive book set and was subsequently termed the “3D tactile book set.” During the third focus group meeting, the design validation committee, composed of field experts, evaluated the overall design of the 3D tactile book set. The committee unanimously concluded that the set was developed in accordance with the fundamental design principles, that all feedback provided during the second cycle had been fully addressed, and that the product had reached a level suitable for use by SVIs.

E3: *“I believe this is a highly meaningful product, particularly in the context of producing materials for individuals with visual impairments through three-dimensional printing technologies.”*

E2: *“I also really liked it. The use of black color, contrast, readability, and color harmony all reflect adherence to many design principles. The size is also very appropriate. I find this final version highly successful.”*

In response to the question regarding potential deficiencies or suggested revisions, the majority of experts did not raise any criticisms. Only one expert, rather than proposing changes to the current product, suggested that future developments could incorporate flexible filaments to create materials that appeal to a wider range of tactile sensations. Regarding the approval of the final design, all experts explicitly stated that they found the product successful and unanimously agreed that the current prototype could be accepted as the final design without requiring any further revisions.

E6: *“I also approve it. As I mentioned earlier, I think it is now usable. It has reached a stage where it can be presented to students.”*

E2: *“Absolutely. I approve it. I have already stated that I find it successful at this stage. I also really liked the color harmony.”*

The design criteria that emerged throughout the iterative cycles of the development phase are presented in Table 5.

Table 5

Design Principles Derived from Development Phase

Design Cycle 1
Geometric supports (e.g., bases) should be added to models to prevent breakage during tactile exploration.
3D models should be designed in simple, clear forms that avoid unnecessary complexity and accurately represent real-life objects.
To enhance inclusivity, characters should be colored in a realistic manner so that students with low vision can also benefit from the materials.
To improve accessibility, quick and easy access should be ensured between the physical material (3D tactile book) and the digital platform (website) via QR codes.
Given the time-intensive nature of 3D printing processes, planning should be conducted accordingly.
Design Cycle 2
A compartmentalized storage box should be designed, with dedicated sections for each object to ensure safe storage of materials.
A consistent layout should be maintained throughout the book to enhance learner familiarity.
Backup production should be implemented to address faulty outputs and fragile 3D objects.
Durable and robust materials suitable for intensive use should be preferred for binding and outer covers.
3D models should be designed in alignment with the cultural context of the target group (e.g., appropriate forms of street lamps).
Parent/teacher guides that include instructions for use and maintenance should be integrated into the system.
Audio narrations in digital content should be delivered at a slow and clear pace, appropriate to the cognitive processing speed of the target audience.
Design Cycle 3
No further design principles were emerged in this phase.

Phase 4 & 5: Implementation and Evaluation

Expert evaluations of the general features of the 3D tactile book set revealed that findings converged around two primary themes: design and usability. The design theme encompasses sub-dimensions including aesthetic quality, dimensional appropriateness, structural durability, visual-tactile simplicity, and craftsmanship. The majority of experts noted that the material was successfully designed in both visual and tactile terms, with the 3D objects produced in dimensions appropriate for children's palmar grip. One

particularly representative evaluation regarding the book's alignment with its target audience was as follows: E18: *"This book is suitable not only for those with total visual impairment but also for those with low vision. In particular, the contrast of the materials turned out very well."*, E9: *"The size of the materials is critically important in that it should allow children to touch and grasp them comfortably with their hands. In this respect, the dimensions of the materials were found to be appropriate."* This simplified design approach was noted as an important factor that enhances functional accessibility for individuals with low vision through color contrast. It was also emphasized that the thick page structure prevents deformation, while the 3D-printed objects demonstrate durability suitable for prolonged use (E7: *"The durability of the pages and the robustness of the materials are satisfactory. This is particularly important for students with visual impairments, as it ensures sustained usability during intensive tactile interaction."*).

The usability theme attracted the highest frequency of expert commentary and covers sub-dimensions such as functionality, ease of access, reusability, and portability. It was particularly emphasized that the Braille-supported page layout facilitates reading comprehension, while QR code integration enables audio playback of the text, thereby reducing reliance on parental assistance. The fact that the book simultaneously stimulates multiple sensory channels was considered an especially valuable feature by experts: E6: *"The placement of the text in Braille on the left page and the arrangement of related visuals as 3D elements on the right page are appropriate. By rereading the text and interacting with the 3D objects, students can achieve a deeper understanding of the content and enhance their cognitive engagement. In this way, the absence of visual input can be compensated for through the effective use of other sensory modalities, such as tactile and auditory perception."*

Experts also evaluated the educational features of the 3D tactile book set, and all agreed that the book is appropriate for the developmental characteristics of 4th-grade SVIs (E12: *"I believe that the target group - fourth-grade students—will be able to use the book without difficulty"*). The findings regarding the educational features of the 3D tactile book set converged across the dimensions of motivation, cognitive contribution, motor skill development, learning retention, and peer learning.

In the dimension of motivation, it was underscored that enriching the typically abstract and theory-bound learning experiences of SVIs through concrete, multi-sensory materials would have a decisive impact on motivation (E8: *"Even for typically developing students, using materials is very effective; in the education of students with visual impairments, education without materials is unthinkable. In this respect, their motivation and interest in lessons will certainly increase"*). As for cognitive contribution, experts indicated that the book facilitates higher-order language skills such as vocabulary development, story writing, and narrative diversification. Given that SVIs perceive the world through tactile exploration but encounter difficulties in comprehending large objects that require holistic touch, the 3D models were assessed as effectively bridging this gap:

E15: *"Students with visual impairments perceive the world through their fingertips, but they cannot grasp some things holistically... Thanks to the developed three-dimensional models, they will have the opportunity to recognize many things. It is an advantageous material for concrete storytelling and skill development"*.

Regarding motor skill development, experts noted that attach-detach activities simultaneously target multiple learning outcomes beyond reading skills alone. Therefore, it supports fine motor skills and strengthens tactile awareness, which, in turn, increases the retention of learned information. (E16: *"Considering that not only students' reading skills but also their tactile awareness and fine motor skills will be supported, it may be possible to achieve multiple learning outcomes"*, E9: *"Touching the characters they read about in the story will provide an incredibly lasting experience for the child"*). In the context of peer learning, the material's suitability for group work and family-supported home learning was viewed positively (E9: *"I think this is a well-designed resource for active learning. It provides an excellent opportunity for group work or for studying with a friend or a sibling at home."*)

Although all the participants expressed positive views on the book design, there are certainly some concerns regarding the use of the book in the classroom. The participants identified potential difficulties in durability,

security, portability, and familiarity. Below, the participants' views and their proposed solutions on these difficulties are presented.

In terms of durability, it was noted that Braille page inserts may detach from the book (E2: *"While using the book, the Braille pages inside may come loose"*) and Braille text may fade with intensive use (E10: *"With repeated use, the materials may deteriorate, and the Braille text may become less legible"*). This was expected to gradually diminish the material's functionality, particularly in classroom settings where multiple students share the same material. To address the issue of Braille page inserts becoming detached, a fixative adhesive or binding system that does not interrupt the student's tactile contact was recommended. From an activity management perspective, it was recommended that students systematically touch all materials in sequence before beginning the activity to recognize and categorize objects by function. This pre-recognition phase was assessed as capable of both reducing search time and generating an additional educational outcome by fostering classification skills (E6: *"Before starting the activity, it would be good for the student to touch each object, perceive what it is, and group objects on one side and animals on the other. This way, the student can find what they are looking for more easily and can also make connections between objects and living things while classifying."*).

The most prominent concern in the safety domain was that 3D-printed materials may be sharp or hard. This was assessed as a critical risk factor, especially for students with multiple disabilities who may exhibit a tendency to put objects in their mouths (E9: *"The materials should not be hard or sharp in a cutting manner. If you consider the possibility that a student with multiple disabilities might also use this book."*). The risk of objects accidentally tipping over during desk-based activities was also addressed as a safety concern. To address these concerns, the use of soft-textured, child-safe, and food-grade-certified materials was recommended. The use of magnetic or Velcro-based fastening systems was suggested to prevent objects from tipping over.

From a logistical standpoint, the book's dimensions may complicate portability, potentially limiting its use in out-of-school settings. Furthermore, it was emphasized that the effective use of the material requires family and teacher support and that relevant stakeholders should be briefed in advance (E18: *"They cannot use it entirely on their own. I believe family support is also important. Both families and teachers should be informed about this"*).

Concerns were also raised about whether the relatively longer duration of attach-detach operations might initially create limitations; however, experts predicted that this issue would diminish with increased familiarity with the material (E1: *"The only limitation I foresee is that the attach - detach operations may take longer than necessary. However, I anticipate that this limitation will diminish as students become more familiar with the material."*)

The design criteria that emerged during the Implementation & Evaluation phase, based on the perspectives of classroom practitioners (teachers) and academics, are presented in Table 5.

Table 6

Design Principles Derived from Implementation & Evaluation Phase

Design Principles
3D objects and Braille outputs in the book should be secured to prevent frequent detachment during use.
Material surfaces should be soft-textured and free from sharp or pointed edges.
A separate version should be developed for students with low vision, incorporating large fonts, high color contrast, and enhanced visuals.
The diversity of tactile stimuli in objects should be increased.
An orientation session for material familiarization should be conducted prior to use.
A roadmap should be documented to guide the use of the materials across different subjects and grade levels.

Last but not least, participants were asked to share their viewpoints regarding their suggestions for changes and improvements. Experts' improvement suggestions are presented below.

Among the design suggestions, the most comprehensive suggestion was to expand the booksets' scope to address the needs of students with low vision. Accordingly, visual accessibility measures such as large print, increased color contrast, and clearer drawings and visuals were proposed. Recognizing the difficulty of incorporating all such modifications within a single book set, the preparation of a separate adapted version for students with low vision was also proposed. Participants also recommended expanding the scope and increasing the number of books in the set, advising that future work develop materials covering different subject areas (mathematics, science, social studies), different grade levels, and profiles of students with multiple disabilities. Direct quotations of the participants are: E10: (*"One of the subjects that teachers of students with visual impairments find particularly challenging is mathematics... Materials could be developed for topics such as geometric shapes, fractions, and units of measurement. Similar studies could also be conducted for fourth-grade Social Studies and Science courses"*).

E5: *"It may not be feasible to accommodate both tactile users and students with low vision within the same book. In such cases, a separate version adapted for students with low vision can be developed. In addition, ensuring tactile diversity through the use of different surfaces and textures would be beneficial"*.

Lastly, the use of varied surface textures and materials to enhance tactile diversity was likewise included among the recommendations.

5. Conclusion and Suggestions

This study sets out to derive evidence-based design principles for a 3D tactile book set developed for primary-school SVIs, using a DDR approach. Across four iterative phases (analysis, design, development, and implementation/evaluation) and with continued input from teachers of students with visual impairments (TVIs), field experts, and a design validation committee, the study produced a multimodal 3D tactile book set that brings together three sensory channels: tactile perception through fully 3D page designs, printed Braille texts, book characters and objects; auditory narration delivered through a dedicated open-access website; and visual perception through high-contrast colored elements and digital access to the web-site via QR codes printed on the book covers. As examined in the literature, this combination has not been put together in a single instructional artifact for SVIs at the primary-school level before, and it is the main original contribution of the study.

The wider literature confirms that 3D-printed materials can improve academic achievement, motivation, and social skills in courses for SVIs (Bülbül et al., 2012; Coşkunserçe, 2025; Jafri & Ali, 2015; Sözbilir et al., 2017; Teke, 2017; Zorluoğlu & Sözbilir, 2017). Most of this work, though, has focused on tactile maps (Albouys-Perrois et al., 2018; Arif et al., 2021; Giraud et al., 2017; Holloway et al., 2018; Moustakas et al., 2007; Shi et al., 2019; Urbas et al., 2016) rather than tactile books. The few prior tactile book studies (Ramadan, 2019; Stangl et al., 2014; Wonjin et al., 2016) typically use 2.5-dimensional rather than fully three-dimensional representations and do not combine auditory and digital channels in a systematic way. The present study extends this body of work in three ways: it uses *fully* 3D representations for all main characters and objects; it embeds these objects in Braille-formatted books with dedicated placement compartments and an accompanying parent–teacher guide; and it links the physical object to an open-access web platform that hosts both audio narrations and downloadable 3D model files, so that components can be reprinted when they are damaged or lost (Karbowski, 2020). Furthermore, the literature reveals that studies involving the development and evaluation of 3D tactile books for use in the education of SVIs across different subject areas remain quite limited (Ramadan, 2019; Stangl, Kim, & Yeh, 2014; Wonjin et al., 2016).

How the findings sit alongside the existing literature

Teachers and experts kept returning to one observation: combining touch with audio raised motivation and active classroom participation. Several earlier studies report something similar. Edirisinghe et al. (2018) evaluated a multi-sensory picture book in a special school in Malaysia. They found that the 25 children and

10 educators in the study described the touch-and-sound combination as engaging in a way that print Braille alone was not. Valente et al. (2023) tested a multimodal book whose illustrations referred to haptic and audio modalities rather than visual reality, and reported that blind and low-vision children comprehended the book at the same level and enjoyed the experience. QR-coded audio designs land in the same place. Astuti et al. (2022) attached QR codes to 3D fruit models so that blind primary-school children could trigger audio descriptions in three languages, and Maćkowski and Brzoza (2022) showed that an audio-tactile platform improved memorisation and learning outcomes among blind primary and secondary students. Across very different artifacts and populations, adding a coordinated audio channel to a tactile object seems to do real work rather than just being a nice extra.

Fully three-dimensional objects, rather than the 2.5D raised illustrations more common in tactile book research, supported holistic comprehension and let students grasp shapes that were otherwise too large or too abstract to access through touch. Holloway et al. (2022) report a parallel result with 3D printed maps: in a comparative study with sixteen adults, participants strongly preferred 3D over equivalent 2D tactile maps and understood three-dimensional features (such as ramps and elevation) that 2D could not represent. Sargsyan et al. (2023) extended this to multi-storey buildings and showed that 3D printed models help with spatial elements 2D maps simply cannot encode. Earlier tactile book work that has been described as three-dimensional (Stangl et al., 2014) is more accurately characterised as 2.5D in retrospect (Ramadan, 2019), so treating fully 3D representations as the default rather than the exception is one of the gaps the present study fills.

Braille placement is a more interesting case, because the result here sits in dialogue with the literature rather than simply confirming it. In this present study, experts in Design Cycle 2 asked to remove Braille labels from the 3D objects themselves and to keep Braille reading text and instructions in fixed positions on each spread, on the grounds that on-object labels would let students short-cut the tactile exploration phase. Reinders et al. (2023) document a related concern in interactive 3D printed models: “Braille labels can occupy considerable space, limiting the amount of information that can be conveyed directly on the model. Separate legends can be provided, but these add to cognitive load as blind users may have to constantly shift between the model and the legend.” The field has tended to handle this trade-off by replacing Braille with audio labels triggered by touch (Reinders et al., 2023) or QR codes (Mukhiddinov & Kim, 2021). The present study took a third path: keep Braille in the book, but standardise its position so it does not crowd the object, and add audio at the level of the whole text rather than the individual object. The legibility of 3D-printed Braille is itself sensitive to print orientation and surface quality (Puerta et al., 2024), which is one more reason to keep it on flat printed pages rather than curved object surfaces. Standardised Braille placement is one workable answer to a problem the field has been actively trying to solve.

The same artifact can serve students with low vision and students with no vision when it is designed deliberately around the full range of visual impairment. Real-world coloration on the characters, high-contrast page elements, large print on the cover, and full tactile and Braille access were combined in a single book. Phutane et al. (2022), in interviews with 21 TVIs, document this exact need: most current tactile materials are designed for students with no vision, even though TVIs report that the majority of their students retain some residual vision and rely on large print rather than Braille. The present design responds to that gap directly. Sensory-art work outside the classroom converges on the same principle. Arunthavalingam et al. (2025), designing a tactile diorama for a public exhibition for blind, low-vision, and diverse-needs audiences, used a yellow colour scheme for high contrast and combined Braille, large-font text, and verbal descriptions in one piece. In both cases, the goal is one shared artifact rather than two parallel “special” versions.

Classroom use depends on adult support. Experts predicted students would not be able to use the book entirely on their own and that families and teachers would need a brief orientation. This is consistent with classroom studies of reading instruction for visually impaired students, which document that students typically need help from a sighted teacher or peer for tasks beyond pure Braille reading (Setiawan et al.,

2020), and with the educators' caveats reported by Edirisinghe et al. (2018). One nuance in the literature is worth flagging, though. Maćkowski and Brzoza (2022) report that a well-designed digital layer on a tactile material can reduce dependency: students using their tutoring platform improved learning outcomes while working more independently than they did with traditional Braille books. Read together, the level of adult support a tactile book demands looks less like a fixed property of the medium and more like a design variable. The audio narration and QR-code access in the present book push in that direction, even though full classroom validation could not be conducted within this study.

Material durability and safety came up repeatedly. Experts raised concerns that PLA+ and ABS prints can be too rigid for sustained tactile exploration and may pose risks for students with multiple disabilities who put objects in their mouths. The literature is moving in similar directions. Sargsyan et al. (2023) note that 3D printed models are more durable than 2D tactile maps, but only when the filament and print parameters are chosen with the use case in mind. Studies of FDM-printed Braille (Puerta et al., 2024) document that surface quality and orientation affect both legibility and tactile comfort, which matters directly for hand-held models that students grip rather than only run a finger across. Toy design work for visually impaired children (Zheng & Zhou, 2024) recommends softer, child-safe materials with varied textures for sustained sensory development. The recommendation here to move toward flexible filaments is therefore an extension of an existing direction rather than an isolated suggestion.

The open-access website with downloadable 3D model files responds to a problem the literature has named more often than it has solved. Karbowski (2020) and the See3D initiative argue that without open distribution channels, well-designed tactile materials end up confined to the institutions that produced them. Sargsyan et al. (2023) similarly report that having a shared library of objects substantially reduces the time it takes practitioners to assemble new tactile materials. In Tekgül's study (2024), SVIs indicated that they typically encounter challenges in accessing auditory course materials on online platforms, which impedes their learning experiences. Publishing both the audio narrations and the printable model files openly turns a single research output into something a teacher with access to a 3D printer can actually use.

Taken together, these findings above make most sense when read through two converging theoretical lenses. The first is multisensory learning research. Information delivered through more than one modality is processed and remembered better than the same information delivered through one (Shams & Seitz, 2008), and recent classroom-level reviews extend this finding to environments where visual, auditory, and haptic cues are deliberately coordinated (Gori et al., 2022; Sathian & Lacey, 2022). For learners without functional vision, this is not a nice-to-have. Touch and hearing have to take on the integrative load that vision usually carries, and materials need to be designed around that fact (Cuturi et al., 2021; Gori et al., 2021).

Theories of multimedia learning offer a complementary lens. Paivio's dual coding theory and Mayer's cognitive theory of multimedia learning together describe two related but separate channels for verbal and non-verbal information, and they argue that learning improves when content uses both at the same time, provided the design does not overload working memory (Albers et al., 2023). In the book set, Braille text and audio narration carry the verbal channel, while 3D objects, raised graphics, and (for students with low vision) high-contrast colored elements carry the non-verbal one. The Design Cycle 2 decision to standardise Braille placement and avoid duplicating it on the 3D objects is a concrete instance of these theories in practice: spatial contiguity, modality, and coherence translated from a visual-auditory to a tactile-auditory learner.

Multisensory enrichment, on its own, does not make a design inclusive. The framework that fits this study's findings most directly is Universal Design for Learning (UDL), developed by CAST. UDL organizes instructional decisions around three principles: multiple means of representation, multiple means of action and expression, and multiple means of engagement (Levey, 2021; Plantin Ewe & Galvin, 2023). It is proactive rather than reactive: instead of waiting for a need to be identified and then bolting on an

accommodation, it builds flexibility in from the start (Plantin Ewe & Galvin, 2023). Each of the design decisions reported here lines up with one of the three UDL principles.

On *representation*, the book set offers Braille text, fully three-dimensional tactile objects, audio narration, and (for students with low vision) high-contrast coloring and large print at the same time. This is what UDL Principle I asks for: more than one path to the same information (Foxworth et al., 2021; Fundelius et al., 2022). Keeping real-world coloration on the characters for students with low vision while preserving full tactile and auditory access for students who are totally blind is consistent with the UDL idea of one flexible artifact rather than separate “special” versions for each subgroup, which is also what Phutane et al. (2022) describe TVIs asking for in interviews. UDL-informed book boxes for diverse learners report a similar pattern: combining tangible objects, Braille, and sensory cues in one set improves access without splitting students into different tracks (Fundelius et al., 2022).

On *action and expression*, the attach–detach 3D components, the QR-linked audio playback, and the thick durable pages let learners interact with the text by touch, by listening, or by both. Experts pointed out that this opens up forms of expression beyond reading aloud, including grouping, sorting, and reconstructing the narrative—activities that work for students regardless of vision status. This matches what Abrahamson et al. (2018) describe in inclusive mathematics: accessibility is not adapting an existing visual artifact but redesigning the interaction itself, so that students with and without vision can work on the same object together.

On *engagement*, several features feed into motivation rather than access. The texts come from the national Turkish-language curriculum, so the content is familiar in a way that reduces the social cost of using a “special” material. The audio narration cuts down on how much help students need from a parent at home. Sharing the 3D model files publicly means teachers can reprint and reuse the materials in their own classrooms (Karbowski, 2020; Sargsyan et al., 2023). Experts kept coming back to motivation and active participation when discussing these features, which is consistent with what other multisensory reading designs for visually impaired children have reported (Edirisinghe et al., 2018; Fadlaoui & Archambault, 2025) and with the broader UDL literature on multimodal environments (Plantin Ewe & Galvin, 2023).

Reading the findings through UDL also explains a recurring observation in the data: features designed to remove barriers for SVIs ended up benefiting other learners as well, including students with low vision and students with multiple disabilities. This is the so-called curb-cut effect, and it is well documented in studies of universally designed materials, where the same supports help peers without disabilities too (Foxworth et al., 2021; Plantin Ewe & Galvin, 2023). The contribution of this study is a concrete artifact that puts that pattern into practice for primary-school Turkish-language instruction.

Recommendations for Future Research

Future studies may employ research designs beyond the design-and-development approach adopted in the present study. Experimental or quasi-experimental designs could be utilized to empirically assess the effectiveness of 3D tactile book set on learning outcomes such as reading comprehension, vocabulary development, and academic achievement. Qualitative approaches incorporating observational methods or think-aloud protocols during classroom use would provide in-depth understanding of how students with visual impairments interact with tactile materials. Additionally, longitudinal research designs may be employed to examine the long-term effects of tactile book use on reading motivation, tactile literacy development, and overall academic progress. Comparative studies evaluating the relative effectiveness of 3D tactile books against other tactile or assistive materials currently in use in visual impairment education would also contribute meaningfully to the field. Because the present study could not include direct classroom implementation due to the COVID-19 pandemic, replication under non-pandemic conditions with the target population is the most pressing next step.

Recommendations Regarding Design and Development

Several directions are suggested for future design and development efforts. Studies targeting different grade levels and subject areas - particularly mathematics, science, and geography, which teachers identified as especially challenging - would broaden the applicability of 3D tactile book sets. To reduce the time and resource demands of the design and printing process, future projects may opt for a narrower scope, including fewer books and objects. The use of flexible filaments offering greater softness, durability, and resistance to breakage upon impact is recommended as an alternative to the ABS and PLA+ materials employed in this study. The accompanying digital content may be expanded beyond audio narration to include synchronized animated text and large-print versions, which would strengthen the representation principle of UDL for students with low vision.

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