

Article

A UDL-Driven Framework for Designing Digital Tactile Graphics in Cultural Heritage Learning

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Abstract

This study develops a digital tactile graphic learning framework based on Korean cultural heritage images to support potential concept learning of students with visual impairments and examines its educational appropriateness through expert validation. The lack of standardized tactile graphic guidelines in visual-centric educational environments imposes considerable burden on teachers, who must restructure content individually. Using a design-based research (DBR) methodology grounded in the Universal Design for Learning (UDL) framework, this study constructed a dataset of 200 cultural heritage images from elementary textbooks across four categories—architecture, artifacts, cultural symbols, and traditional objects—and restructured them through illustration simplification, initial tactile graphic conversion (informed by braille production principles), and two expert revision cycles. Ninety educationally applicable items were finalized for second-stage validation, and five tactile graphic design guidelines were derived. A panel of 15 experts evaluated the materials using a 5-point Likert scale and Content Validity Index (CVI) analysis. The overall mean was $M = 4.69$ ($SD = 0.51$), with the final 15-item instrument yielding an overall S-CVI/Ave of 0.99 (initial 0.98 across the original 16 items, refined after removal of one underperforming item per standard CVI practice); the practical usability domain reached S-CVI/Ave = 1.00, indicating full expert agreement. The study contributes a cultural heritage image dataset, a systematic image restructuring procedure, UDL-based design guidelines, iteratively refined and expert-validated CVI evaluation criteria, and a prototype TUI-based tactile learning environment configuration.

Keywords: content validity index; cultural heritage education; design-based research; digital tactile graphics; students with visual impairments; tangible user interface; universal design for learning



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1. Introduction

Globally, an estimated 253 million people live with vision impairment [1], and ensuring equitable access to educational content for this population remains a persistent challenge in inclusive education systems worldwide [2,3]. Cultural heritage education—central to developing historical understanding and cultural identity—is among the most visually mediated domains in the school curriculum, making it one of the least accessible areas for learners who are blind or have low vision. Despite growing international attention to inclusive education policy, the structural conditions that shape how these students access heritage content have received comparatively little empirical attention, particularly at the level of instructional material design.

In contemporary society, where digital transformation is accelerating, visualized information such as graphs, charts, maps, and images has become a primary medium for delivering knowledge in educational settings. Visualized information is more than a presentation device; it underpins how learners analyze and interpret meaning, forming a foundation for the literacy that classrooms increasingly demand [4]. This is especially true of history and culture education, where heritage imagery anchors learners' understanding of cultural meaning and historical context.

Yet a heavily visual instructional environment poses real access barriers for students who are blind or have low vision. Because these students rely on touch and hearing to perceive information, image-driven content frequently leaves them without a clear pathway to the underlying concept. Hatlen [5] framed access to visual information as a defining educational concern for this population. Heritage images are particularly demanding: their structural complexity and dense visual cues mean that, without a tactile counterpart, conceptual access is often closed off [6,7].

This problem mirrors a well-documented issue in braille textbook production. Lee [8] noted that variation in braille transcription practices across transcribers reflects either weak regulation or inconsistent enforcement of existing rules. Tactile graphics show the same fragmentation: identical visual content can be rendered in markedly different ways depending on the producer or institution, and these inconsistencies ripple through students' literacy development. The pattern is not unique to Korea. Butler et al. [7] reported that teachers of the visually impaired (TVIs) in the United States invest substantial time and effort in producing tactile materials and describe the work as complex and labor-intensive. Without a shared production standard, every piece of tactile content must be produced individually, vetted by experts, and then distributed—an arrangement that delays delivery to students and pushes the burden of content adaptation onto classroom teachers.

Tactile graphics translate visual information into a tactile form that students who are blind or have low vision can interpret, and they remain one of the most established alternative learning materials in the field [9]. Most tactile graphics on the market, however, are produced as fixed artifacts, which limits their capacity to convey changes in information structure or extended conceptual variations [10]. Reviewing domestic research on digital alternative learning materials, Lee and Lee [11] observed a shortage of empirical work on tactile graphic devices and called for production guidelines that better protect the right to learn for students with visual impairments.

Recent advances in information and communication technology (ICT) have begun to open new pathways. Refreshable tactile displays, in particular, employ pin matrices of several hundred cells to render graphics dynamically, allowing learners to actively explore information through touch [12]. Holloway et al. [13] have shown that such displays can convey motion graphics to blind users, and Fusco and Morash [14] provided empirical evidence that tactile graphics support STEM learning for students with visual impairments. Beyond improving access, these technologies enable embodied learning experiences in which physical interaction grounds conceptual understanding [15].

While the educational potential of tactile graphics has been broadly discussed, design methods and pedagogical applications grounded specifically in cultural heritage imagery have received far less attention. Work that integrates the systematic restructuring of heritage images for digital tactile graphics with a UDL-based learning design framework remains particularly limited [16,17].

Against this backdrop, the present study develops digital tactile graphic learning materials that support cultural heritage concept learning for students with visual impairments. The work systematizes how visual heritage information can be converted into tactile-based learning content and proposes a set of standardized design guidelines. In

doing so, it generates design knowledge intended both to ease the content-adaptation burden on special education teachers and to work toward securing the right to learn for students with visual impairments [2,3]. The study addresses three research questions:

RQ1. On the basis of which structures and design principles can digital tactile graphic images be developed to support cultural heritage concept learning for students with visual impairments?

RQ2. How might digital tactile graphic learning materials delivered through TUI-based tactile displays potentially address the limitations of conventional tactile graphic textbooks?

RQ3. How can the developed digital tactile graphic learning materials be validated through expert evaluation in terms of educational suitability and practical applicability?

2. Theoretical Background

2.1. Literacy of Students with Visual Impairments and the Standardization Issue of Tactile Graphics

Literacy refers to more than the ability to read; it encompasses the broader capacity to understand, interpret, and use information [4]. For students who are blind or have low vision, this capacity is built primarily through touch and hearing, with braille texts and audio-based materials serving as the principal learning resources [5]. Such resources, however, are largely text-centered and struggle to convey visualized information such as graphs and maps [6]. Lee and Lee [11] found that domestic tactile graphic displays in Korea offer fewer cells than their overseas counterparts, which makes guidelines for image restructuring all the more necessary.

The absence of standardization in braille materials production has long been acknowledged as a structural problem in the field. Lee [8] argued that variation in transcription practices across braille transcribers signals either a lack of regulation or weak enforcement of existing rules. The same issue takes a sharper form in tactile graphics. In the development of digital tactile graphic devices in Korea, the absence of content standards has been a recurring concern, and producers continue to render the same visual information in widely divergent ways [16]. Although the BANA [18] tactile graphics guidelines have been translated for domestic use, textbook transcription routinely omits photographs and images, and implementation falls well short of the original guidance [8]. Findings from outside Korea confirm the pattern: in a study of TVIs in the United States, Butler et al. [7] reported that producing tactile materials is not only time-consuming but also demands difficult design judgments that teachers feel ill-equipped to make.

2.2. Tactile Graphics and Cultural Heritage Learning Accessibility

Tactile graphics translate visual information into a form perceptible through touch, and they remain among the most established alternative learning materials for students who are blind or have low vision [9]. Edman [9] characterized tactile graphics as one of the most effective tools for supporting these learners' understanding of graphical content. Park [19] extended this work into the three-dimensional domain, using 3D printing to produce textbook images and artworks in physical form, and reported gains in spatial cognition for students with visual impairments. Empirical evidence has accumulated on similar lines: Fusco and Morash [14] showed that tactile graphics directly contribute to STEM achievement among students with visual impairments, and Memeo et al. [20] demonstrated that learning three-dimensional tactile graphics through a 3DOF haptic mouse improves object recognition. Most existing tactile graphic materials, however, are produced as fixed artifacts and remain limited in their capacity to express changes or extended conceptual variations [10].

Cultural heritage images function as core teaching materials in history and culture education. Korean elementary textbooks, for instance, draw on a wide range of heritage imagery—historical buildings, cultural artifacts, traditional symbols—to explain instructional content [4]. Items such as Seokgatap Pagoda, Sungnyemun Gate, the Silla Gold Crown, and Eosahwa serve as essential visual references for understanding Korean history and culture. Their visual complexity, however, places them out of reach for many students with visual impairments, which makes systematic methods for restructuring heritage images into tactile graphics a pressing research need.

2.3. Learning Environments Based on Tangible User Interfaces

A tangible user interface (TUI) lets users manipulate digital information through physical objects [21]. In educational contexts, TUI has drawn attention as an interface that promotes engagement and immersion, with reported benefits for experiential and interaction-centered learning [17,21]. Refreshable tactile displays extend this approach: pin matrices can convert and present graphic information in real time, overcoming the limitations of static, paper-based tactile graphics [12]. Holloway et al. [13] demonstrated this experimentally, showing that motion graphics can be conveyed to blind users through a refreshable tactile display—an extension of the format’s expressive range from static to dynamic content. Within Korea, the Dot Pad (Dot Incorporation, Seoul, Republic of Korea) has emerged as a representative device, providing a 300-cell (2400-pin) tactile graphics display driven by an AI image-analysis engine; it received the Innovation Award in Accessibility at CES 2023 [22]. Field evaluations with teachers at schools for the blind in Korea have confirmed the educational potential of such displays, but they have also highlighted a persistent obstacle: the lack of standardized content, which forces teachers to restructure each image themselves and undermines classroom adoption [16].

2.4. Linkage Between Universal Design for Learning and Tactile Graphic Design

Universal Design for Learning (UDL) is a neuroscience-grounded educational framework that designs goals, materials, methods, and assessment to be accessible to the widest possible range of learners [3,23,24]. UDL is anchored in three brain networks—recognition, strategic, and affective—and operationalizes them through three corresponding principles: Multiple Means of Representation, Multiple Means of Action and Expression, and Multiple Means of Engagement [23,25]. Across special and inclusive education settings, these principles are now widely applied as a design approach that removes learning barriers proactively rather than retrofitting them after the fact [3].

The tactile graphic design guidelines proposed in this study connect directly to UDL’s principle of Multiple Means of Representation. Restructuring visual information into tactile form is, in itself, a representative UDL practice—delivering the same instructional content through a different sensory modality. Design choices such as shape simplification, differentiated outline thickness, and adequate object spacing serve the same logic: they raise the likelihood that information will be perceived through tactile exploration, making the resulting environment accessible to learners with diverse sensory profiles. By providing standardized materials that teachers can use without further adaptation, this approach realizes the proactive design principle that lies at the heart of UDL [2,3]. The spatially organized description structure further supports the principle of Multiple Means of Engagement: it scaffolds learner-led exploration and, in doing so, strengthens both motivation and access. UDL therefore operates throughout this study not as a parallel reference but as the criterion that anchors design decisions at every stage of the DBR process, with iterative refinement directed toward putting UDL principles into practice.

3. Materials and Methods

3.1. Research Design

This study was conducted as a design-based research (DBR) project encompassing both the development and the expert validation of digital tactile graphic learning materials for cultural heritage concept learning of students with visual impairments. DBR served as the methodological frame, while UDL functioned as the theoretical criterion that informed each stage of the design. The work corresponds to the design and development phase described by McKenney and Reeves [26]; at this phase, securing design validity through expert review is methodologically more appropriate than empirical testing with learners, and learner-based effectiveness studies are reserved for later research. DBR is characterized by an iterative analyze–design–develop–evaluate cycle that refines design principles rather than terminating after a single development pass. Its strength lies in narrowing the gap between theory and practice and in producing design knowledge that travels into actual instructional contexts [26,27].

More concretely, the UDL principle of Multiple Means of Representation framed the analysis stage by shaping the research questions, informed the design stage as the criterion for deriving the guidelines, and grounded the evaluation stage by shaping the structure of the expert review items. The image restructuring stage proceeded through two cycles of expert-informed revision. In the first cycle, reviewers flagged inconsistent outline thickness and insufficient spacing between adjacent objects in the initial drafts; in response, outlines were standardized at two-line thickness and interior lines at one-line thickness, and a minimum spacing rule was introduced. In the second cycle, the application range of fill patterns and the order of the spatial description structure were revisited, leading to a hierarchical descriptive sequence of “scene description → spatial structure description → supplementary description” [28]. Through these iterative refinements, both the internal consistency of the design guidelines and their applicability to actual instructional settings improved progressively.

The study followed a seven-stage procedure: (1) construction of the traditional cultural image dataset, (2) restructuring of cultural heritage images, (3) digital tactile graphic generation, (4) derivation of expert validation criteria, (5) expert validation (Likert and CVI), (6) derivation of tactile graphic design guidelines, and (7) application within a TUI-based tactile learning environment. Figure 1 visualizes the seven-stage DBR procedure together with the cross-cutting role of UDL as the theoretical frame for each stage.

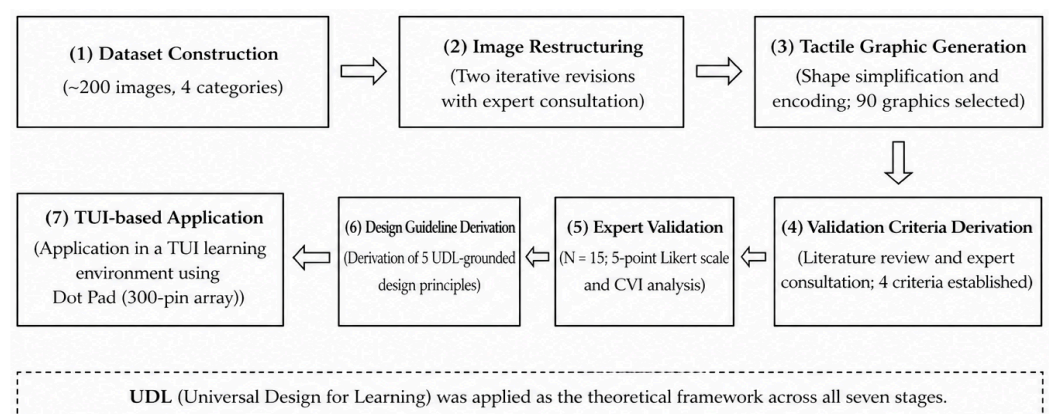


Figure 1. DBR–UDL integrated research procedure. The purple band represents UDL as a theoretical framework across all seven stages.

3.2. Construction of the Cultural Heritage Image Dataset

Approximately 200 cultural heritage images were collected from Korean elementary school textbooks, focusing on traditional cultural elements, to construct the dataset. The images were used solely for non-commercial academic research purposes in accordance with Article 25 of the Korean Copyright Act, which permits the reproduction of published works for educational research by educational institutions without prior authorization. The images were organized into four broad categories based on their external characteristics—architecture, artifacts, cultural symbols, and traditional objects—as summarized in Table 1.

Table 1. Cultural heritage image dataset categories.

Category	<i>n</i>	Representative Examples
Architecture	9	Seokgatap Pagoda, Sungnyemun Gate, Cheomseongdae, Tangpyeongbi, Mireuksaji Stone Pagoda, etc.
Artifacts	48	Silla Gold Crown, Rain Gauge (Cheugugi), Hunminjeongeum, Dolmen, Traditional Coin (Yeokjeon), etc.
Cultural Symbols	57	Eosahwa, Gat (traditional hat), Gayageum, Jegi-chagi, Gama (palanquin), Janggu, Kkwaenggwari, Jangseung, etc.
Traditional Objects	86	Millstone (Maetdol), Farming tools, Nolttwigi (seesaw), Earthen jar, Inkstone, Jige (backpack frame), Hoe, etc.
Total	200	—

3.3. Image Restructuring Process

All 200 cultural heritage images collected from elementary school textbooks underwent a first-round tactile graphic restructuring process. The pipeline followed five stages: original image → illustration simplification → initial tactile graphic conversion (informed by braille production principles) → first revision → second revision yielding the final tactile graphic. The first stage analyzed the visual elements of each image to identify the structural form essential for tactile recognition. The second stage simplified complex visual content into illustration-based images, with researchers in traditional cultural image production and restoration consulted on the appropriateness of the simplification. In the third stage, the illustrations were converted into tactile graphic form, applying design criteria such as outline emphasis, shape simplification, and adequate object spacing [7,18]. Subsequent expert consultation refined the structure of each tactile graphic and produced the final outputs. Figure 2 shows this stage-by-stage transformation using Seokgatap Pagoda, a representative stone pagoda from the Unified Silla period, as the illustrative case.

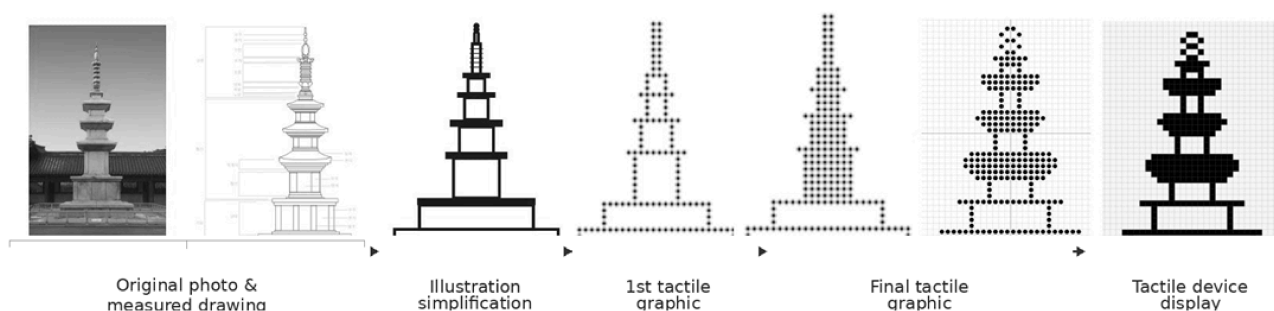


Figure 2. Stage-by-stage image restructuring process of cultural heritage images (Seokgatap Pagoda example).

3.4. Derivation of Expert Validation Criteria

The expert validation criteria were derived through a systematic literature review of prior work on tactile graphics. First, international studies on the design validity of tactile graphics [7,9,18,29,30] were reviewed to extract the core elements of tactile graphic quality assessment. Second, the domestic literature on alternative learning material evaluation in education for students with visual impairments [8,11,16] was examined to ground the criteria in the Korean educational context. Third, an initial draft was prepared on the basis of these reviews and finalized into four items through preliminary consultation with the expert panel. Table 2 presents the four criteria together with the literature on which each is based.

Table 2. Expert validation criteria and supporting references.

Domain	Item Definition	Key References
Clarity of Tactile Graphic Structure	Degree to which structural forms can be clearly perceived through tactile exploration	[9,29]
Comprehensibility of Information Delivery	Degree to which the meaning of visual information can be accurately understood through tactile perception	[18,30]
Potential for Supporting Concept Learning	Degree to which cultural heritage concept learning for students with visual impairments is effectively supported	[11,16]
Practical Usability in Educational Settings	Degree to which the material can be used directly in real educational settings without additional restructuring by teachers	[7,8]

The “practical usability in educational settings” item was set deliberately to capture the field-level burden created by the absence of standardization in tactile graphic content—a problem analogous to the literacy inequity that arises when braille transcription practices vary across transcribers. Beyond confirming theoretical soundness, this item asks whether the resulting tactile graphics are usable as-is, without further restructuring on the teacher’s part.

3.5. TUI-Based Tactile Learning Environment Configuration

A learning system was configured to deploy the restructured tactile graphics within a TUI-based tactile interface environment. The system comprises four components: the cultural heritage tactile graphics dataset, a graphic input interface, a control system running on mobile or PC, and the Dot Pad tactile display. The Dot Pad uses 300 braille pin cells (2400 pins) to render graphic information in tactile form and supports active exploration of graphic content through touch [22]. Figure 3 presents the overall configuration of the TUI-based tactile learning system together with a photograph of the Dot Pad device.

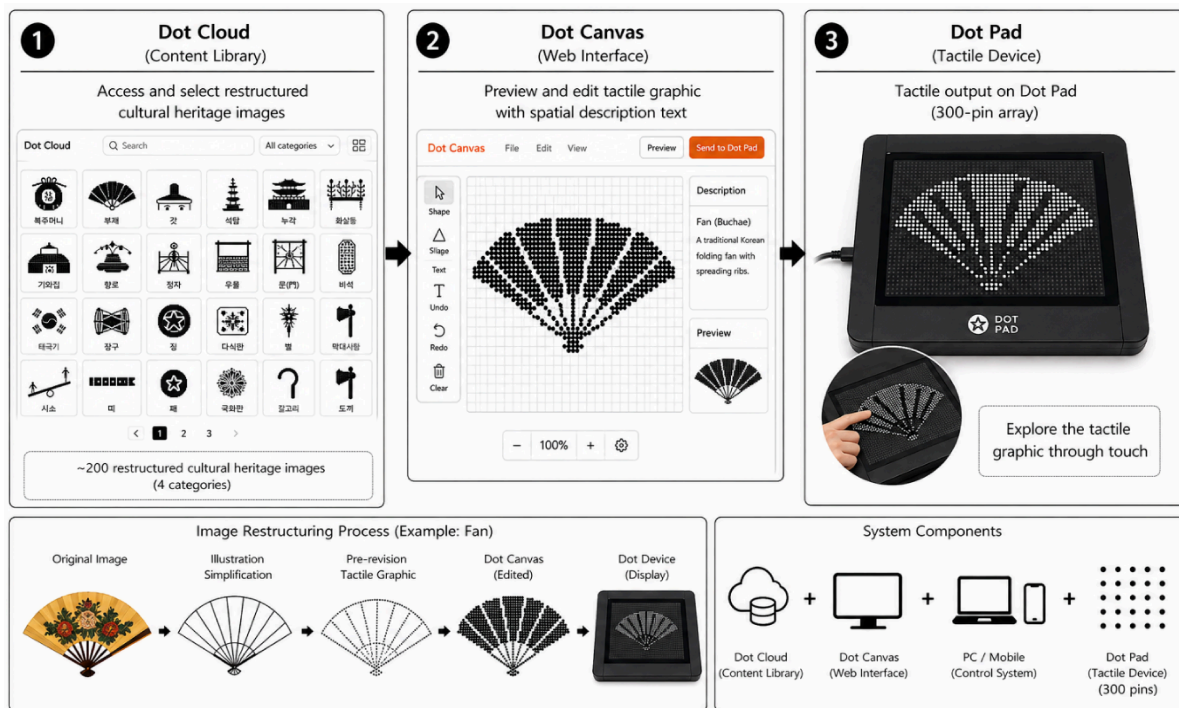


Figure 3. TUI-based tactile learning system: Dot Cloud → Dot Canvas → Dot Pad. The Dot Cloud panel (left) displays Korean labels of cultural heritage items in the actual operating interface; representative items include Bokjumeoni (lucky pouch), Buchae (folding fan), Gat (traditional hat), Seokgatap (stone pagoda), Giwajip (tiled-roof house), Taegukgi (Korean national flag), and Janggu (Korean drum).

3.6. Expert Validation Procedure

The final tactile graphic dataset was subjected to expert validation in order to identify items suitable for educational use. The expert panel consisted of 15 specialists drawn from five fields: education for students with visual impairments, assistive technology and accessibility, tactile graphic design, content development, and traditional cultural image research. Notably, one of the two accessibility researchers had acquired visual impairment and thus contributed an end-user perspective on tactile accessibility, offering first-hand experiential feedback on the legibility and usability of the tactile graphic materials. Among the three content developers, two were current employees of Dot Incorporation and one was a former employee now working independently; all three conducted physical tactile evaluation using the Dot Pad device itself, rather than relying solely on screen-based Dot Canvas renderings, thereby ensuring that the expert-judged compatibility scores reflected actual pin-matrix tactile output. Selection criteria required at least three years of experience in education for students with visual impairments or in assistive technology, prior research or practical work in tactile graphics or accessibility design, three or more years of relevant content development experience for content developers, and verified experience in producing or researching traditional cultural images for image researchers. Lynn [31] recommended a minimum of 10 experts for content validity calculations; assembling a panel of 15 thus exceeded that threshold and supported statistical reliability for both I-CVI and S-CVI/Ave. Table 3 summarizes the expert panel composition by area of expertise.

Expert validation proceeded in two stages. The first stage used a 5-point Likert scale across the four criteria derived in Section 3.4 to evaluate the educational validity of the tactile graphic learning materials. The second stage examined the content validity of the four criteria themselves through a 4-point CVI scale (1 = not relevant; 4 = highly relevant). I-CVI was calculated as the proportion of experts rating an item 3 or 4 [31], and S-CVI/Ave

was calculated as the average of all I-CVI values [32]. S-CVI/UA was computed as the proportion of items receiving a 3 or 4 from every expert. To correct for chance agreement, a Modified Kappa (κ^*) was calculated using $\kappa^* = (I\text{-CVI} - P_c)/(1 - P_c)$ [33]. The acceptance thresholds were set at $I\text{-CVI} \geq 0.78$, $S\text{-CVI}/Ave \geq 0.90$, and $\kappa^* \geq 0.74$ [32,33]. The Likert evaluation was conducted on 90 images selected from the 200 first-round restructured items through a two-stage selection process designed to align the validation corpus with both curricular relevance and practical content utility. In the first stage, candidate items were prioritized according to the frequency of their appearance as recurring keywords in elementary school textbooks used for instruction of students with visual impairments, ensuring that the validation set reflected the cultural heritage content these students most often encounter in their learning environment. In the second stage, the prioritized items were further screened in collaboration with Dot Incorporation content developers, who identified items most likely to be deployed in tactile content for visually impaired users in actual practice. Items retained through both stages additionally required a Likert score of 4 or higher across the four evaluation domains in the panel's preliminary review. This two-stage curricular-then-practical filter yielded the final 90 items used for full expert validation while maintaining representation across the four image categories (architecture, artifacts, cultural symbols, and traditional objects). Figure 4 presents the two-stage selection procedure and the final distribution of the 90 items across the four categories.

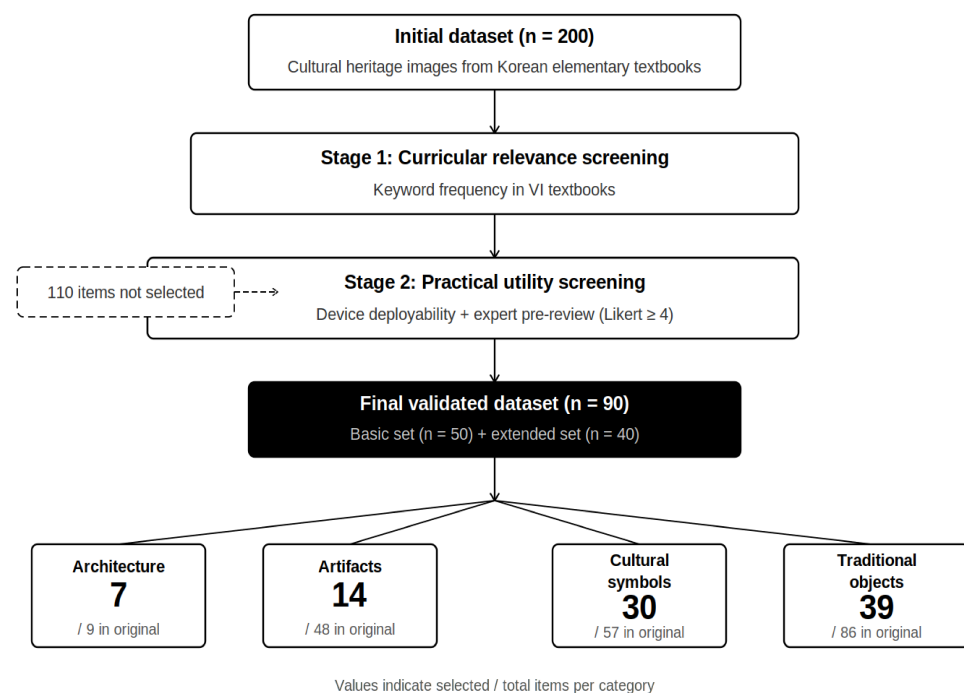


Figure 4. Two-stage image selection procedure and final distribution of the 90 validated items across four cultural heritage image categories. Values in category boxes indicate selected items/total items in the original 200-image dataset.

Table 3. Expert panel composition.

Category	N	Area of Expertise
Special Education Expert	3	Education of students with visual impairments
Accessibility Researcher	2	Assistive technology and accessibility
Design Researcher	5	Tactile or graphic design
Content Developer	3	Dot device content development

Table 3. *Cont.*

Category	N	Area of Expertise
Traditional Culture Image Researcher	2	Traditional cultural image production
Total	15	

4. Results

4.1. Cultural Heritage Image Restructuring Results

All 200 cultural heritage images were collected and restructured into tactile graphic form. Seokgatap Pagoda, the representative case, lent itself well to tactile representation: its tiered structure is clearly delineated and its overall form is relatively simple, so the tower's stories were reduced to a line-centered configuration. Sungnyemun Gate was structured around its roof and the form of its podium. The Silla Gold Crown, with its intricate decorative elements, was reorganized around its principal structural features while ornamental detail was simplified. For Eosahwa, formal characteristics were preserved while the image was simplified to ensure tactile recognizability. Following expert validation, 90 of the most educationally promising tactile graphics passed second-round final review and were finalized as learning materials; the remaining 110 are scheduled for sequential expansion through additional validation. Figure 5 presents four representative final outputs, one from each dataset category.



Figure 5. Final tactile graphic outputs of four representative cultural heritage items (Sungnyemun Gate, Silla Gold Crown, Eosahwa, Gayageum).

4.2. Tactile Graphic Design Guidelines

Addressing RQ1 and RQ2, the design guidelines that emerged from the restructuring process and expert consultation indicate that image simplification and the layered organization of information are central to improving tactile recognizability. The five guidelines derived in this study are as follows.

- (1) Shape Simplification: Remove complex visual elements and structure the graphic around principal forms.
- (2) Outline Thickness Differentiation: Render outlines in two-line thickness and interior lines in one-line thickness to enhance tactile recognition.
- (3) Object Spacing: Maintain sufficient spacing between graphic elements so that forms can be distinguished during tactile exploration.
- (4) Shape Filling: Apply fill patterns to make forms and features more readily identifiable through touch.
- (5) Spatial Description Structure: Sequence descriptions in the order of “scene description → spatial structure description → supplementary description.”

Table 4 presents a mapping of each guideline to the corresponding UDL principle, operative checkpoint, accessibility function it serves, and the design evidence from which it was derived. This mapping clarifies the theoretical logic underlying each design decision

and demonstrates that the five guidelines collectively operationalize UDL principles at the level of specific, reproducible production choices rather than abstract aspirations.

Table 4. Mapping of five tactile graphic design guidelines to UDL principles, checkpoints, accessibility functions, and design evidence.

Guideline	UDL Principle	UDL Checkpoint [25]	Accessibility Function	Design Evidence
Shape Simplification	Multiple Means of Representation	1.1 Customize display options; 1.2 Multiple modes of perception	Reduces cognitive load by removing irrelevant visual complexity; allows learners to identify principal structural forms without interference from decorative detail.	Cycle 1: complex outlines (e.g., Silla Gold Crown) hindered tactile recognition. Cycle 2: simplification improved form-identification rates [7,18].
Outline Thickness Differentiation	Multiple Means of Representation	1.2 Multiple modes of perception; 2.1 Clarify symbols and structures	Differentiates figure from ground and primary from secondary elements via tactile salience; two-line outer contours create a distinct haptic boundary that guides exploratory touch.	Cycle 1: inconsistent line thickness blurred structural boundaries. Standardizing two-line outer/one-line interior resolved inter-rater disagreement [9,29].
Object Spacing	Multiple Means of Representation	1.1 Customize display options; 1.2 Multiple modes of perception	Prevents tactile merging of adjacent elements; adequate inter-element spacing keeps spatially distinct features perceptually discrete under fingertip exploration.	Cycle 1: insufficient spacing caused form confusion (e.g., pagoda stories, gate components). Cycle 2: minimum spacing rule eliminated finger-crossing errors [18].
Shape Filling	Multiple Means of Representation	1.2 Multiple modes of perception; 2.5 Multiple media representations	Adds a second tactile channel (texture contrast) to contour information; helps distinguish foreground from background and differentiate surface regions without relying solely on edge detection.	Cycle 2: uniform filling obscured interior detail. Selective filling of principal form regions improved region identification [30].
Spatial Description Structure	Multiple Means of Engagement; Multiple Means of Action and Expression	6.3 Organize information and resources; 7.2 Relevance, value, authenticity	Provides a sequenced scaffold (scene → spatial structure → supplementary detail) for self-directed tactile navigation; reduces reliance on teacher mediation by embedding orientation information into the material itself.	Cycle 2: initial ordering was non-hierarchical. The three-level sequence was endorsed by special education experts as congruent with how blind learners build spatial mental models [11,15].

These guidelines are intended less as quality criteria for individual pieces of content than as foundational reference points for standardizing tactile graphic production. They are offered with the expectation that they may serve as a basis for future tactile graphic production standards. Figure 6 compares the production process across the five guidelines,

showing the optimization steps tied to each principle (excluding illustration restructuring) and the final digital tactile graphic image as rendered on the device.

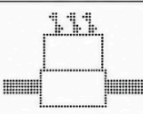
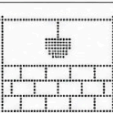
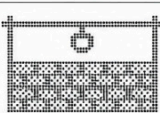
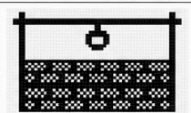
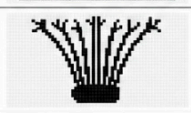
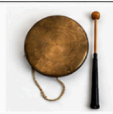
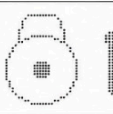
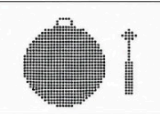
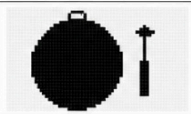
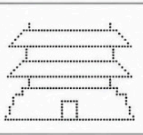
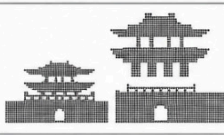
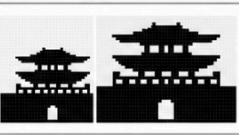
	Original Image (Restructured)	Pre-revision Tactile Graphic (Pre-revision)	Dot Canvas Rendering (Optimized)	Dot Device Output (300-pin Array)
1 Shape Simplification King's Bestowed Paper Flower Decoration (Eosahwa)				
2 Outline Thickness Differentiation Traditional Korean Well (U-mool)				
3 Object Spacing Korean Shuttlecock (Jegi-chagi)				
4 Shape Filling Small Gong (Kkwaenggwari)				
5 Spatial Description Structure Sungnyemun Gate				

Figure 6. Before-and-after comparisons illustrating the application of five tactile graphic design guidelines: (1) Shape Simplification—King's Bestowed Paper Flower Decoration (Eosahwa); (2) Outline Thickness Differentiation—Traditional Korean Well (U-mool); (3) Object Spacing—Korean Shuttlecock (Jegi-chagi); (4) Shape Filling—Small Gong (Kkwaenggwari); (5) Spatial Description Structure—Sungnyemun Gate. Each row shows the original image, pre-revision tactile graphic, Dot Canvas rendering, and Dot Device output.

4.3. Expert Validation Results

In response to RQ3, the expert validation showed that the digital tactile graphic learning materials received consistently high evaluations. Table 5 reports the descriptive statistics from the 5-point Likert evaluation by the 15 experts; Table 6 presents the CVI analysis.

Table 5. Expert validation results—descriptive statistics (5-point Likert scale, N = 15).

Evaluation Item	Mean (M)	SD	Interpretation
Clarity of Tactile Graphic Structure	4.53	0.60	High
Comprehensibility of Information Delivery	4.63	0.49	High
Potential for Supporting Concept Learning	4.80	0.40	Very High
Practical Usability in Educational Settings	4.78	0.49	Very High
Overall Mean	4.69	0.51	Very High

Figure 7 presents the domain-level Likert evaluation results. All four domains exceeded $M = 4.50$, indicating consistently high expert endorsement across the full evaluation framework. The highest-rated domain was Potential for Supporting Concept Learning ($M = 4.80$, $SD = 0.40$), reflecting strong expert agreement that the developed tactile graphic materials are designed to scaffold cultural heritage concept learning for students with visual impairments. Practical Usability in Educational Settings ranked second ($M = 4.78$, $SD = 0.49$), and notably, items 4-1 (immediate teacher use) and 4-2 (Dot Pad compatibility) within this domain both achieved $M = 5.00$, indicating unanimous consensus that the

standardized materials can be deployed directly in classrooms without further adaptation. Comprehensibility of Information Delivery ($M = 4.63$, $SD = 0.49$) and Clarity of Tactile Graphic Structure ($M = 4.53$, $SD = 0.60$) also received strong evaluations, though the comparatively wider SD for the latter domain suggests slightly greater inter-rater variability, consistent with experts' qualitative feedback noting the heightened challenge of simplifying intricately decorated heritage items such as the Silla Gold Crown.

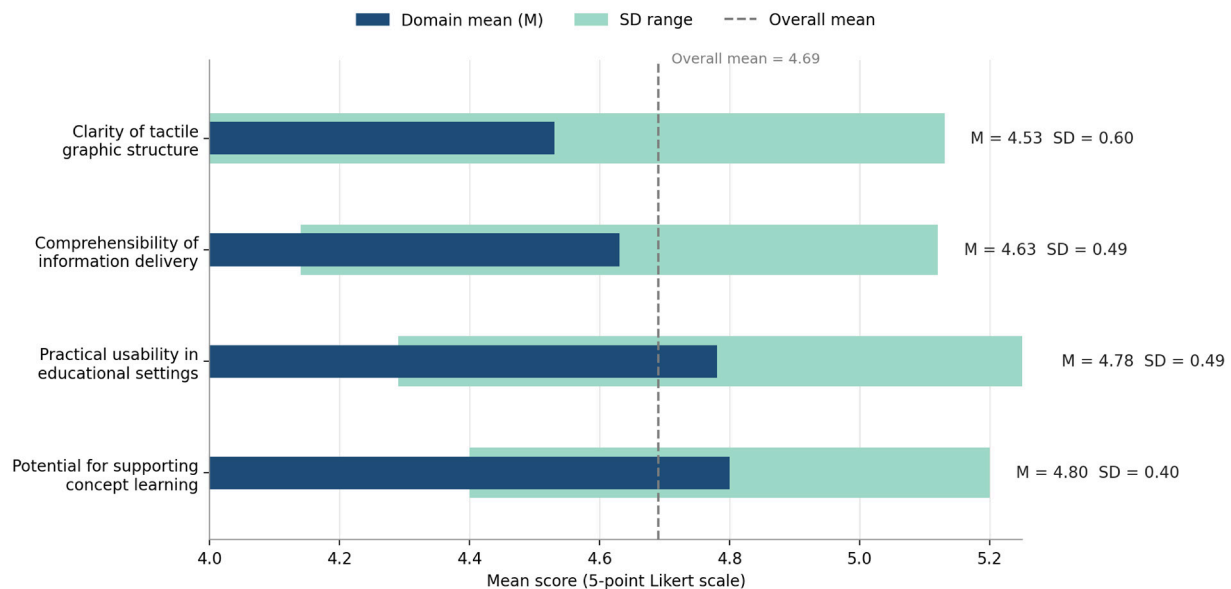


Figure 7. Expert validation results by domain (5-point Likert scale, $N = 15$). Dark blue bars indicate domain mean scores (M); shaded green bands represent the standard deviation (SD) range; the dashed vertical line denotes the overall mean ($M = 4.69$, $SD = 0.51$).

The overall mean of $M = 4.69$ ($SD = 0.51$) places the evaluation in the 'very high' band on the 5-point scale. Rather than treating these figures as endpoints, it is instructive to ask why the ratings landed where they did. The narrowest SD appeared in the domain of Potential for Supporting Concept Learning ($SD = 0.40$), suggesting consistent inter-rater agreement—an indication that the UDL-grounded design rationale produced materials whose educational intent was transparent and legible to specialists across five different professional backgrounds. The domain of Practical Usability in Educational Settings ranked second in mean ($M = 4.78$) but matched the Concept Learning domain precisely on the two items that bear most directly on classroom deployment: items 4-1 (immediate teacher use) and 4-2 (Dot Pad compatibility), both of which reached $M = 5.00$. The unanimity on these items is not incidental—it reflects a shared expert reading that tactile graphics built to a common design standard can be handed to a teacher and used without further preparation, directly addressing the burden that Butler et al. [7] identified as one of the defining frustrations of TVIs working without standardized production references. The comparatively wider SD in the Clarity of Tactile Graphic Structure domain ($SD = 0.60$) points to a real design tension: some cultural heritage items resist clean simplification, and experts diverged most on items that required trading off visual fidelity against tactile legibility—a tension the design guidelines address in principle but cannot fully resolve at the level of individual items.

To address the inter-rater reliability of the Likert-scale evaluations, both Fleiss' κ and Gwet's AC1 were computed across all 15 raters for each evaluation domain. The analysis revealed a pronounced ceiling effect: across all four domains, between 95% and 100% of expert ratings concentrated at scale points 4 or 5. Under such skewed distributional conditions, Fleiss' κ systematically underestimates true agreement—a limitation known

as the kappa paradox, whereby high prevalence of a single response category artificially deflates κ toward zero or below [34]. This pattern was clearly observed in the present data: Fleiss' κ values ranged from -0.06 to 0.52 across domains, with the lowest κ values occurring in the domains showing the strongest ceiling effects. Gwet [35] demonstrated that the AC1 statistic provides a more stable and prevalence-robust alternative to κ when rating distributions are highly concentrated. The corresponding AC1 values were as follows: Clarity of Tactile Graphic Structure (AC1 = 0.38), Comprehensibility of Information Delivery (AC1 = 0.45), Potential for Supporting Concept Learning (AC1 = 0.67), and Practical Usability in Educational Settings (AC1 = 0.84). The Practical Usability domain reached substantial agreement (AC1 ≥ 0.80), while the Concept Learning domain approached this threshold. The Clarity and Comprehensibility domains yielded fair-to-moderate AC1 values, indicating that genuine within-ceiling variation existed between scale points 4 and 5—experts converged on positive evaluations (no rater scored below the “agree” level on any of the 16 items) but differed meaningfully in the degree of positive endorsement. This pattern is consistent with the Clarity domain showing the largest SD (0.60), which reflects real differences in expert opinion on items involving complex ornamentation (e.g., the Silla Gold Crown) rather than measurement noise, while also acknowledging that not all four-versus-five distinctions reached the conventional substantial-agreement threshold.

Table 6. CVI analysis results (N = 15; acceptance criteria: I-CVI ≥ 0.78 , S-CVI/Ave ≥ 0.90 , $\kappa^* \geq 0.74$).

Evaluation Domain	CVI Result	S-CVI/Ave	Decision
Clarity of Tactile Graphic Structure	Items 1–3: I-CVI = 1.00, $\kappa^* = 1.00$. Item 4 (CVI-1-4: “Degree to which the effect of applying design guidelines can be measured through tactile exploration”): I-CVI = 0.67, $\kappa^* = 0.63$ (below threshold). This item was removed from the final instrument following standard CVI practice [31,32], as the item assessed guideline measurability rather than structural clarity itself, introducing construct ambiguity. The remaining three items in this domain were retained. Initial S-CVI/Ave ($n = 4$ items) = 0.92; Final S-CVI/Ave ($n = 3$ items, after removal) = 1.00.	0.92 $\rightarrow$ 1.00	Accepted
Comprehensibility of Information Delivery	All items: I-CVI = 1.00, $\kappa^* = 1.00$	1.00	Accepted
Potential for Supporting Concept Learning	CVI-3-4: I-CVI = 0.93, $\kappa^* = 0.93$; items 1–3: I-CVI = 1.00, $\kappa^* = 1.00$	0.98	Accepted
Practical Usability in Educational Settings	All items: I-CVI = 1.00, $\kappa^* = 1.00$	1.00	Accepted
Overall	Initial instrument ($n = 16$ items): S-CVI/Ave = 0.98; S-CVI/UA = 0.88 (≥ 0.80 in 2 of 4 domains; CVI-1-4 and CVI-3-4 fell below universal agreement). Final instrument ($n = 15$ items, after CVI-1-4 removal): S-CVI/Ave = 0.99; S-CVI/UA = 0.93 (CVI-3-4 retained at I-CVI = 0.93, with one dissenting rater).	0.98 $\rightarrow$ 0.99	Accepted

Across the panel's qualitative comments, two principles drew shared support: outline thickness differentiation and object spacing were viewed as effective levers for improving the efficiency of tactile exploration. Special education experts noted that simplified line-centered structures aid form recognition for students with visual impairments and that the spatially organized description structure helps scaffold self-directed exploration. A subset of experts, however, raised a point requiring caution: for items with intricate ornamentation such as the Silla Gold Crown, simplification without information loss is harder to achieve, and additional, image-type-specific guidelines may be needed.

5. Discussion

This study set out to develop digital tactile graphic learning materials designed to support cultural heritage concept learning for students with visual impairments and to examine their expert-judged educational appropriateness through content validation. The findings suggest that tactile graphic learning materials grounded in traditional cultural images show promise for expanding cultural heritage learning access for these students, as assessed by a panel of domain specialists.

First, the dataset of 200 traditional cultural images assembled in this study constitutes a foundational resource for cultural heritage learning by students with visual impairments—and its scale marks a meaningful departure from prior work. Earlier studies have produced tactile graphics in limited quantities and within narrow subject-specific scopes [14,16,36]. Zebehazy and Wilton [37] observed that the piecemeal, item-by-item approach to tactile graphic production that currently dominates the field makes it difficult to accumulate the coherent, reusable material base that sustained curriculum integration would require. By building a dataset around the cultural heritage images that appear in elementary school textbooks and organizing it across four categories, this study moves toward exactly that kind of base—one organized around actual curricular content rather than illustrative examples chosen for convenience.

Second, the restructuring procedure and the five design guidelines proposed here speak directly to the standardization challenge in tactile graphic production, and their significance extends beyond the Korean context. Just as variation among braille transcribers introduces uneven literacy outcomes for students [8], inconsistent practices among tactile graphic producers risk distorting the development of tactile literacy. Butler et al. [7] reported that TVIs in Australian universities describe the production of tactile materials as demanding difficult design judgments for which they feel poorly equipped—a finding that parallels the Korean field situation documented by Park et al. [16]. The BANA [18] guidelines represent an international attempt to address this problem, but as Lee [8] showed, their domestic implementation remains partial. The five guidelines derived in this study can serve as a concrete, expert-validated complement to those guidelines—one developed specifically for the demands of dynamic, pin-matrix-based tactile displays rather than static embossed paper. To situate the novelty of this contribution more precisely, and to respond to the concern that the relationship between UDL principles and the design guidelines may appear underspecified: Table 4 in Section 4.2 provides a checkpoint-level mapping that links each of the five guidelines to the specific UDL principle and CAST [25] checkpoint it operationalizes, the accessibility function it serves, and the DBR revision cycle evidence from which it was derived. This level of specification demonstrates that the guidelines are not loosely inspired by UDL but are directly traceable to UDL's neuroscientific rationale for how learners with diverse sensory profiles perceive and interact with information. The BANA [18] guidelines address general tactile graphic production across a range of media, whereas the present guidelines are distinguished by four specific foci: (1) adaptation for Korean cultural heritage imagery, which presents unique iconographic and structural

challenges absent from Western heritage corpora; (2) optimization for refreshable pin-matrix displays operating under a 300-cell resolution constraint; (3) explicit grounding in UDL principles as the design criterion at each DBR iteration; and (4) derivation through a DBR process that documents the iterative revision logic rather than presenting guidelines as finished prescriptions. Recent work by Butler et al. [38], whose systematic review of 292 touch-based accessible graphics publications identified the absence of production standards as a persistent structural gap, reinforces the urgency of the present contribution. Their finding that the field lacks coherent design guidance for dynamic tactile displays is precisely the gap the present guidelines are designed to narrow. Two recent complementary studies further document the consequences of this gap from the practitioner side. Phutane et al. [39] conducted interviews with 21 teachers of the visually impaired and reported that the absence of shared production standards forces individual TVIs to make ad hoc design judgments that vary widely across schools and districts, a pattern that directly mirrors the Korean field situation. Race et al. [40] took the analysis a step further through a co-design study with blind designers themselves, demonstrating that the absence of standardized production workflows excludes BLV practitioners from leading the design of the tactile media they consume. Together, these findings indicate that the standardization gap is felt not only by educators producing tactile content but by the very communities such content is intended to serve, strengthening the case for empirically grounded, openly shared production guidelines such as those proposed in this study.

Third, by deriving evaluation criteria through a systematic literature review and combining Likert evaluation with CVI analysis through a 15-member expert panel, the study secured both reliability and academic justification for its assessment process. The overall S-CVI/Ave of 0.98 across the initial 16-item instrument exceeded the conventional threshold (≥ 0.90), and after removal of CVI-1-4 the final 15-item instrument yielded an S-CVI/Ave of 0.99, indicating that the four criteria are content-appropriate for measuring the educational validity of tactile graphics [31,32]. The complete agreement (S-CVI/Ave = 1.00) observed for the practical usability domain carries particular theoretical weight. UDL has long argued that proactive design—building accessibility into materials from the outset—is more effective than retrofitting [3,23]. The expert consensus that these materials can be used without further teacher adaptation provides preliminary expert-level evidence, in the cultural heritage tactile graphics domain, that UDL-grounded design can produce materials that are judged to meet this bar by specialists; empirical confirmation with classroom learners remains a direction for future research. The inclusion of Dot Incorporation-affiliated content developers in the expert panel warrants methodological clarification. The Dot Pad is a specialized refreshable tactile display operating on a 300-cell, 2400-pin matrix architecture; evaluating whether tactile graphic content is compatible with and optimally rendered on this device requires direct, hands-on expertise that is specific to the device itself. No generic tactile graphics specialist can substitute for this device-specific knowledge, because content that reads clearly on screen may degrade substantially when translated to pin-matrix output at this resolution. The inclusion of two current Dot Incorporation employees and one former employee (now working independently) among the content developer subgroup was therefore not a concession to convenience but a methodological necessity: without raters who possess device-level technical knowledge, the practical usability and Dot Pad compatibility items (4-1 and 4-2) could not have been evaluated with the precision the validation required. All three content developers conducted their evaluation using the physical Dot Pad device itself rather than screen-based renderings, ensuring that their ratings reflected actual tactile output. Future studies may consider complementing device-specialist panels with independent usability evaluators to triangulate findings across perspectives. The one item below threshold—CVI-

1-4 (I-CVI = 0.67)—indicates that the construct of ‘measuring the effect of design guidelines’ requires a sharper operational definition, and future studies can address this by refining the criterion’s wording and scope.

Fourth, the study demonstrates the viability of deploying tactile graphic learning materials within a TUI-based tactile interface environment—and connects that viability to a broader international concern. Refreshable tactile displays such as the Dot Pad render graphic information dynamically, enabling students with visual impairments to actively explore information structure rather than receiving it passively [12,22]. Holloway et al. [13] demonstrated that this expressive range can extend to motion graphics, pointing toward a future in which tactile content is not merely a static surrogate for visual information but a distinct medium with its own dynamic possibilities. Sánchez et al. [2] documented that mandated assistive technology frequently goes underused in classrooms because teachers feel unprepared—a pattern that matches the Korean field evaluations reported by Park et al. [16]. The unanimous expert agreement on practical usability (S-CVI/Ave = 1.00) suggests that standardized, ready-to-use tactile content offers a route to narrowing that gap: if teachers do not need to restructure materials before use, the preparedness barrier that drives non-adoption is substantially reduced.

Fifth, the methodological contribution of this study lies in its integrated treatment of DBR and UDL—and in what that integration makes possible theoretically. Rather than running the two frameworks in parallel, this study embedded UDL principles within each iterative DBR cycle as the criterion for design decisions. UDL frames the problem of learning access in theoretical terms; DBR generates the iterative design knowledge needed to address it. This relationship is genuinely complementary: UDL without a mechanism for iterative refinement risks remaining at the level of aspiration, while DBR without a principled theoretical criterion risks producing design knowledge that is locally useful but theoretically thin. The integration demonstrated here addresses both risks simultaneously, and the resulting model is portable to subsequent research in special education learning material development that seeks to narrow the gap between theory and practice [3,27]. This study also extends the empirical base for DBR in inclusive education: whereas DBR has been applied productively in general K–12 and technology-enhanced learning contexts [26], its application to the development of alternative learning materials for students with disabilities remains limited, and the present study offers a worked example of how its iterative logic can operate in this domain.

Limitations

Several limitations should be noted. First, because the study centered on expert validation, empirical investigation involving students with visual impairments in actual classrooms was outside its scope. Expert validation establishes the content and structural appropriateness of learning materials but does not, in itself, demonstrate learning effects [28]. Second, CVI-1-4 (“degree to which the effect of applying design guidelines can be measured through tactile exploration”; I-CVI = 0.67, κ^* = 0.63) fell below the acceptance threshold and was removed from the final instrument in accordance with CVI methodology [31,32]. Its removal signals that assessing guideline effectiveness empirically requires a distinct measurement approach beyond the scope of this expert validation study. In addition, although CVI-3-4 met the I-CVI threshold (0.93), one of the 15 raters dissented, indicating that this item may benefit from further refinement in future iterations of the instrument. Third, the design guidelines were derived from Korean traditional cultural images; their generalizability to heritage imagery from other cultural contexts—or to other subject domains such as science or mathematics—will require further validation. Fourth,

the 300-pin constraint of the Dot Pad imposes a hard ceiling on resolution, which in turn shapes the level of design complexity that tactile graphics can carry.

6. Conclusions

This study developed digital tactile graphic learning materials based on Korean traditional cultural images to support cultural heritage concept learning for students with visual impairments and examined their expert-judged educational appropriateness through content validation. In the 5-point Likert evaluation, the 15 experts produced an overall mean of $M = 4.69$ ($SD = 0.51$), with consistently high ratings across all domains. The CVI analysis returned an overall S-CVI/Ave of 0.99 for the final instrument (initial 0.98 across the original 16 items, refined to 0.99 after removal of one underperforming item), satisfying the content validity threshold (≥ 0.90) and confirming the academic reliability of the evaluation criteria.

The study makes five principal contributions. It establishes a textbook-based dataset of 200 traditional cultural images; it proposes a systematic design method for restructuring cultural heritage images into tactile graphics; it anchors the educational validity of the resulting materials in expert validation against criteria derived from a literature review; it distills five design guidelines aimed at standardizing tactile graphic production; and it presents a prototype TUI-based tactile learning environment configuration demonstrating the deployability of the validated materials on a refreshable pin-matrix display.

Inconsistent transcription practices across braille transcribers, and the structural shortfall created by the absence of standardization in tactile graphics, are problems that must be addressed if the right to learn for students with visual impairments is to be more fully realized. The design guidelines proposed here are offered as a preliminary empirical reference point that may inform future tactile graphic production standards, pending further independent validation. Subsequent work should test these materials with students with visual impairments in actual classrooms to validate learning effects, and the integration of AI-based automatic tactile graphic conversion may further increase the efficiency of content distribution. To support direct dissemination of the validated materials to field practitioners, the 90 finalized tactile graphics together with their accompanying braille-based descriptions have been compiled into a practitioner-oriented guide, “Guidelines for Braille Education of Korean Traditional Culture Contents” [41], providing a tangible bridge between the present research outcomes and classroom practice in Korea.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki. Ethical review and approval were not required for this study under Article 15(2) of the Bioethics and Safety Act of the Republic of Korea and Article 13(1) of its Enforcement Rule, which provide for the exemption from institutional review board review of non-invasive research that does not collect or record personally identifiable information. The research did not involve any direct intervention on, or data collection from, individuals with visual impairments. The study was limited to expert evaluation of instructional materials, in which a panel of 15 professional experts in visual impairment education, assistive technology and accessibility, tactile graphic design, content development, and traditional cultural image research conducted a two-stage assessment using a 5-point Likert scale and Content Validity Index (CVI) measurement. No personally identifiable information, sensitive personal data, or any clinical or behavioral intervention on human participants was involved. Empirical effectiveness testing with learners with visual impairments was not performed in this study and is acknowledged as a direction for future research.

Informed Consent Statement: Informed consent was obtained from all 15 expert panelists who participated in the content validation process. All participants were informed of the purpose, procedure, and intended scholarly use of the study prior to their participation, and voluntarily agreed to take part. No personally identifiable information was collected or reported in this study.

Data Availability Statement: The raw Likert and CVI rating datasets (15 experts $\times$ 16 items), the anonymized item-level rating data, and the evaluation instrument are available from the corresponding author upon reasonable request. The finalized 90-item tactile graphic dataset is archived on the Dot Incorporation platform and is accessible via the corresponding author. Under Article 25 of the Korean Copyright Act, reproduction of published works for educational research is permitted without prior authorization, but this provision does not extend to the open redistribution of derived works. Because the source images were drawn from elementary school textbooks, direct redistribution of the derived tactile graphic files would exceed the scope of this exemption.

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Conflicts of Interest: The author declares no personal conflicts of interest. The Dot Pad devices used in this study were purchased by the researcher. Two current employees and one former employee of Dot Incorporation participated in the expert panel as content developers; their inclusion was necessitated by the device-specific technical expertise required for pin-matrix-based evaluation, as described in Section 5.

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