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Augmented Reality Integrated Sensory Books for Contextual Vocabulary Learning in Deaf and Hard-of-Hearing (DHH) Children: A Systematic Literature Review (2021–2026)

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ABSTRACT - Children who are deaf or hard of hearing (DHH) frequently have enduring obstacles in early vocabulary development, which may limit subsequent reading and classroom engagement. Augmented reality (AR) has progressively been integrated with multimodal books to deliver contextualized, multi-sensory vocabulary learning; yet, the evidence remains disjointed across special education, educational technology, and design/HCI domains.

This systematic literature review synthesized empirical data published from 2021 to 2026 about AR-integrated sensory-book methodologies for vocabulary acquisition in DHH youngsters. Investigations were performed across four databases (ACM Digital Library, Scopus, Web of Science Core Collection, and SpringerLink) and were supplemented by backward and forward snowballing techniques. Study selection adhered to PRISMA 2020 protocols, and methodological quality was evaluated using the Mixed Methods Appraisal Tool (MMAT, 2018). Seventy-one eligible studies were incorporated into the final synthesis from a total of 862 database entries and supplementary snowballing records (January 2026 update). The findings were synthesized narratively in relation to three study questions: (RQ1) The integration of AR inside sensory-book contexts, (RQ2) the design-feature clusters linked to vocabulary-related outcomes, and (RQ3) the identified advantages and limitations. The research indicates that AR-sensory book therapies are typically structured to enhance attention, engagement, and contextual word-meaning mapping; nevertheless, there is significant variability in intervention designs, outcome measures, and reporting quality. The review provides a design-focused taxonomy and evidence-based recommendations to facilitate more reproducible, classroom-appropriate AR-sensory book designs for vocabulary acquisition in DHH learners.

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1 INTRODUCTION

Vocabulary enhancement is fundamental to early literacy, reading comprehension, and daily communication. For numerous youngsters who are deaf or hard of hearing (DHH), limited incidental access to spoken language and inconsistent exposure to sign language and print might impede vocabulary development, resulting in subsequent effects on scholastic advancement.Recent research has investigated technology-assisted methods to enhance accessible, repeated, and significant word exposure. Augmented reality (AR) can superimpose visualizations, prompts, and interactive feedback onto tangible learning materials, possibly connecting physical objects, symbols, and printed text.
Sensory (multi-sensory) books offer a physical medium for organized, page-oriented activities that include tactile, visual, and kinetic elements. When combined with augmented reality, sensory books can enhance contextual vocabulary acquisition through interactive sceneries, task sequences, and multi-modal cues (e.g., image overlays, QR codes, or markerless tracking).Despite increasing interest, research on augmented reality-integrated sensory books for deaf and hard of hearing learners is fragmented among special education, learning sciences, educational technology, and design/human-computer interaction(Lunny et al, 2022). Research varies in target age, auditory profiles, intervention dosage, auditory rehabilitation triggering mechanisms, and outcome metrics, complicating the translation of individual findings into applicable design guidelines.
This review synthesizes papers published from 2021 to 2026 on augmented reality-supported sensory-book therapies that report vocabulary-related results for deaf and hard of hearing children. Instead of solely concentrating on effectiveness assertions, we investigate the implementation of augmented reality in sensory-book scenarios and identify the design choices most frequently associated with enhancements in vocabulary(Chuang & Jamiat, 2023).Contribution to design. This review not only summarizes outcomes but also (i) presents a taxonomy that disaggregates AR-sensory book interventions into actionable design elements (context, triggering, interaction, scaffolding, and assessment), and (ii) consolidates evidence-based design principles aimed at facilitating inclusive vocabulary instruction in the classroom.

2 METHODS AND MATERIALS

2.1 Review Design and Reporting Standard

We performed a comprehensive literature study to synthesize design and evaluation findings transparently and reproducibly. The review adhered to PRISMA 2020 guidelines, and the PRISMA checklist is included in Appendix A. The review questions and eligibility criteria were structured according to the PICOS framework (Population, Intervention, Comparison, Outcomes, Study design).

2.2 Research Questions

RQ1: How is augmented reality (AR) integrated into sensory (multisensory) books to support contextual vocabulary learning for DHH children?
RQ2: Which AR design-feature clusters are associated with improved vocabulary-related outcomes for DHH children?
RQ3: What are the advantages and disadvantages of using AR technology in sensory-book vocabulary instruction for DHH children?

2.3 Search Strategy and Eligibility Criteria

Operational definition of sensory (multisensory) literature. This review defines sensory (multisensory) books as book-based educational materials that (i) incorporate a physical, tactile component facilitating sensory engagement (e.g., textured elements, flaps, manipulatives, matching pieces), (ii) display printed vocabulary targets alongside corresponding visual representations (print–image mapping), and (iii) integrate vocabulary-focused tasks within the page-based activities (e.g., matching, retrieval prompts, guided practice, or contextual use tasks). Digital-only storybooks or e-books lacking a tactile sensory-book component were omitted. AR interventions were permissible solely when the AR content was activated by or integrated into the specified book-based sensory items to facilitate vocabulary acquisition (Haoming & Wei, 2024).

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2.4 Time Window and Databases

The review included studies published from 2021 to 2026. Searches were conducted in ACM Digital Library, Scopus, SpringerLink, and Web of Science. The initial search was completed in June 2025 and updated in January 2026.

2.5 Search String

The search criteria encompassed (i) the DHH/hearing impairment demographic, (ii) AR and sensory-book environments, and (iii) vocabulary/language results. The definitive database-specific search strings are documented in Appendix B. Records obtained through expansive book terminology (e.g., storybook/picture book) were preserved solely if the whole text validated the presence of a physical sensory-book element in accordance with the operational criteria.

Table 1. Final search strategy and keywords (2021-2026)

Scope	String
Concept	Keywords (example; adapt to each database syntax/fields)
Population (P)	("deaf" OR "hearing impairment" OR "hard of hearing" OR DHH OR "hearing-impaired")
Intervention (I)	("augmented reality" OR AR)
Context	(“sensory book” OR “multisensory book” OR “tactile book” OR “touch-and-feel book” OR “interactive physical book” OR “manipulative book”)
Outcomes (O)	(vocabulary OR "word learning" OR "language development" OR "contextual learning" OR literacy)

2.6 Inclusion and Exclusion Criteria

The inclusion criteria were: (1) participants consisted of children who are deaf or hard of hearing (DHH) or DHH subsamples with distinct data; (2) the intervention employed an augmented reality-integrated sensory (multisensory) book or a closely analogous page-based multisensory resource; (3) the study reported at least one vocabulary-related outcome (e.g., word recognition, receptive/expressive vocabulary, word-meaning comprehension) or explicitly defined vocabulary-learning performance; (4) the full text was peer-reviewed and available in English or Chinese; and (5) the study was published between 2021 and 2026.

Exclusion criteria: (1) Augmented Reality (AR) utilized in contexts unrelated to literature or lacking book-related activities; (2) solely digital storybooks or e-books without a physical sensory book component; (3) samples excluding Deaf and Hard of Hearing (DHH) individuals with indistinct DHH data; (4) lack of vocabulary-related outcomes; (5) non-peer-reviewed materials (e.g., abstracts only) or insufficient reporting of interventions/outcomes for extraction.

Table 2. Inclusion and exclusion criteria (PICOS framework).

Domain	Inclusion criteria	Exclusion criteria
Population	Children who are DHH / hearing-impaired	Non-DHH population; DHH data not separable
Intervention	AR integrated into sensory/multisensory books as operationally defined (tangible hands-on component + print–image representation + vocabulary-targeted tasks); AR must be triggered by or embedded in the book activity	AR used in non-book settings; AR used with digital-only storybooks/e-books without physical sensory-book components; general AR apps not tied to book-based vocabulary learning.
Comparison	Any comparison condition or single-group evaluations	—
Outcomes	Vocabulary/word learning/language development outcomes	No language/vocabulary-related outcomes

continued

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Study design	Empirical studies (experimental/quasi/DBR/mixed-method/pilot)	Conceptual/opinion; abstract only; no full text
Source type	Peer-reviewed journal or full conference paper	Book chapters, non-peer-reviewed reports
Time window	Published 2021–2026	Outside 2021–2026
Language	English or Chinese	Not in included language(s)

2.7 Study Selection Procedure

The study selection adhered to four stages of PRISMA 2020: identification, screening, eligibility, and inclusion (Figure 1). Subsequent to deduplication, records were evaluated based on title and abstract, followed by a comprehensive full-text assessment in accordance with the established PICOS criteria (Table 2).

Two reviewers separately evaluated titles and abstracts, as well as analyzed complete texts. Disputes were settled through dialogue, with third-party review employed as necessary. Screening and deduplication were conducted in Rayyan. To enhance reproducibility, reviewers standardized screening choices on a pilot subset prior to comprehensive screening and preserved a record of inclusion determinations.

2.8 Snowballing Strategy

Based on the eligible database research, backward and forward snowballing were carried out to improve coverage and lessen database bias. While forward snowballing used Google Scholar to find subsequent citing papers, backward snowballing looked at the reference lists of relevant studies. The inclusion and exclusion criteria used in the database screening were also used in both steps(Lunny et al, 2022).

2.9 Data Extraction and Synthesis

A systematic extraction form was created and tested on a preliminary subset of included papers to enhance coding rules and increase consistency. For each study included, we extracted: (i) bibliographic details; (ii) participant demographics (age/grade, hearing profile including cochlear implant/hearing aid usage, communication mode, and the separability of DHH-specific outcomes); (iii) intervention details (tangible book components, AR trigger and functional role, learning environment, implementer, and intervention dosage—sessions, duration, and frequency); (iv) study design and comparison condition (if applicable); and (v) outcomes and measures (receptive, expressive, and contextual vocabulary; engagement/usability; and the use of standardized instruments).

Due to the variability in intervention designs and outcome measures, we performed a design-focused narrative synthesis. Research studies were categorized to address RQ1–RQ3 by organizing (a) augmented reality integration patterns, (b) design-feature configurations and scaffolding methodologies, and (c) identified benefits and limitations. Two reviewers independently retrieved and classified studies; discrepancies were resolved through discussion and third-party adjudication. The extraction template and coding method are contained in Appendix C.

2.10 Methodological Quality Appraisal

We evaluated methodological quality with the Mixed Methods Appraisal Tool (MMAT, 2018) due to the inclusion of research with qualitative, quantitative, and mixed-method designs. Each study was initially classified into the relevant MMAT category and subsequently evaluated according to five specific criteria within that category(Hong et al, 2020). Quality appraisal was employed to contextualize confidence in the synthesis rather than to eliminate research(Edgar Marçal, 2024).

In mixed-methods research, we evaluated the quality of the pertinent qualitative and quantitative elements, together with the coherence of their integration. Appendix D contains item-level judgments (Yes/No/Can't tell) for all studies to ensure transparency.

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3 RESULTS AND DISCUSSION

3.1 Data collection

We examined four databases (ACM Digital Library, Scopus, SpringerLink, and Web of Science) to optimize coverage across HCI/design and educational platforms. The preliminary search was finalized in June 2025 and revised in January 2026. The discovery and selection of studies are encapsulated in the PRISMA flow diagram (Figure 1).

A total of 862 records were obtained from the four databases utilizing the established search method. Following the elimination of non-eligible publication categories or records lacking accessible full text (n=312), duplicates (n=142), and evidently irrelevant records during title/abstract screening (n=228), 180 records advanced to full-text evaluation. Out of these, 138 were removed for failing to meet PICOS-based eligibility criteria (e.g., non-book AR settings; non-DHH samples or non-separable DHH data; absence of vocabulary-related outcomes), not being peer-reviewed full articles, or lacking adequate intervention/outcome reporting for extraction. This yielded 42 qualifying database studies.

The qualifying database studies were allocated as follows: ACM Digital Library (n=9), Scopus (n=12), SpringerLink (n=10), and Web of Science (n=11) (Table 3).

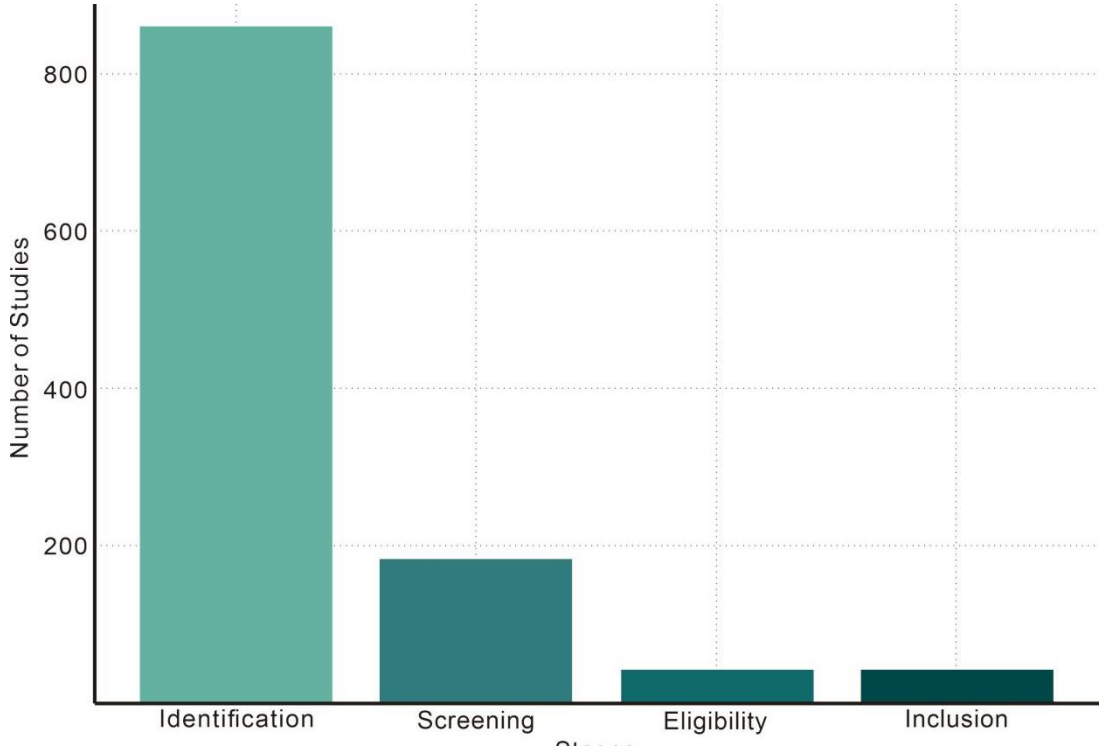

Figure 1. PRISMA flow diagram of study identification and selection (2021–2026)

Table 3. Distribution of eligible database studies by source (n = 42)

Database	Number of Studies
ACM Digital Library	9
Scopus	12
SpringerLink	10
Web of Science	11

3.2 Snowballing

The 42 qualifying database studies constituted the initial set for backward and forward snowballing to mitigate retrieval bias beyond database indexing (Figure 2). The identical inclusion and exclusion criteria were utilized.

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Backward snowballing analyzed the reference lists of the 42 foundational works, resulting in 865 records. Following the elimination of duplicates (n=96) and non-scholarly items (n=112), 657 entries were evaluated based on title and abstract. Subsequently, we evaluated the whole texts of items deemed potentially suitable following screening; 18 more research satisfied the inclusion criteria and were incorporated.

Forward snowballing employed Google Scholar citation tracking, resulting in 284 records. Following title and abstract screening, 165 records advanced to full-text evaluation, resulting in the inclusion of 11 more suitable research.

Snowballing yielded a total of 29 supplementary eligible papers (18 from backward citation and 11 from forward citation). The integration of these with the 42 database-eligible research resulted in a total of 71 studies included for synthesis. Duplicate items from various sources were eliminated during screening to ensure that each included study was counted only once.

Table 4. Snowballing results and additional eligible studies

Step	Backward Snowballing	Forward Snowballing	Total
Records retrieved	865	284	1149
Duplicates removed	96	Not assessed separately*	—
Non-scholarly records removed	112	Not assessed separately*	—
Records screened	657	284	941
Full texts assessed (eligibility confirmed)	18	165	183
Eligible studies added	18	11	29

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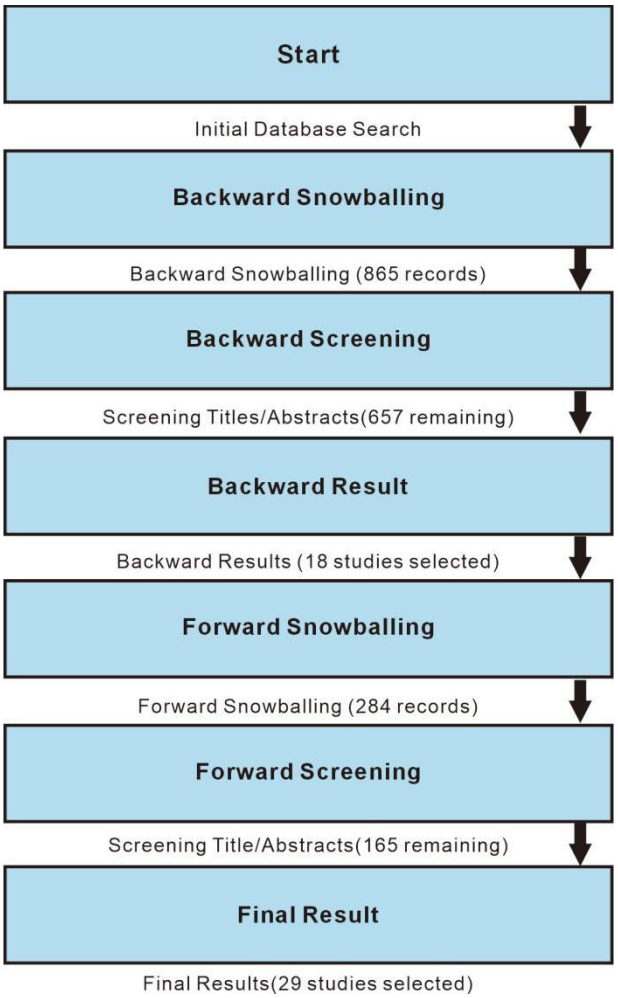

Figure 2. Forward and backward snowballing procedure for study identification and screening

Note. In backward snowballing, full-text screening was performed only for records judged potentially eligible after title/abstract screening; therefore, the reported number of full texts corresponds to the number of additional included studies at this stage. For forward snowballing, full-text assessment counts are reported explicitly (165 assessed; 11 included).

3.3 Quality appraisal results（MMAT）

The quality of the study was evaluated utilizing the Mixed Methods Appraisal Tool (MMAT, 2018). Each study was assessed according to the five MMAT criteria pertinent to its design category, with item-level determinations documented as Yes/No/Can't tell. The complete item-level appraisal table for all studies is presented in Appendix D to ensure a transparent audit trail.

A total of 18 studies were classified as high quality (≥ 4 "Yes"), 32 as moderate quality (3 "Yes"), and 21 as low quality (≤ 2 "Yes"). The predominant limitations identified within the corpus encompassed small sample sizes and inadequately powered designs, insufficient reporting of DHH-relevant participant characteristics (such as CI/HA usage and communication modalities), diverse and often non-standardized vocabulary assessments, and restricted control of confounding variables in non-randomized designs (including baseline equivalence and intervention dosage).

Synthesis informed by quality. To mitigate over-interpretation stemming from inadequate or selectively provided evidence, we approached effectiveness claims with caution and prioritized patterns that were more reliably linked to favorable vocabulary-related outcomes and corroborated by higher-quality research(González-Cuenca et al, 2024).

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3.3.1 Synthesis by research questions

Question 1: In what manner is augmented reality (AR) included into multisensory books to facilitate contextual vocabulary acquisition for deaf and hard of hearing (DHH) children?
Design synthesis of RQ1 (augmented reality integration patterns). In the examined research, augmented reality was generally incorporated as a visual support layer linked to page-based activities. Typical configurations comprised: (i) meaning visualization through animations or 3D objects and scene overlays activated by page images or markers; (ii) accessible language prompts, such as sign or gesture demonstrations, captions, and mouth-shape cues, delivered in synchrony with printed targets; and (iii) interaction-triggered feedback during straightforward tasks, including tapping or scanning to reveal, match, or confirm. When augmented reality content was closely aligned with the learning purpose, rather than serving just as cosmetic novelty, studies consistently indicated enhancements in attention and vocabulary-related performance(Chang et al, 2025).

Question 2: Which clusters of AR design features correlate with enhanced vocabulary outcomes for DHH children?
Design synthesis of RQ2 (configurations of design features associated with vocabulary-related outcomes). The research frequently attributes vocabulary improvements to a combination of design choices rather than a singular 'optimal' feature. Three repeating configurations were identified across studies(Hettiarachchi et al, 2021): (1) Multimodal alignment—synchronizing print, static imagery, augmented reality visualization, and accessible language supports (e.g., sign language, gestures, or captions) to mitigate ambiguity in word-meaning associations; (2) Scaffolded practice sequences—advancing from recognition to guided retrieval and subsequently to contextual application within scenes or narrative events; and (3) Classroom-compatible interaction flow—minimal friction triggers, uniform interface patterns, and prompt feedback that educators can consistently implement within time limitations. These configurations can be regarded as design patterns for AR-sensory novels and are detailed as actionable ideas in the Discussion.

Question 3: What are the benefits and drawbacks of employing AR technology in vocabulary instruction for sensory books aimed for DHH children?
Design synthesis of RQ3 (advantages and limitations). Documented advantages focused on enhanced engagement, prolonged visual attention, and deeper contextualization of language when augmented reality offered immediate, visually available cues and feedback integrated into concrete routines. Nevertheless, research has indicated limitations that directly influence design choices: device accessibility, technological unreliability (tracking/recognition errors), development and maintenance expenses, and the necessity for educator training and lesson incorporation(Schorr et al, 2024). These limits suggest that scalable AR-sensory books must emphasize dependable triggering, rapid initiation, straightforward interaction pathways, and explicit advice for educators, in addition to accessible multimodal linguistic assistance.

3.3.2 Overall summary of the evidence base

Through identification, screening, eligibility evaluation, and snowball sampling, 71 studies were incorporated into the final synthesis (42 from database searches; 29 from snowball sampling). All listed papers were published from 2021 to 2026. The evidence base encompasses special education, educational technology, and HCI/design domains, although exhibits considerable variability in intervention design, assessment, and reporting specificity(Samaradivakaa et al, 2025).

Commonly reported outcomes across research included vocabulary recognition, receptive understanding, expressive usage, and contextual application, as well as process variables including engagement, attention, and usability(Solichah & Fardana, 2024). Due to the variability in interventions and outcome measurements, we synthesized the data narratively employing the coding scheme in Appendix C and analyzed design claims with a focus on methodological quality (Section 3.3).

This section converts the synthesis of the review into interpretations pertinent to design. Due to the variability in rigor and reporting detail among primary research, we see design claims as recurring patterns within the literature and as hypotheses to be explored and developed by more rigorous reviews.

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3.3.3 Key design insights

Synthesising across heterogeneous designs, the literature points to a consistent interaction logic: vocabulary learning is supported when AR functions are tightly coupled to page-based tasks (rather than added as decoration), and when multisensory book elements and AR overlays are orchestrated as a coherent routine. Below we translate recurring mechanisms into actionable design principles intended for designers, teachers, and developers working with DHH learners(Windson Viana, 2023).

Table 5. Design principles for AR-integrated sensory books (DHH vocabulary learning).

Principle	What to do (mechanism)	Practical notes / risks
Synchronise multimodal cues	Align print, image, AR visualisation, and sign/gesture/captions in time and space.	Keep overlays near the printed target; allow replay; avoid presenting too many cues at once.
Scaffold from recognition to use	Sequence tasks from recognition → guided retrieval → contextual use within scenes/stories.	Use short page-level loops; fade prompts gradually; ensure teachers can pace activities.
Low-friction interaction loops	Use reliable triggers and consistent interaction patterns with immediate feedback.	Prefer simple scan/tap; fast start-up; provide clear 'ready' state; plan for tracking failures.
Pacing and repetition control	Provide pause/replay and learner/teacher control of timing and repetition.	Keep clips short; chunk content; too much repetition can reduce engagement.
Accessibility as first-class design	Embed accessible language supports (sign/gesture, captions) as core content.	Ensure legibility (size/contrast); avoid competing visuals; keep sign and print mapping consistent.
Classroom deployment readiness	Provide teacher-facing guidance, offline-safe options, and troubleshooting support.	Minimise device dependency; include lesson scripts per page; consider training and maintenance costs.

3.4 Implications for evaluation in design research

In design-oriented studies, evaluation must link outcome measures with the planned interaction mechanisms. Reports must, at a minimum, delineate participant hearing profiles (e.g., CI/HA utilization, communication modality), intervention dosage (sessions, length), and the specific AR functions employed each page/task. In situations when controlled designs are impractical, researchers must record baseline equivalency, employ repeated assessments, and link vocabulary outcomes with process measures (attention, usability, engagement) to enhance interpretability.

4 CONCLUSION

AR-integrated sensory books exemplify a promising approach to inclusive design for contextual vocabulary acquisition in DHH children, since they merge tactile interaction with visually accessible cues and feedback. Nevertheless, the quality and reporting of evidence remain inconsistent throughout the profession. Future research should delineate participant characteristics pertinent to DHH, quantify intervention dosage, employ standardized vocabulary outcome measures, and evaluate retention and transfer over extended durations. Designers and practitioners should prioritize dependable, seamless interaction loops that include print, graphics, and accessible language aids, while continuously validating prototypes through quality-informed evaluation.

5 LIMITATIONS OF THIS REVIEW

This review is constrained by variability in intervention designs and outcome measurements, which precluded quantitative meta-analysis. Moreover, not all studies provided adequate material regarding DHH-relevant participant characteristics and dosage to provide precise comparison. Although quality appraisal (MMAT) guided interpretation, reporting limitations in primary studies may still skew synthesis towards more well documented therapies.

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7 FUNDING

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8 CONFLICT OF INTEREST

The authors declare no conflicts of interest.

9 AVAILABILITY OF DATA AND MATERIALS

All data used in this review were derived from published studies identified through database searches and snowballing procedures. The PRISMA checklist (Appendix A), database-specific search strings (Appendix B), and extraction/coding scheme (Appendix C) are provided within the article and its supplementary appendices. Additional materials (e.g., the full MMAT item-level appraisal table) can be made available by the authors upon reasonable request, subject to copyright and access restrictions of the original publications.

10 DECLARATION OF GENERZTIVE AI

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to enhance the clarity and readability of the writing. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

11 ETHIC STATEMENTS

This research constitutes a systematic literature review reliant solely on published and publicly available sources. The study did not entail the recruitment of human subjects, the acquisition of personal data, or any form of intervention. Consequently, formal ethical approval and informed consent were unnecessary.

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13 APPENDIX

Appendix A PRISMA 2020 checklist (with manuscript cross-references)

Note: "Location in manuscript" is reported by section/subsection headings to avoid pagination differences across formats. Items marked "Not reported" are recommended additions for PRISMA completeness.

Section/Topic	Item	PRISMA 2020 checklist item (abridged)	Location in manuscript
TITLE	1	Identify the report as a systematic review.	Title
ABSTRACT	2	See PRISMA 2020 for Abstracts checklist.	Abstract
INTRODUCTION	3	Describe the rationale for the review in the context of existing knowledge.	Introduction
INTRODUCTION	4	Provide an explicit statement of the objective(s) or question(s) addressed by the review.	Methods 2.2 Research Questions
METHODS	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for syntheses.	Methods 2.3–2.3.3; Table 2

continued

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METHODS	6	Specify all information sources searched or consulted and the date when each was last searched.	Methods 2.3.1
METHODS	7	Present the full search strategies for all databases and registers, including any filters and limits.	Appendix B (to be inserted)
METHODS	8	Specify the methods used to decide whether a study met the inclusion criteria.	Methods 2.4
METHODS	9	Specify the methods used to collect data from reports.	Methods 2.6; Appendix C
METHODS	10a	List and define all outcomes for which data were sought.	Methods 2.6 (Outcomes and measures)
METHODS	10b	List and define all other variables for which data were sought.	Methods 2.6 (bibliographic, participants, intervention, design)
METHODS	11	Describe the methods used to assess risk of bias/quality in individual studies.	Methods 2.7; Results 3.3; Appendix D
METHODS	12	Specify the effect measures used for each outcome (if applicable).	Not reported (narrative synthesis; recommend adding in Methods 2.6/2.7)
METHODS	13a	Describe the processes used to decide which studies were eligible for each synthesis.	Methods 2.6; Results 3.1–3.2
METHODS	13b	Describe methods required to prepare the data for presentation or synthesis.	Not reported (recommend adding brief statement on coding/normalisation in Methods 2.6)
METHODS	13c	Describe methods used to tabulate or visually display results of individual studies and syntheses.	Results by RQ; Appendix C (coding); recommend adding included-study summary table
METHODS	13d	Describe any methods used to synthesize results and provide rationale for choice(s).	Methods 2.6 (narrative synthesis rationale)
METHODS	13e	Describe any methods used to explore possible causes of	Not reported (recommend adding quality-informed stratification/notes)

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		heterogeneity among study results.	
METHODS	13f	Describe any sensitivity analyses conducted to assess robustness of results.	Not reported
RESULTS	14	Describe the results of the search and selection process, from number of records identified to included studies.	Results 3.1–3.2; Figures 1–2; Tables 3–4
RESULTS	15	Cite studies that might appear to meet inclusion criteria but were excluded, and explain why.	Partially reported (reasons in 3.1; recommend adding a short excluded-full-text reasons table)
RESULTS	16a	Describe the characteristics of included studies.	Partially reported (Table 3 for database sources; recommend adding full included-study characteristics table in Appendix C)
RESULTS	16b	Present the results of risk of bias/quality assessments for each study.	Appendix D (template) + Results 3.3 summary
RESULTS	17	Present results of individual studies and syntheses.	Results by RQ (Q1–Q3)
RESULTS	18	Present results of investigations of heterogeneity (if conducted).	Not reported
RESULTS	19	Present results of sensitivity analyses (if conducted).	Not reported
DISCUSSION	20	Provide a general interpretation of the results in the context of other evidence.	Not reported as standalone Discussion (recommend adding Discussion section)
DISCUSSION	21	Discuss limitations of the evidence included in the review.	Partially reported (Overall Summary; quality appraisal notes)
DISCUSSION	22	Discuss limitations of the review processes used.	Not reported (recommend adding a brief limitations paragraph)
DISCUSSION	23	Discuss implications of the results for practice, policy, and future research.	Partially reported (Q3 closing + Overall Summary; recommend strengthening)
OTHER	24	Provide registration information for the review (if registered).	Not reported (state “Not registered” or provide ID)
OTHER	25	Describe sources of support and role of funders.	Not reported (add Funding/Support statement)

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OTHER	26	Declare competing interests.	Not reported (add Competing Interests statement)
OTHER	27	Report availability of data, code, and other materials.	Not reported (recommend Data availability statement; appendices included)

Appendix B Database-specific full search strings (2021–2026)

Searches were conducted in June 2025 and updated in January 2026. The following strings operationalize the four concept blocks used in Table 1 (Population; Intervention; Context; Outcomes) and were adapted to each database syntax/field options.

ACM Digital Library

Search dates: Initial: June 2025; Update: January 2026
Fields searched: All fields (with filters: Publication Years 2021–2026; Content type: journal article / conference proceeding full paper)

Full search string:

- ("deaf" OR "hard of hearing" OR "hearing impairment" OR DHH OR "hearing-impaired") AND ("augmented reality" OR AR) AND ("sensory book" OR "multisensory book" OR "tactile book" OR "touch-and-feel book" OR "interactive physical book" OR "manipulative book") AND (vocabulary OR "word learning" OR "language development" OR "contextual learning" OR literacy)

Scopus

Search dates: Initial: June 2025; Update: January 2026
Fields searched: TITLE-ABS-KEY (with filters: 2021–2026; Language: English or Chinese; Source type: journals or conference proceedings)

Full search string:

- TITLE-ABS-KEY(("deaf" OR "hard of hearing" OR "hearing impairment" OR DHH OR "hearing-impaired") AND ("augmented reality" OR AR) AND ("sensory book" OR "multisensory book" OR "tactile book" OR "touch-and-feel book" OR "interactive physical book" OR "manipulative book") AND (vocabulary OR "word learning" OR "language development" OR "contextual learning" OR literacy))
- AND (PUBYEAR > 2020 AND PUBYEAR < 2027)
- AND (LANGUAGE(english) OR LANGUAGE(chinese))
- AND (DOCTYPE(ar) OR DOCTYPE(cp))

Web of Science Core Collection

Search dates: Initial: June 2025; Update: January 2026
Fields searched: Topic (TS) (with filters: 2021–2026; Document types: Article, Proceedings Paper; Languages: English, Chinese)

Full search string:

- TS=(("deaf" OR "hard of hearing" OR "hearing impairment" OR DHH OR "hearing-impaired") AND ("augmented reality" OR AR) AND ("sensory book" OR "multisensory book" OR "tactile book" OR "touch-and-feel book" OR "interactive physical book" OR "manipulative book") AND (vocabulary OR "word learning" OR "language development" OR "contextual learning" OR literacy))
- Refined by: DOCUMENT TYPES=(ARTICLE OR PROCEEDINGS PAPER)
- Refined by: LANGUAGES=(ENGLISH OR CHINESE)
- Timespan: 2021–2026

SpringerLink

Search dates: Initial: June 2025; Update: January 2026
Fields searched: Full-text (with filters: 2021–2026; Discipline filters as applicable; Language: English/Chinese when available)

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Full search string:

- (("deaf" OR "hard of hearing" OR "hearing impairment" OR DHH OR "hearing-impaired")) AND (("augmented reality" OR AR)) AND (("sensory book" OR "multisensory book" OR "tactile book" OR "touch-and-feel book" OR "interactive physical book" OR "manipulative book")) AND ((vocabulary OR "word learning" OR "language development" OR "contextual learning" OR literacy))
- Filters applied: Year=2021–2026; Content type=Article/Conference Paper (full); Language=English/Chinese (when available)

Note: For records retrieved using broader book terms (e.g., storybook/picture book), eligibility was confirmed only if the study explicitly reported a physical sensory-book component consistent with the operational definition in Methods 2.3.

Appendix C Data extraction form and coding scheme

This appendix documents the extraction template and coding rules used for narrative synthesis across RQ1–RQ3, consistent with Methods 2.6.

C0. Unit of analysis and counting rules

Unit of analysis: one record per included study (Study ID: S01–S71).
Missing information is coded as NR (Not Reported). If not applicable, code as NA.
Multi-label coding: studies may contribute to multiple codes (e.g., multiple AR triggers or settings). Counts therefore represent the number of studies mentioning each feature; category totals may exceed 71.

C1. Structured data extraction form (one row per study)

Extraction field	Operational definition / what to record	Coding options
Study identification	Study_ID; full citation; country/region; venue; publication type; language.	Free text; controlled options for publication type and language.
Participants (DHH characteristics)	Age/grade; total sample size; hearing profile (CI/HA/unaided/mixed); communication mode; whether DHH-specific data are separable; comorbidities.	Controlled options + NR.
Sensory (multisensory) book embodiment	Eligibility check against operational definition: tangible component + print–image representation + vocabulary-targeted tasks. Record tangible component types and book format.	Yes/No for eligibility components; multi-select for tangible types.
AR characteristics	AR trigger type; AR content functions (e.g., meaning visualisation; sign/gesture prompts; prompts/feedback); device/platform; authoring tool/app.	Multi-select + NR.
Implementation context	Setting; implementer; dosage (sessions x minutes x weeks); delivery mode (individual/group/class).	Multi-select + NR.
Study design	Design type (experimental/quasi/DBR/mixed/pilot/descriptive); comparison condition; randomisation; baseline equivalence.	Controlled options + NR/NA.
Outcomes and measures	Vocabulary domain (receptive/expressive/contextual use); engagement/usability outcomes; standardized test used; main finding direction.	Multi-select; direction coded as positive/mixed/null/negative/not tested.

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C2. Coding scheme for synthesis

C2.1 RQ1 codes: AR integration patterns in sensory-book contexts

RQ1 codes are non-mutually exclusive (0/1/NR).

Code	Definition (code as 1 if explicitly described)
RQ1_Trigger_MarkerImage	Marker-based or image-target trigger used (e.g., printed image recognised to launch AR).
RQ1_Trigger_QR	QR-code trigger used.
RQ1_Trigger_Markerless	Markerless trigger used (object recognition/spatial tracking).
RQ1_Tangible_TouchFeelFlapManipulative	Touch-and-feel pages, flaps/pop-ups, or manipulatives present.
RQ1_Tangible_MatchingVelcroSlotCards	Matching pieces, Velcro-backed items, slot-in cards/tokens present.
RQ1_Setting_SpecialEdClassroom	Implemented primarily in special-education classroom setting.
RQ1_Setting_TherapyRehab	Implemented in therapy/rehabilitation/clinical setting.
RQ1_Setting_Home	Implemented at home (parent-led or child-led).
RQ1_Role_RepresentationalOverlay	AR overlays meaning cues (animation/3D object) onto print/visuals.
RQ1_Role_PracticeGuidance	AR provides prompts/retrieval cues guiding practice tasks.
RQ1_Role_Feedback	AR provides corrective/confirmatory feedback during tasks.
RQ1_Role_ContextualScene	AR provides contextual scene/story grounding for word learning.
RQ1_Role_AccessibilitySupport	AR provides accessibility supports (sign/gesture prompts, captions, mouth-shape cues).

C2.2 RQ2 codes: Design-feature clusters linked to vocabulary-related outcomes

RQ2 codes record (a) presence of design features (0/1/NR) and (b) outcome direction (positive/mixed/null/negative/not tested).

Code	Definition
RQ2_Context_VisualScenes	Vocabulary introduced within meaningful scenes/story contexts (contextual grounding).
RQ2_Context_CurriculumAligned	Vocabulary targets are curriculum/IEP aligned (explicitly stated).
RQ2_Context_TransferTasks	Tasks require transfer/contextual use beyond recognition.
RQ2_Scaffold_RecognitionToUse	Explicit staged progression (recognition -> guided practice -> contextual use).
RQ2_Scaffold_GuidedPractice	Guided prompts or retrieval practice embedded in tasks.
RQ2_Scaffold_FeedbackLoop	Feedback loop supports correction and consolidation.
RQ2_Scaffold_DosageReported	Dosage clearly reported (sessions/duration/frequency).
RQ2_Multi_PrintImageAligned	Printed word/character tightly aligned with image cues.
RQ2_Multi_SignGestureSupport	Sign/gesture prompts or visual language scaffolds included.
RQ2_Multi_TemporalSync	Temporal synchronisation of prompts/cues with attention to the target word.

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RQ2_Usability_LowCognitiveLoad	Interface designed for low cognitive load (simple, consistent interaction).
RQ2_Usability_ReliableTracking	Tracking/recognition stability explicitly discussed.
RQ2_Usability_TeacherReady	Teacher guidance/manual/training for implementation provided.

Outcome direction fields (record per study):

- RQ2_VocabEffect: positive / mixed / null / negative / not tested
- RQ2_EngagementEffect: positive / mixed / null / negative / not tested
- RQ2_UsabilityEffect: positive / mixed / null / negative / not tested

C2.3 RQ3 codes: Reported advantages and constraints

Code	Definition
RQ3_Adv_EngagementAttention	Engagement/attention/motivation improvements reported.
RQ3_Adv_Comprehension	Improved comprehension/word-meaning mapping reported.
RQ3_Adv_Retention	Improved retention/recall reported.
RQ3_Adv_Accessibility	Accessibility gains via visual language supports (e.g., sign/gesture prompts).
RQ3_Adv_IndependentLearning	Support for self-paced/independent practice reported.
RQ3_Con_TechnicalInstability	Technical instability (bugs, recognition failures) reported.
RQ3_Con_DeviceAvailabilityCost	Device availability/cost/maintenance burden reported.
RQ3_Con_TeacherWorkloadTraining	Teacher/parent workload or training needs reported.
RQ3_Con_MeasurementHeterogeneity	Heterogeneous/non-standardised measures limit comparability.
RQ3_Con_ReportingGaps_DHH	Missing DHH-critical reporting (CI/HA, communication mode, separability).
RQ3_Con_DosageNotReported	Intervention dosage insufficiently reported.

Appendix D. MMAT (2018) quality appraisal summary

Quality tier (MMAT)	Operational definition	Number of studies
High	>= 4 'Yes' ratings	18
Moderate	3 'Yes' ratings	32
Low	<= 2 'Yes' ratings	21

Note: Item-level MMAT judgments for each included study are available from the authors upon reasonable request.

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