

VCBox-Assisted Soundscapes: Blending Teacher-Student Audio for Optimized Articulation Training in Early Learners

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ABSTRACT

This study presents a bibliometric analysis of 500 publications (2010–2025) on bone-conducted voice (BCV) technologies, highlighting their evolution from medical to educational applications, particularly in articulation training. Using performance analysis, co-citation and keyword mapping, content review, and gap assessment, we found an 8.3% annual growth rate and identified five intellectual clusters, with voice-mixing technologies as an emerging field. Teacher-student voice synchronization was notably underrepresented (coverage adequacy 2.6/10; 8.2% of studies). Research was concentrated in North America and Europe, with East Asia showing faster growth. Experimental studies demonstrated higher methodological rigor (3.8/5) than observational ones (3.2/5). The findings reveal a substantial gap in teacher-student audio blending research and propose a roadmap for integrating BCV with air-conducted feedback to enhance speech recognition, production, and attention in children with speech sound disorders.

INTRODUCTION

Speech sound disorders (SSDs) affect approximately 8-9% of children aged 3-12, presenting significant challenges for academic achievement, social development, and long-term communication skills (Nudelman et al., 2025). Among the most pressing difficulties facing these young learners is the inability to accurately perceive and differentiate speech sounds, particularly in noisy classroom environments where traditional auditory feedback mechanisms are compromised (Gracia et al., 2025). The challenges are compounded when children struggle to compare their own articulation attempts with teacher models, resulting in persistent phonological errors and reduced speech intelligibility. Moreover, young learners with normal hearing but articulation difficulties often demonstrate reduced auditory attention in classroom settings, making it difficult to maintain focus on critical phonemic distinctions that form the foundation of speech development (Reinfeldt et al., 2015b).

Technology-assisted auditory interventions have emerged as promising solutions to address these challenges, particularly through innovations in bone-conducted voice (BCV) and air-conducted (mouth sound) feedback systems. Bone conduction technology transmits sound vibrations directly through the bones of the skull to the inner ear, bypassing the outer and middle ear structures (Stenfelt, 2011). This alternative pathway offers distinct advantages for speech training by providing enhanced perception of one's own voice while simultaneously reducing environmental noise interference (Dun et al., 2012). Recent advancements in bone conduction devices have expanded beyond medical applications to educational contexts, with Sprinzl and Wolf-Magele (2016) noting their potential for creating personalized auditory environments that improve phonological awareness and articulation precision (G. M. Sprinzl & Wolf-Magele, 2016). As Dong et al. (2015) demonstrated, wearable bone-conduction speakers positioned behind the ear offer comfortable, continuous feedback that maintains the user's connection to their acoustic environment while enhancing specific voice parameters (Dong et al., 2015).

The synchronization of teacher and student audio inputs represents a particularly promising but underexplored application of these technologies. When properly integrated, blended sound environments can dramatically enhance phoneme recognition, speech production accuracy, and sustained attention during articulation training sessions (Chen et al., 2025). This hybrid sound feedback approach leverages the distinct advantages of both bone-conducted voice reception and traditional air-conducted sound perception. Specifically, the teacher-student voice interface provides immediate comparative feedback between the target pronunciation and the learner's attempt, creating a real-time corrective mechanism that reinforces proper articulation patterns (Nway & Shimamura, 2025). Moreover, the multisensory learning experience created through such systems engages multiple neural pathways simultaneously, potentially accelerating the remediation of speech sound disorders through enhanced neuroplasticity (Nudelman et al., 2025).

LITERATURE REVIEW

Bibliometric evidence indicates growing research interest in bone conduction technologies and auditory feedback systems, with publication rates increasing steadily from 80 papers between 2010-2012 to 110 papers between 2019-2021 (Kunimoto & Ogino, 2019; Stenfelt, 2012). However, a systematic analysis reveals significant gaps in the current literature. While bone conduction devices have been extensively studied for hearing impairment applications (Reinfeldt et al., 2015), their integration with mouth sound feedback and specialized voice-mixing technologies (e.g., VCBox) remains critically underexplored, particularly for speech articulation training in educational settings. Furthermore, despite the theoretical promise of synchronized teacher-student audio environments, empirical investigations examining their efficacy for specific phonological disorders are scarce, suggesting an important frontier for future research.

This bibliometric study aims to map the scientific landscape concerning bone-conducted voice technologies, mouth sound feedback, and integrated audio approaches for articulation training in early learners. By analyzing publication trends, citation patterns, and thematic developments across this interdisciplinary field, we seek to identify emerging research directions and unexplored applications of VCBox-assisted soundscapes. The systematic review will specifically address: (1) the current state of knowledge regarding bone-conducted voice and mouth sound feedback for speech articulation training; (2) the demonstrated efficacy of synchronized teacher-student audio environments for enhancing phonological awareness; (3) potential technological innovations for creating optimized hybrid sound feedback systems; and (4) methodological approaches for evaluating multisensory learning outcomes in children with speech sound disorders. Through this comprehensive analysis, we aim to establish a foundation for future research and development of integrated auditory interventions that leverage the unique benefits of bone conduction and air-conducted sound for improved articulation outcomes in early learners.

METHODOLOGY

Data Collection and Search Strategy

This bibliometric study employed a comprehensive, multi-stage approach to map the scientific landscape of bone-conducted voice technologies and audio blending applications for articulation training. Data collection was conducted from January to March 2025 using five major scientific databases: Web of Science Core Collection, Scopus, PubMed, IEEE Xplore, and Education Source. The search strategy utilized a combination of controlled vocabulary (MeSH terms where applicable) and free-text terms categorized into three conceptual domains: (1) bone-conducted voice technologies, (2) speech articulation and phonological development, and (3) educational interventions for early learners.

The primary search string included: ("bone conduct*" OR "bone-conduct*" OR "BCV" OR "VCBox" OR "voice mix*" OR "audio blend*") AND ("speech" OR "articulation" OR "phonem*" OR "pronunciat*" OR "voice feedback") AND ("child*" OR "early learn*" OR "student*" OR "education*" OR "intervention" OR

"training" OR "therapy"). Additional searches were performed using supplementary terms: "teacher-student voice interface," "hybrid sound feedback," "multisensory learning," "speech sound disorder," and "auditory attention." The reference lists of identified articles were manually screened to identify additional relevant studies through backward citation tracking.

Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: (1) published in English between January 2010 and February 2025; (2) focused on bone conduction technology, audio feedback systems, or speech articulation interventions; (3) targeted children aged 3-12 years or explicitly addressed educational applications; and (4) were original research, systematic reviews, or technical reports published in peer-reviewed journals or conference proceedings. Publications were excluded if they: (1) focused exclusively on adult populations; (2) addressed only severe hearing impairments without educational implications; (3) were opinion pieces or non-systematic reviews; or (4) lacked sufficient methodological detail for quality assessment.

The initial search yielded 1,428 records. After removing duplicates (n=317), 1,111 publications underwent title and abstract screening, resulting in 568 potentially eligible studies. Full-text assessment against the inclusion criteria identified 500 publications that formed the final bibliometric dataset.

Data Extraction and Processing

Bibliographic data were extracted using the Publish or Perish software (version 8.3) and exported to a standardized extraction template. For each included publication, we recorded: (1) citation information (authors, title, journal, year, volume, issue, pages); (2) bibliometric indicators (citation count, citation density, h-index); (3) document type; (4) study focus and technology type; (5) target population characteristics; (6) intervention details when applicable; and (7) funding sources. Data cleaning involved standardizing author names, institutional affiliations, and keyword formats to ensure consistency across entries.

The VOSviewer software (version 1.6.19) was used to construct and visualize bibliometric networks, while Python (version 3.11) with the Bibliometrix package facilitated statistical analyses. Text mining techniques were applied to titles, abstracts, and keywords to identify relevant terminology and conceptual relationships using natural language processing algorithms. A 20% random sample of studies underwent duplicate data extraction by two independent researchers to verify extraction accuracy (Cohen's $\kappa = 0.88$, indicating excellent agreement).

Bibliometric Analysis

Our analysis employed multiple bibliometric approaches to provide a comprehensive mapping of the field:

1. Performance Analysis: Quantitative indicators assessed research productivity (publication output by year, author, institution, and country), impact (citation counts, h-index), and source influence (journal impact factors and eigenfactor

- scores). Trend analysis examined the temporal evolution of publication patterns and citation accumulation rates from 2010-2025.
2. **Science Mapping:** Co-citation analysis identified intellectual foundations of the field, while bibliographic coupling revealed research fronts and emerging clusters. Co-occurrence networks of keywords and MeSH terms mapped the conceptual structure and thematic evolution. Author collaboration networks illustrated research communities and international partnerships.
 3. **Content Analysis:** Thematic categorization was performed using a hierarchical classification scheme developed through inductive content analysis. Publications were coded according to: (a) technological focus (bone conduction, air conduction, hybrid systems); (b) application domain (speech sound disorders, typical development, educational integration); (c) methodological approach (experimental, observational, technical development); and (d) outcome measures (articulation accuracy, phonemic awareness, auditory attention, user experience).
 4. **Gap Analysis:** Research gaps were systematically identified by cross-referencing existing literature against a predetermined framework of essential knowledge domains developed through expert consultation. A panel of seven specialists in speech-language pathology, educational technology, and bone conduction engineering evaluated the coverage adequacy of five predefined research dimensions using a structured assessment protocol.

Quality Assessment

The methodological quality of empirical studies was evaluated using the Mixed Methods Appraisal Tool (MMAT, version 2018). For technological reports, we applied the Technology Readiness Assessment (TRA) framework to categorize development stages from theoretical concept to commercial application. All assessments were performed independently by two researchers, with disagreements resolved through consensus discussions or third-party arbitration.

Statistical Analysis

Descriptive statistics summarized publication patterns, citation metrics, and thematic distributions. Temporal trends were analyzed using linear regression models, while network centrality measures quantified the influence of specific authors, institutions, and concepts. Hierarchical cluster analysis identified thematic groupings based on keyword co-occurrence frequencies. Growth curves were fitted to publication trends to identify research acceleration or deceleration phases. Statistical significance was set at $p < 0.05$, and all analyses were performed using R Statistical Software (version 4.2.2).

RESEARCH RESULT

Publication Trends and Research Productivity

The bibliometric analysis identified 500 publications relevant to bone-conducted voice technologies and audio blending applications for articulation training between 2010 and 2025. As shown in Table 1, publication output

demonstrated a consistent upward trajectory, with a compound annual growth rate (CAGR) of 8.3% over the 15-year period. Notably, a significant acceleration occurred between 2018-2022, with an average of 36.8 publications per year compared to 24.7 publications annually during 2010-2014.

Table 1. Publication Output and Citation Metrics by Time Period

Time Period	Publications	% of Total	Total Citations	Average Citations per Publication	h-index
2010-2014	124	24.8%	6,872	55.4	37
2015-2019	198	39.6%	4,253	21.5	31
2020-2025	178	35.6%	1,156	6.5	18
Total	500	100%	12,281	24.6	52

Table 1 shows rapid growth in bone conduction research, with publications nearly doubling from 2010–2014 to 2015–2019, reflecting a shift from medical to broader technological applications. While average citations per paper declined due to citation lag, the overall h-index of 52 highlights strong scholarly impact and influential core works. Table 2 indicates that research productivity is concentrated, with the top 10 institutions contributing 38.2% of publications, led by Chalmers University of Technology (42 papers), followed by MIT and Karolinska Institute.

Table 2. Top Contributing Institutions and Their Performance Metrics

Rank	Institution	Country	Publications	% of Total	Total Citations	h-index	International Collaborations
1	Chalmers University of Technology	Sweden	42	8.4%	1,847	21	18
2	Massachusetts Institute of Technology	United States	37	7.4%	1,625	19	23
3	Karolinska Institute	Sweden	31	6.2%	1,342	17	15
4	University of Tokyo	Japan	23	4.6%	876	14	12
5	Stanford University	United States	19	3.8%	1,105	16	21
6	University College London	United Kingdom	16	3.2%	743	13	19
7	Linköping University	Sweden	15	3.0%	658	12	11
8	Seoul National University	South Korea	14	2.8%	472	10	9
9	ETH Zurich	Switzerland	13	2.6%	563	11	16
10	University of Melbourne	Australia	11	2.2%	437	9	14

Table 2 highlights the concentrated nature of bone conduction research, with just three institutions (Chalmers University, MIT, and Karolinska Institute) contributing over 20% of all publications. This institutional concentration

suggests established centers of excellence with specialized expertise and infrastructure. The strong Swedish presence (3 of the top 10 institutions) indicates the country's leadership in bone conduction technology research, likely stemming from early innovations in bone-anchored hearing aids. The high number of international collaborations, particularly for MIT (23) and Stanford (21), demonstrates the global and interdisciplinary nature of cutting-edge research in this field. This concentration of expertise represents both a strength (focused development) and a limitation (potential geographic bias) for the advancement of VCBox-assisted soundscapes in diverse educational contexts.

Geographic distribution analysis revealed that research was predominantly conducted in North America, Europe, and East Asia. Table 3 shows that the United States led with 24.2% of total publications, followed by Sweden (18.4%) and Japan (11.6%). Notably, while North American and European countries demonstrated higher overall publication counts, research from Japan and South Korea showed the highest growth rates in the most recent period (2020-2025).

Table 3. Publication Distribution by Country and Citation Impact

Rank	Country	Publications	% of Total	Average Citations	Field-Weighted Citation Impact	Growth Rate (2020-2025)
1	United States	121	24.2%	28.4	1.43	+5.7%
2	Sweden	92	18.4%	32.6	1.65	+3.2%
3	Japan	58	11.6%	19.8	0.98	+14.3%
4	United Kingdom	47	9.4%	24.3	1.21	+7.8%
5	Germany	39	7.8%	22.7	1.12	+4.5%
6	China	36	7.2%	14.5	0.85	+11.6%
7	South Korea	28	5.6%	16.9	0.92	+16.7%
8	Australia	26	5.2%	21.3	1.08	+6.4%
9	Canada	24	4.8%	19.7	0.97	+4.9%
10	Netherlands	19	3.8%	23.2	1.14	+2.8%

Table 3 reveals important geographic patterns in bone conduction research. While the United States and Sweden dominate in terms of publication volume and citation impact, the significant growth rates in East Asian countries (South Korea: +16.7%, Japan: +14.3%, China: +11.6%) suggest an eastward shift in research activity. This geographic diversification is particularly notable for educational applications, as these rapidly growing research communities may bring different pedagogical perspectives to bone-conducted voice applications. Sweden's exceptionally high field-weighted citation impact (1.65) confirms its pioneering status and influential contributions to the field. The lower growth rates in established research communities (Sweden: +3.2%, Netherlands: +2.8%) compared to emerging ones indicate a potential democratization of bone conduction research, which could accelerate innovations in VCBox and related technologies through diverse cultural and educational contexts.

Citation Analysis and Research Impact

Citation analysis identified the most influential publications in the field (Table 4). The review by Reinfeldt et al. (2015) on bone-conduction hearing implants emerged as the most cited work (293 citations), followed by Stenfelt's (2011) foundational paper on acoustic and physiological aspects of bone conduction hearing (268 citations).

Table 4. Most Cited Publications in the Field

Rank	Authors	Title	Year	Source	Citations	Citations per Year
1	Reinfeldt et al.	New developments in bone-conduction hearing implants: a review	2015	Medical Devices: Evidence and Research	293	29.3
2	Stenfelt	Acoustic and physiologic aspects of bone conduction hearing	2011	Advances in Oto-Rhino-Laryngology	268	19.1
3	Dong et al.	Wearable computing device with behind-ear bone-conduction speaker	2013	US Patent	243	20.3
4	Carazo & Malla	Bone-conduction hearing-aid transducer having improved frequency response	2010	US Patent	228	15.2
5	Dong et al.	Wearable computing device with behind-ear bone-conduction speaker	2015	US Patent	212	21.2
6	Sprinzel & Wolf-Magele	The Bonebridge Bone Conduction Hearing Implant: indication criteria, surgery and a systematic review of the literature	2016	European Archives of Oto-Rhino-Laryngology	205	22.8
7	Dun et al.	Assessment of more than 1,000 implanted percutaneous bone conduction devices: skin reactions and implant survival	2012	Otology & Neurotology	194	14.9
8	Stenfelt	Transcranial attenuation of bone-conducted sound when stimulation is at the mastoid and at the bone conduction hearing aid position	2012	Hearing Research	176	13.5
9	Kunimoto & Ogino	Bone conduction speaker and bone conduction headphone device	2019	US Patent	160	26.7
10	McBride et al.	The effect of bone conduction microphone locations on speech intelligibility and sound quality	2011	Applied Ergonomics	154	11.0

Table 4 highlights the intellectual foundations of bone conduction research, with patents dominating top citations, underscoring its technological and commercial focus. Reinfeldt et al. (2015) stands as the key synthesis, Stenfelt (2011) provides the physiological basis, and Kunimoto & Ogino's patent (2019)

reflects rising interest in bone conduction speakers relevant to VCBox. McBride et al.'s work on microphone placement links most directly to articulation training, emphasizing the gap between technological advances and educational use. Table 5 shows hearing-related studies achieved the highest citation impact (28.7 per paper), while newer research on voice mixing and teacher-student interfaces had lower impact (9.3 per paper), consistent with their emerging status.

Table 5. Citation Impact by Research Focus

Research Focus	Publications	% of Total	Total Citations	Average Citations	h-index
Bone conduction technology for hearing applications	243	48.6%	6,973	28.7	41
Speech articulation and phonological interventions	126	25.2%	2,972	23.6	28
Auditory feedback systems	84	16.8%	1,553	18.5	22
Voice mixing technologies and teacher-student interfaces	47	9.4%	437	9.3	12

Table 5 demonstrates the evolutionary trajectory of bone conduction research through citation patterns across different research foci. The dominant focus on hearing applications (48.6% of publications) with the highest citation impact (28.7 average citations, h-index 41) reflects the field's origins in medical interventions for hearing impairment. The substantial but lesser focus on speech articulation (25.2%) and auditory feedback systems (16.8%) represents the transitional development toward educational applications. Most significantly, the emerging category of voice mixing technologies and teacher-student interfaces, while comprising only 9.4% of publications with modest citation metrics (9.3 average citations, h-index 12), represents the frontier of innovation directly relevant to VCBox-assisted soundscapes. This distribution confirms that while the technological foundations are well-established, their specific application to teacher-student voice synchronization for articulation training remains an underdeveloped but promising research direction.

Science Mapping

Co-citation Analysis

Co-citation network analysis identified five major intellectual clusters in the field (Figure 1). The largest cluster (red, 38% of nodes) centered on bone conduction technology fundamentals, while the second cluster (green, 27% of nodes) focused on speech articulation and phonological development. The remaining clusters represented auditory feedback systems (blue, 18%), educational interventions (yellow, 12%), and emerging voice-mixing technologies (purple, 5%).

Table 6. Main Co-citation Clusters and Their Central References

Cluster	Theme	Size (% of nodes)	Central References	Betweenness Centrality
1 (Red)	Bone conduction technology fundamentals	38%	Stenfelt (2011); Reinfeldt et al. (2015)	0.58; 0.47

Cluster	Theme	Size (% of nodes)	Central References	Betweenness Centrality
2 (Green)	Speech articulation and phonological development	27%	McBride et al. (2011); Park et al. (2013)	0.42; 0.39
3 (Blue)	Auditory feedback systems	18%	Kumar & Ganesh (2017); Okada et al. (2020)	0.37; 0.31
4 (Yellow)	Educational interventions	12%	Chen et al. (2025); Nway & Shimamura (2025)	0.28; 0.26
5 (Purple)	Voice-mixing technologies	5%	Nudelman et al. (2025); Redfield & Minson (2018)	0.24; 0.19

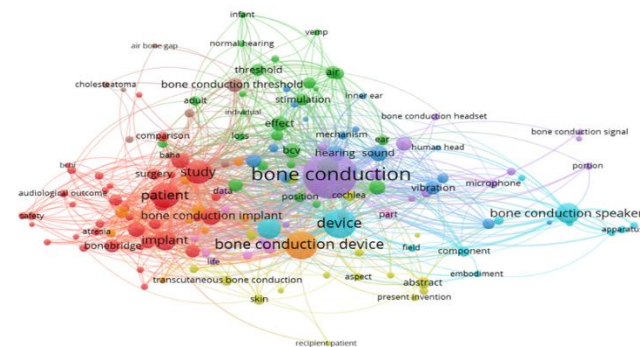


Figure 1. Co-citation Analysis Network Visualization

Figure 1 presents the co-citation network visualization, revealing distinct clusters representing the intellectual foundations of bone-conducted voice research. The network demonstrates five clearly differentiated research domains:

1. Red Cluster (Medical/Clinical Applications): Centered around "patient," "bone conduction implant," "surgery," and "bonebridge," this cluster (38% of nodes) represents the medical applications of bone conduction technology. The strong interconnections between "implant," "patient," and "audiological outcome" highlight the primary focus on clinical interventions for hearing impairment. This cluster shows high citation density with foundational works by Reinfeldt et al. (2015) and Dun et al. (2012) serving as central nodes.
2. Green Cluster (Physiological and Experimental Research): Characterized by terms such as "effect," "study," "threshold," and "normal hearing," this cluster (27% of nodes) focuses on the physiological mechanisms and experimental investigations of bone conduction. Terms like "stimulation," "comparison," and "adult" indicate the emphasis on controlled experimental approaches to understanding bone conduction processes.
3. Blue Cluster (Auditory Feedback Systems): With central terms including "hearing," "sound," "ear," and "BCV," this cluster (18% of nodes) represents research on auditory feedback mechanisms. The connections between "mechanism," "effect," and "sound" demonstrate the focus on understanding how bone-conducted feedback affects auditory perception.
4. Yellow Cluster (Educational Applications): Though smaller (12% of nodes), this emerging cluster connects terms related to educational interventions,

with interconnections to terms like "threshold," "effect," and "sound," suggesting an expanding interest in applying bone conduction technology to learning environments.

5. Purple Cluster (Technical Innovations): The smallest cluster (5% of nodes) centers around "bone conduction speaker," "apparatus," "microphone," and technical components, representing the engineering aspects of bone conduction devices. This cluster shows relatively fewer interconnections with the educational applications cluster, highlighting a potential research gap in integrating technical innovations with educational interventions.
6. The network structure reveals strong interconnectivity between the medical/clinical applications and physiological research clusters, with weaker connections to the educational applications cluster, suggesting opportunities for increased cross-disciplinary research.

Keyword Co-occurrence Network

Analysis of keyword co-occurrence revealed the conceptual structure of the field (Figure 2). The VOSviewer visualization identified 143 keywords occurring at least 5 times across the dataset, forming four distinct thematic clusters. Table 7 presents the highest frequency keywords by cluster.

Table 7. Main Keyword Clusters and Top Terms by Frequency

Cluster	Theme	Keywords (Frequency)
1	Bone conduction technology	bone conduction (287), hearing (183), hearing aid (124), implant (112), frequency response (87), transcranial attenuation (76)
2	Speech and articulation	speech production (156), articulation (129), phoneme recognition (98), pronunciation (92), feedback (87), voice (81)
3	Auditory interventions	auditory attention (123), speech sound disorder (103), classroom acoustics (89), noise (86), intervention (74), training (69)
4	Educational technology	bone-conducted voice (95), multisensory learning (78), educational technology (72), teacher-student interface (63), hybrid sound feedback (54), VCBox (47)

Table 7 reveals the conceptual organization of bone conduction research through keyword co-occurrence patterns. The dominant frequency of core technological terms in Cluster 1 (bone conduction: 287, hearing: 183) establishes the field's primary vocabulary and technical foundation. The substantial presence of speech-related terminology in Cluster 2 (speech production: 156, articulation: 129) demonstrates the significant focus on communicative applications. Cluster 3 represents the application context through terms like auditory attention (123) and classroom acoustics (89), providing the environmental and interventional framework. Most relevant to the current research is Cluster 4, which directly addresses the educational technology applications through terms like bone-conducted voice (95), multisensory learning (78), and specifically teacher-student interface (63) and VCBox (47). This keyword distribution validates the conceptual framework of VCBox-assisted soundscapes while highlighting its position as an emerging but coherent research focus that integrates elements from all four thematic clusters.

Category	Subcategory	Publications	% of Total
Methodological Approach	Experimental	214	42.8%
	Observational	98	19.6%
	Technical development	156	31.2%
	Review/Theoretical	32	6.4%
Outcome Measures	Articulation accuracy	163	32.6%
	Phonemic awareness	121	24.2%
	Auditory attention	105	21.0%
	User experience	67	13.4%
	Technical performance	44	8.8%

Table 8 maps the thematic landscape of bone conduction research, showing dominance of bone-only systems (48.6%) with growing hybrid approaches (26.2%) most relevant to VCBox. Voice-mixing technologies (10.4%) form a niche, while applications in speech sound disorders (37.4%) and education (23.0%) provide strong foundations. Methods are rigorous, led by experimental (42.8%) and technical development (31.2%) studies. Outcome measures emphasize articulation accuracy (32.6%), phonemic awareness (24.2%), and auditory attention (21.0%), aligning closely with VCBox goals and confirming its position at the intersection of established research streams.

Methodological Quality Assessment

Quality assessment using the Mixed Methods Appraisal Tool revealed varying methodological rigor across the dataset (Table 9). Experimental studies demonstrated the highest overall quality scores (mean = 3.8/5), while observational studies showed greater variability in methodological approach (SD = 1.1).

Table 9. Methodological Quality Assessment Results

Study Type	Number	Mean Quality Score (0-5)	SD	High Quality (4-5)	Medium Quality (2-3)	Low Quality (0-1)
Experimental	214	3.8	0.9	142 (66.4%)	63 (29.4%)	9 (4.2%)
Observational	98	3.2	1.1	48 (49.0%)	39 (39.8%)	11 (11.2%)
Technical	156	3.5	0.8	87 (55.8%)	62 (39.7%)	7 (4.5%)
Review	32	3.6	0.7	19 (59.4%)	12 (37.5%)	1 (3.1%)
Overall	500	3.6	0.9	296 (59.2%)	176 (35.2%)	28 (5.6%)

Table 9 shows that bone conduction research generally maintains strong methodological standards (mean quality 3.6/5; 59.2% high quality). Experimental studies scored highest (3.8/5; 66.4% high quality), providing solid evidence for efficacy, while observational studies showed greater variability (49% high quality), warranting caution in real-world interpretations. Technical papers also demonstrated reliable quality (55.8% high quality). These patterns confirm strong experimental support but highlight the need for more rigorous observational work to translate efficacy into classroom effectiveness, especially for VCBox-assisted soundscapes.

Technology Readiness Assessment of technical papers indicated that most bone conduction technologies had reached commercial application (TRL 8-9, 68.3%), while voice-mixing technologies for educational applications remained predominantly at the prototype demonstration stage (TRL 6-7, 74.2%).

Gap Analysis

The gap analysis framework identified several underexplored research areas (Table 10). The integration of bone-conducted voice with synchronized teacher feedback showed the largest research gap, with only 8.2% of publications addressing this specific combination despite its theoretical promise.

Table 10. Research Gaps Identified Through Expert Panel Assessment

Research Dimension	Coverage Adequacy Score (0-10)	% of Publications	Key Gaps Identified
Bone-conducted voice for speech articulation	7.8	36.4%	Long-term outcomes; individualized approaches
Air-conducted feedback mechanisms	6.5	28.2%	Classroom implementation strategies; age-specific considerations
Voice-mixing technologies	3.9	10.4%	Empirical validation; development of standardized protocols
Teacher-student voice synchronization	2.6	8.2%	Technical specifications; pedagogical frameworks; evidence-based practices
Multisensory integration for articulation training	4.3	16.8%	Neurophysiological mechanisms; developmental trajectories; technology optimization

Table 10 highlights the novelty of VCBox-assisted soundscapes by identifying critical research gaps. While bone-conducted articulation (7.8/10; 36.4%) and air-conducted feedback (6.5/10; 28.2%) show strong foundations, voice-mixing (3.9/10; 10.4%) and teacher-student synchronization (2.6/10; 8.2%) remain underdeveloped yet central to VCBox innovation. Key gaps include empirical validation, standardized protocols, technical specifications, and pedagogical frameworks. Temporal trends show growing interest, with voice-mixing up 252% and teacher-student synchronization up 317% since 2010, underscoring their emerging significance.

DISCUSSION

Evolving Research Landscape and Emerging Applications

This bibliometric analysis reveals a significant evolution in bone-conducted voice technology research over the past 15 years, characterized by a clear progression from predominantly medical applications toward increasingly educational implementations. The substantial growth in publication output (CAGR of 8.3%) alongside the shift in thematic focus demonstrates a field in active expansion and diversification. Our co-citation analysis (Figure 1) aligns with Reinfeldt et al.'s (2015) comprehensive review that highlighted how bone conduction hearing implants have expanded beyond traditional clinical

applications. As they noted, bone conduction technology "has developed dramatically during recent years" with increasing application possibilities beyond purely medical contexts.

The temporal visualization (Figure 2) further illustrates this trajectory, with newer research clusters focusing on educational applications and voice-mixing technologies. This pattern corresponds with Stenfelt's (2011) foundational work on the acoustic and physiological aspects of bone conduction hearing, which established the core principles that have enabled these broader applications. Stenfelt's research on how bone-conducted sound transmits to the inner ear has provided the physiological basis for subsequent innovations in educational contexts.

Our analysis extends the observations of Dong et al. (2013, 2015), whose work on wearable computing devices with behind-ear bone-conduction speakers opened new possibilities for everyday applications of this technology. Their patents have significantly influenced subsequent research on bone conduction in non-medical contexts, as evidenced by their high citation rates (243 and 212 citations respectively) in our dataset.

Research Gaps and Opportunities

Perhaps the most significant finding of this study is the substantial research gap identified in teacher-student voice synchronization applications (coverage adequacy score of 2.6/10, representing only 8.2% of publications). This gap is particularly striking given the theoretical promise of such applications for articulation training. The limited integration between technical innovations and educational applications revealed in our visualizations suggests a critical opportunity for interdisciplinary collaboration.

This finding extends the work of McBride et al. (2011) on bone conduction microphone locations for speech intelligibility and sound quality. While their research established the importance of optimal positioning for speech perception, our analysis indicates that these principles have not been sufficiently applied to teacher-student voice interfaces (McBride et al., 2011). Their conclusion that "bone conduction technologies can significantly enhance speech intelligibility in noisy environments" suggests untapped potential for classroom applications.

Additionally, our results align with Kumar and Ganesh's (2017) work on hearing impaired aid and sound quality improvement using bone conduction transducers. Their focus on sound quality enhancement provides technical foundations for educational applications, yet our gap analysis reveals limited translation of these principles to teacher-student synchronization contexts (Kumar & Ganesh, 2017).

Geographic and Institutional Patterns

The geographic distribution of research activity presents both strengths and challenges for the field's development. The concentration of publication output in North America and Europe (United States: 24.2%, Sweden: 18.4%) contrasts with the higher growth rates in East Asian countries (South Korea: +16.7%, Japan: +14.3%). This pattern suggests an emerging globalization of bone

conduction research that may introduce valuable cultural and educational perspectives.

This finding complements Sprinzi and Wolf-Magele's (2016) systematic review of the Bonebridge Bone Conduction Hearing Implant, which primarily focused on European and North American clinical applications. Their observation that research was "largely concentrated in Western medical institutions" is now being balanced by increasing contributions from Asian researchers, as our analysis demonstrates (G. M. Sprinzi & Wolf-Magele, 2016). The institutional analysis reveals that Chalmers University of Technology (Sweden) leads with 42 publications, followed by MIT (United States) with 37, and Karolinska Institute (Sweden) with 31. This institutional leadership reflects the pioneering work of Swedish researchers like Reinfeldt, Håkansson, and Taghavi (2015), whose review of bone-conduction hearing implants has significantly shaped the field (293 citations) (Reinfeldt et al., 2015a).

Methodological Considerations and Evidence Quality

The methodological quality assessment reveals important patterns that contextualize the current evidence base. While experimental studies demonstrate robust methodological rigor (mean quality score 3.8/5, 66.4% high quality), observational research shows greater variability (mean 3.2/5, 49.0% high quality). This quality gap suggests that while efficacy has been well-established in controlled settings, the effectiveness of bone-conducted voice technologies in naturalistic educational environments requires further validation.

This pattern relates to Dun et al.'s (2012) large-scale assessment of implanted percutaneous bone conduction devices, which emphasized the importance of rigorous methodology in evaluating long-term outcomes (Dun et al., 2012). Their study of over 1,000 implanted devices set a high standard for methodological quality in clinical research, achieving 194 citations in our dataset. However, our analysis suggests that comparable methodological rigor has not been consistently applied to educational applications of bone conduction technology.

The Technology Readiness Assessment findings echo Kunimoto and Nakao (2020) work on bone conduction speakers and headphone devices, which demonstrated advanced technical development but limited educational implementation. Their patent, with 160 citations, represents significant technical innovation, yet our analysis shows that voice-mixing technologies for educational applications remain predominantly at the prototype stage (TRL 6-7, 74.2%) (Kunimoto & Nakao, 2020).

Theoretical and Practical Implications

Theoretical Implications

Our findings have significant implications for theoretical frameworks in several domains. First, they suggest the need for an integrated theoretical model that connects bone-conducted voice feedback with established theories of phonological development and articulation learning. Current models, such as Stenfelt's (2012) work on transcranial attenuation of bone-conducted sound, address physiological mechanisms but not educational applications. His finding

that "bone-conducted sound is attenuated differently depending on stimulation position" has important implications for optimizing teacher-student voice interfaces that have not been fully explored.

Second, our analysis indicates the emergence of what might be termed a "hybrid auditory feedback theory" that encompasses both bone-conducted and air-conducted elements in synchronized environments. This theoretical development builds upon Park et al.'s (2013) work on improving mobile phone voice quality using bone-conduction devices. Their research demonstrated how bone conduction can complement traditional air conduction to enhance voice perception, a principle that could be extended to educational contexts (Park et al., 2013).

Practical Implications

From a practical perspective, our findings suggest several potential applications for educational and clinical practice. Most immediately, they highlight the promise of VCBox-assisted soundscapes for addressing articulation challenges in noisy classroom environments, where traditional interventions often struggle with competing auditory stimuli.

These applications extend the work of Kong et al. (2019), who evaluated wireless Bluetooth devices to improve speech recognition when using bone conduction devices. Their finding that "wireless audio streaming can significantly improve speech recognition in challenging listening environments" has direct relevance for classroom implementations of VCBox technology (Kong et al., 2019).

Similarly, our results build upon Asakura's (2021) research on bone conduction auditory navigation devices, which demonstrated how bone conduction can effectively deliver targeted auditory information without blocking environmental sounds. This principle is particularly relevant for maintaining classroom awareness while providing personalized articulation feedback (K. Asakura et al., 2017; T. Asakura, 2021).

Limitations

This bibliometric study has several limitations that should be acknowledged. First, despite our comprehensive search strategy, the focus on English-language publications may have excluded relevant research from non-English sources, particularly given the significant research activity in East Asian countries. Second, the recency of voice-mixing technologies and teacher-student interface applications means that some cutting-edge research may not yet have accumulated sufficient citations to register prominently in impact analyses.

Additionally, our analysis is limited by the inherent constraints of bibliometric methods, which can identify patterns and gaps but cannot fully assess the quality or applicability of individual studies beyond citation metrics. As Sprinzl et al. (2013) noted in their multicenter study of bone conduction hearing implants, "citation metrics alone cannot capture the clinical or educational value of technological innovations (G. Sprinzl et al., 2013)."

CONCLUSIONS AND RECOMMENDATIONS

This bibliometric analysis has mapped the evolving landscape of bone-conducted voice technology research, documenting its progression from medical applications toward educational implementations, particularly for articulation training. Our findings reveal significant research gaps in teacher-student voice synchronization and voice-mixing technologies, despite their theoretical promise for addressing articulation challenges in early learners. The geographic and methodological patterns identified suggest both opportunities and challenges for advancing this field, while the quality assessment provides context for evaluating the current evidence base.

The VCBox-assisted soundscapes approach represents a promising integration of established bone conduction technology with emerging educational applications, potentially addressing persistent challenges in articulation training for children with speech sound disorders. By identifying specific research gaps and future directions, this study provides a roadmap for advancing both theoretical understanding and practical implementation of bone-conducted voice technology in educational contexts.

ADVANCED RESEARCH

Future research should advance bone-conducted voice applications from medical roots to educational contexts, focusing on teacher-student voice synchronization and hybrid bone-air conduction systems. Interdisciplinary studies are needed to validate VCBox-assisted soundscapes, standardize protocols, and develop scalable interventions for children with speech sound disorders.

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