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Definition and performance of acoustic personalised environmental control systems (acoustic PECS): A systematic review

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A R T I C L E I N F O

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A B S T R A C T

Personalised Environmental Control Systems (PECS) enable occupants to locally adjust environmental parameters without affecting others. Rooted in the fields of thermal and air quality management, this approach is key for enhancing satisfaction and well-being in the built environment by empowering occupants to control their immediate surroundings. Moreover, it offers energy-saving potential by optimizing conditions in targeted areas rather than across the entire environment. Within the framework of the IEA EBC Annex 87, the concept was explored for the first time in the acoustic domain. After defining Acoustic PECS, a systematic review according to PRISMA guidelines was conducted to unpack (1) technologies in the literature aligning with this concept; (2) their impact on occupants; and (3) current limitations. The literature search, conducted on Scopus, Web of Science, APA, and PubMed, included field or laboratory studies assessing systems enabling local acoustic control in settings that are relevant for office environments. Review papers, medical device studies, and reports without insights on occupant impact were excluded. Thirty-eight studies were selected, covering active and passive systems, building-attached, furniture-integrated, and wearable devices. The qualitative analysis highlighted potential positive effects in challenging acoustic environments, including reduced annoyance, improved work performance, masking or cancellation of intrusive noises, and enhancements in short-term memory, among other benefits, despite existing technological and methodological limitations. The evidence collected is constrained by the limited number of identified studies and methodological gaps stemming from the relatively wide focus of the studies where such devices were investigated. The definition of Acoustic PECS provides a foundation for future research, guiding the development of these systems and fostering high-quality and consistent evidence of their impacts.

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1. Introduction

1.1. Personal environmental control systems

The growing need to reduce building energy consumption while enhancing occupant comfort and well-being has led to increased interest in Personalised Environmental Control Systems (PECS). These systems are devices designed to operate with limited power to adjust specific environmental parameters over a small targeted peripersonal area. PECS aim to optimize individual environmental satisfaction by targeting personal surroundings with minimal energy consumption, without affecting other occupants in the space. This approach helps to limit interpersonal conflicts and reduce energy waste. This concept was initially introduced in the context of HVAC energy savings, focusing on thermal conditions and indoor air quality [1]. Indeed, HVAC systems account for a significant portion of global energy demand, primarily used to maintain narrow temperature ranges that are assumed to be comfortable for the majority of occupants. The introduction of Personalised Ventilation (PV) or Personal Control Systems (PCS), particularly in spaces with shared occupancy and large volumes, allows for a relaxation of the background temperature range, reducing overall HVAC energy consumption, minimizing waste, and improving individual comfort [2]. Moreover, recent research emphasizes the importance of a human-centric approach to occupant well-being, recognizing that individual responses to the same environmental conditions can vary due to personal, physiological, and cultural factors [3]. Rather than relying on HVAC systems with fixed temperatures and schedules, PECS focus on meeting individuals' needs, a trend reflected in the growing interest in personalised comfort modelling, particularly advanced in the thermal domain [4]. It became clear that this concept could also be applied effectively to other domains of indoor environmental quality, such as acoustics, as the benefits of having control over one's environment on occupant satisfaction appear to be broadly applicable. The extension of this concept to the acoustic domain was first explored as part of the International Energy Agency's Energy in Buildings and Communities (IEA-EBC) Programme Annex 87, as detailed below.

1.2. The mission of IEA EBC annex 87

Annex 87, titled "Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (PECS)", is a collaborative initiative under the IEA-EBC Programme. This Annex aims to provide comprehensive guidelines and specifications for the design, operation, optimization, and control of PECS, promoting their widespread adoption and integration, with a focus on office buildings.

In addition to quantifying the benefits of PECS in terms of health, comfort, and energy performance, Annex 87 uniquely addresses all indoor environmental quality (IEQ) domains under the PECS concept. While most existing research on PECS has focused primarily on their impact on thermal comfort and indoor air quality, this Annex expands the scope to include the individual control of acoustic and luminous environments in an occupant's immediate surroundings, highlighting their potential benefits. The present study forms part of a series of reviews dedicated to exploring PECS within the various IEQ domains, advancing a holistic understanding of their applications and advantages.

1.3. Acoustic PECS

In the context of the Annex 87, the general definition of PECS can be expanded to include the personalised and local control of the acoustic environment in buildings [5]. In this sense, Acoustic PECS can be defined as any system that can both provide: (i) a personalised control of the acoustic environment to meet occupant requirements (hereafter also referred to as "individually controlled" acoustic environment), and (ii) a localised control, thereby not affecting the surrounding space or adjacent occupants. Therefore, the following definition can be considered for Acoustic PECS:

> "a system that can provide individually controlled acoustic environments in the immediate surroundings of an occupant, without affecting directly the entire space and other occupants' environment" [6].

While the definition of Acoustic PECS is novel, since traditionally the field of PECS has primary focused on the thermal and indoor air quality, the use of systems or devices by occupants to control and tailor the acoustic environment in the built environment is not new, since several systems are used in everyday life to manage and personalize acoustic environments. An exemplary case is the use of noise-cancelling headphones to mitigate unwanted noise, especially in multi-user working environments. These systems, while not traditionally categorized under PECS, effectively demonstrate the principles of individual acoustic control by allowing users to adjust their acoustic environment to meet personal preferences or needs. However, a clear understanding of what systems can be adopted to devise Acoustic PECS, what the control target is (e.g., sound pressure levels, frequency content, informational content, etc.), to what extent these systems are effective in providing such local and personal control, and their impact on individuals is still missing. In particular, the deliberate provision of Acoustic PECS by building scientist and practitioners during the design or operation of buildings to enable occupants to personalise their acoustic experience represents a novel approach, which would benefit from a clear understanding of current research advances in technologies that can be linked to the concept of Acoustic PECS.

1.4. Objectives and research questions

The primary objective of the present study is to initiate a discussion on the application of the concept of PECS to the acoustic domain, with the aim of fostering a new conceptual development within the PECS field of research. This is achieved through a systematic literature review that seeks to address the following research questions:

(1) What technologies described in literature align with the concept of Acoustic PECS and how can they be categorised?
(2) What is the impact of Acoustic PECS on building occupants psychological, cognitive and physiological state?
(3) What are current technological limitations in Acoustic PECS?

The knowledge derived will help frame the existing literature under the new concept of Acoustic PECS, highlight methodological gaps and technological limitations, and guide future advancements on the topic.

2. Methods

The PRISMA guidelines [7,8] (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) served as a reference framework for conducting the systematic literature review and for data reporting, aimed at enabling authors to clearly convey the rationale behind their review, the methods employed, and the findings obtained. The review was not registered, and no protocol was prepared. Specifically, the reporting of findings is directed by the PRISMA checklist and flow diagram, which were used to structure the content of this manuscript.

2.1. Eligibility criteria

A literature search was conducted to identify studies involving systems that could fall under the definition of Acoustic PECS, as outlined in Section 1.3. The inclusion criteria were defined as follows: (i) field or laboratory studies investigating the impact of systems that enable local control of acoustic conditions by building occupants; (ii) studies with settings, systems, or outcomes applicable to the use of these systems in office environments, which are the target context for Annex 87 activities. The following were excluded: (1) studies focused primarily on the technical details and optimization of systems, rather than their effect on end users; (2) studies related to medical devices for hearing-impaired users, as these fall outside the scope of this review; (3) review papers.

Only English-language studies were considered, including both peer-reviewed journal articles and conference proceedings.

2.2. Information sources

Extensive literature research was conducted using Scopus (1948–2023), Web of Science (WoS) (1991–2023), American Psychological Association (APA) (1917–2023) and PubMed (1966–2023). The search was last updated on July 11, 2023.

2.3. Search strategy and selection process

The search focused on terms related to personal control and customization (e.g., "self* adjust*" OR "individual* control*" OR "personal* control*"), devices that inherently involve control and may therefore not explicitly mention this aspect in the manuscript (e.g., "headphone*"), or systems which had been pre-identified by the authors as Acoustic PECS (e.g., "earphone*", "headset*", "earmuff*"). These terms were combined with keywords identifying the acoustic domain (e.g., "acoustic*", "sound*", "noise"), particularly within the built environment (e.g., "build*", "built environment"), including possible relevant building use cases (e.g., "home*", "school*", "office*"). Studies focused on hearing aids were excluded, as this study centres on non-medical devices. The final search string was:

(TITLE-ABS-KEY ("self* adjust*" OR "individual* control*" OR "personal* control*" OR "personal* audio" OR "sound mask*" OR "noise mask*" OR "personal* sound" OR "headphone*" OR "earphone*" OR "headset*" OR "earmuff*" OR "earplug*" OR "phone booth*" OR "sound zon*") AND TITLE-ABS-KEY ("acoustic*" OR "sound*" OR "noise" OR "audio") AND TITLE-ABS-KEY ("build*" OR "built environment" OR "home*" OR "school*" OR "office*" OR "workplace*" OR "workspace*" OR "hospital") AND NOT TITLE-ABS-KEY ("hearing loss" OR "hearing impair*")) AND (LIMIT-TO (LANGUAGE, "English"))

The articles retrieved from various databases were initially consolidated into a single dataset, with duplicates removed. The items were then assigned to different authors, who independently performed a title and abstract screening according to the eligibility criteria outlined in Section 2.1. Items flagged as uncertain were retained for further consideration in the next step. A more thorough content-based screening followed, involving the creation of a review table with data extracted on key outcomes of interest, as detailed in the next section. Each study was reviewed by two independent reviewers, and additional exclusions were made at this stage, either due to a deeper understanding of the study or if it was identified as already represented in another publication (such as a conference proceeding subsequently expanded in a journal article).

2.4. Data collection process and data items

The data collected from the studies included publication details such as title, authors, journal title, year of publication, DOI, type of scientific output (journal article or conference proceeding), and keywords. Additionally, general information about each study was recorded, covering the experimental design type, categorized into lab studies, field studies with surveys, field studies involving environmental monitoring and surveys, studies focused solely on environmental data collection, simulation-based studies, online surveys, and workshops. Data was also gathered on the study location and the building type under investigation, if specified (e.g., office, residential, industrial, healthcare, school, transportation, unspecified, or other).

Details about the investigated device were also recorded, such as the type of acoustic PECS (e.g., noise-cancelling headphones, with details on the different categories provided later), technical characteristics (material, size, weight, cost), and a description of operation modes (e.g., type and number of modes, open or closed, on or off, etc.). Given that the goal was to investigate the benefits derived from using PECS compared to no device, data were collected on **baseline conditions** (without PECS), **during device operation**, and on the **background environment during PECS usage** (see Fig. 1). This approach aimed to derive insights into the impact of PECS on users by comparing people's response during device use to baseline conditions, within the boundaries of background conditions, in alignment with the rationale followed by other working groups of Annex 87 for literature reviews on thermal, indoor air quality, and visual PECS.

In studies involving participant tests, information was gathered on the total number of participants, male and female participants, ethnicity, age range and mean, noise sensitivity, and other additional aspects. The collected methodological details included the exposure duration of each listening session (min), total duration (min), factor control in factorial design studies, whether participants had control over the PECS during the study (yes/no), and the domains addressed in the study (acoustic, thermal, visual, indoor air quality).

Baseline (no-PECS) conditions were characterized by air changes per hour (m^3/h), air temperature ($^{\circ}C$), relative humidity (%), CO_2 levels (ppm), type of ambient signal, sound pressure level (dB), spectral features, Speech Transmission Index (STI), reverberation time (s), other acoustic parameters, light level (lux), and additional factors. **Operational parameters for the device** included the type of signal generated, sound pressure level (dB), spectral features of generated signals, Speech Transmission Index (STI), equivalent sound absorption area (m^2), and sound insulation or active noise reduction (dB). **Environmental conditions during PECS use** were also documented (e.g., type of signal, sound pressure level, spectral features, Speech Transmission Index, reverberation time, and other parameters).

In simulation-based studies, information gathered covered the type of simulation model used (statistical, wave-based, FEM, ray tracing), acoustic modelling software, computational cost (in hours), generation of acoustic maps, especially at a micro-level near occupants (yes/no), parameters calculated in simulations with PECS, reference standards (ISO, DIN, BS, etc.), validation status (yes/no), use of measurement data as simulation inputs, and accuracy (percentage in relation to a reference). The review table, along with the options for populating its cells, is included as supplementary material.

2.5. Synthesis methods

Upon reviewing the collected papers, significant gaps were identified in the initial data collection framework. Large sections of this framework remained unaddressed due to the absence of relevant information in the literature. Consequently, the review table was simplified to reflect the available data and specific study objectives, while other aspects will be further analysed in future detailed studies.

The performance of the PECS was assessed by qualitative comparison of participants' responses (in studies with human subjects) or sound field during PECS use or implementation against a baseline condition. The baseline condition varied by study: in some, it was defined as a quiet environment without additional sounds (labelled "quiet" in Figs. 1 and 2), while in others, it included contextual sounds (labelled "reference" in Figs. 1 and 2). Specifically, study [9] defines the "quiet" condition as having a background noise level of 25 dBA, while [10] of 35 dBA. Other studies do not provide specific details, therefore this condition is generically identified as a quiet background condition where no specific sounds are present. For "reference" conditions, background noise typically included speech or office sounds, with levels generally ranging from 30 to 60 dBA. Notable exceptions are [11], which tested background noise at 70 and 80 dBA, and [12], which describes noise levels above 60 dBA.

Ideally, the baseline condition would capture participants' responses or the sound field in the absence of PECS, as conceptualized in Fig. 1.

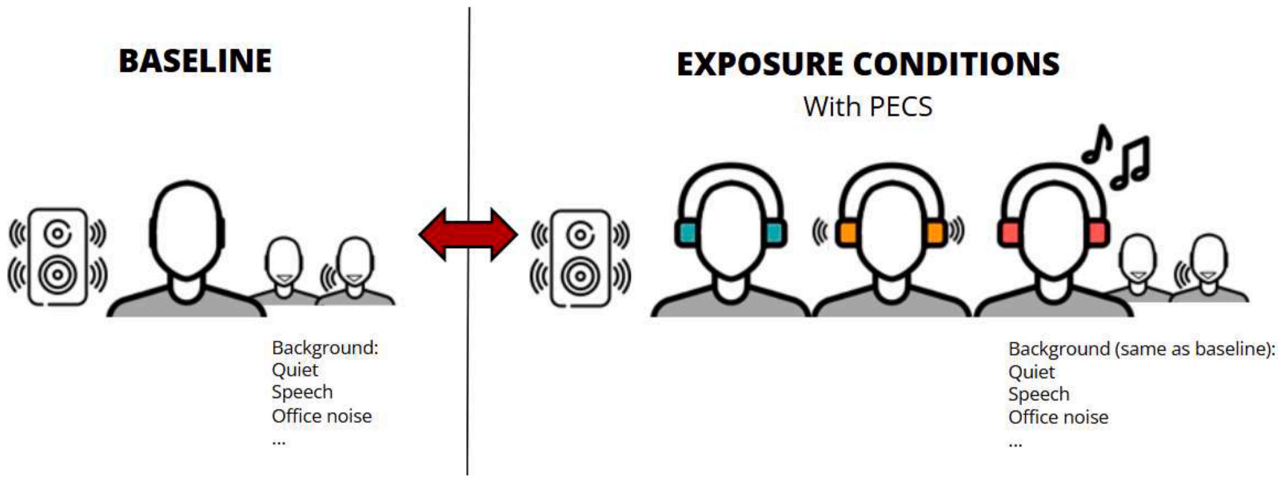

Fig. 1. – Baseline and exposure conditions: ideal scenario in studies investigating acoustic PECS. In the image, headphones are used as an example.

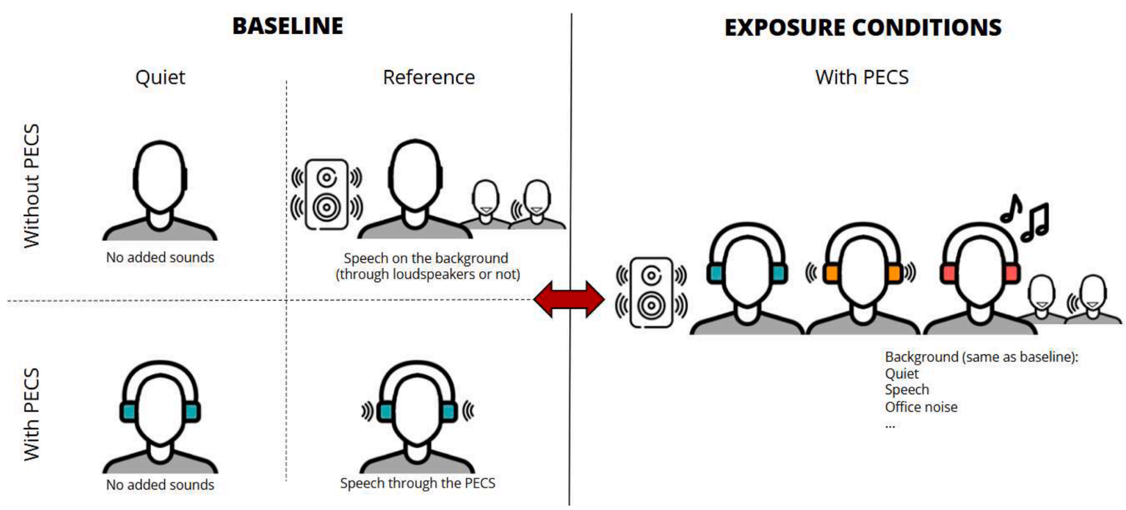

Fig. 2. – Differences in baseline conditions (quiet and reference, with and without PECS) from the retrieved studies.

However, given the diverse objectives of the selected studies compared to this review, in some cases, the identified baseline also involved PECS use. In these cases, the analysis focused on the benefits of PECS under varying conditions (e.g., with or without masking sound, with or without active noise cancelling). Specifically, in cases where the study involved different sound conditions and the use of PECS in all instances, the most disadvantageous condition (e.g., the most detrimental masking noise) was chosen as the reference. Evaluations were conducted separately under quiet and reference conditions, depending on the presence or absence of PECS in the baseline conditions.

In order to compare participants' response or sound fields with PECS with respect to baseline conditions, qualitative graphs were created to show whether PECS use had a positive, negative, or neutral effect across various outcomes identified in the reviewed papers, as detailed below. Specifically, an improvement in a given aspect (e.g., affective response) was recorded if a positive effect was observed in at least one test condition. If all test conditions were found to be detrimental compared to the baseline, a negative effect was noted. Where differences were not statistically significant, no effect was reported.

Additionally, the evaluation included qualitative studies (e.g., workshop findings), where assessments were based on verbal judgments rather than statistical analysis, indicating positive, negative, or neutral effects.

3. Results

3.1. Study selection

The database search returned 2293 results. Initially, 533 duplicates were removed as they appeared in multiple databases. Next, a preliminary selection based on titles and abstracts excluded 1648 items because the topics were not relevant to the review's research questions. The full texts of the remaining 112 articles were then assessed, and 74 items were excluded for not meeting the eligibility criteria. Specifically, 29 studies addressed aspects not applicable to an office environment or had outcomes that were difficult to generalize, 19 studies focused on product design details rather than people-centred impacts, 16 studies involved systems without personal control, 5 were review papers, and 5 were duplicates found across journals and conference proceedings.

In the end, 38 papers were included in the review. Fig. 3 presents a flow diagram of the selection process. Table 1 provides a summary of the 38 studies included in the literature review, organized chronologically by publication date. Following this, a descriptive analysis of the selected papers is provided, and the studies are analysed and discussed in relation to the three main review questions and sub questions.

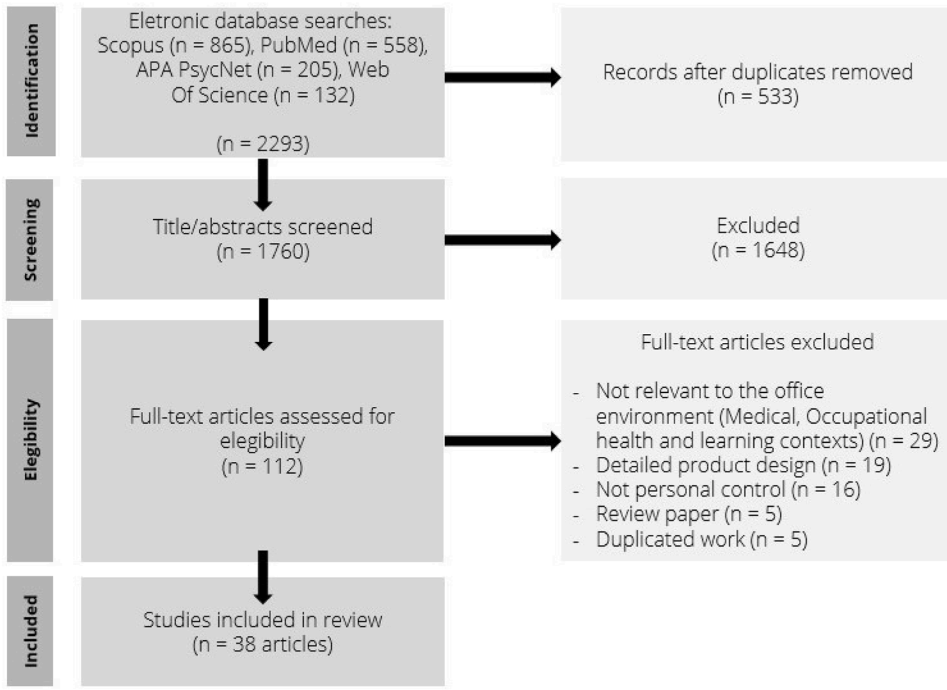

Fig. 3. - Flow diagram showing the number of studies screened, assessed for eligibility, and included in the review.

3.2. Study characteristics

Out of the 38 papers included in the screening process, 63 % were peer-reviewed journal articles, while the remaining ones were conference papers. These contributions were published between 1991 and 2023, with peak publication activity observed between 2016 and 2019 and 2021–2022. The majority of studies originated from researchers in the USA, Germany, and Denmark (see Fig. 4).

The 38 papers included findings from 45 experimental activities. Lab studies involving human subjects represented the largest proportion (34 %), followed by field studies with surveys (22 %), field studies combining environmental monitoring and surveys (11 %), simulation-based studies (11 %), field studies with environmental monitoring only (9 %), lab measurements not involving subjects (7 %), online surveys (4 %), and workshops (2 %). The vast majority of studies focused exclusively on acoustics, with only one study incorporating visual aspects [45]. Regarding the intended use of the environments analysed in the 38 papers, office spaces were the primary focus (33 %), followed by industrial (16 %), care settings and residential (10 % each), transportation (5 %), and other uses (8 %). Notably, 18 % of the studies did not target a specific environment. Participant-based studies reported sample sizes ranging from 6 to 256. Additional details are available in Table 1.

The studies exhibit a range of baseline and exposure conditions. Quiet baseline conditions in offices varied between 25 and 35 dBA, although in some cases, the exact noise level in quiet conditions was not reported. Reference conditions in office settings ranged from 33 to 58 dBA, while exposure conditions spanned from 45 to 63 dBA. The range of noise levels experienced across the studies is illustrated in Fig. 5. Notably, transportation settings (70 dBA) and industrial environments presented the highest reference conditions, with noise levels ranging from 80 dBA to 110 dBA in the latter.

3.3. RQ1. acoustic PECS identification and categorisation

3.3.1. Identification

The majority of the selected studies focused on headphones (39.5 % out of 38 studies), including those evaluating the use of masking signals (21 %), those assessing the effectiveness of active noise cancellation (ANC, 16 %), and those combining both masking and ANC (8 %). The principle of masking involves emitting a sound signal to interfere with the detection or identification of a target sound, most commonly the speech of colleagues, in order to protect privacy or reduce distractions in the workplace. Masking can be informational, where the target sound and the masker are similar and audible, but the listener is unable to distinguish the target sound from the masker, preventing comprehension. Alternatively, energetic masking occurs when physical interactions between the signal and the masker cause the target sound to be obscured by a louder sound with greater energy content. Differently, ANC involves generating anti-noise signals to cancel out incoming sounds. Following headphones, 23.7 % of the studies examined the use of earmuffs and earplugs in attenuating noise entering the ear canal. 13.2 % of the studies investigated sound masking systems, where loudspeakers emit masking signals to cover distracting background noise. Another 13.2 % explored active sound zoning systems, an emerging technology that uses loudspeaker arrays with precise amplitude and phase control to create distinct acoustic zones within a shared space, aiming for minimal interference between zones and personalised soundscapes. 5.3 % of the studies focused on integrating loudspeakers into chairs. Another 2.6 % explored the use of metamaterials to create acoustic lenses capable of, for instance, directing specific sounds to certain parts of an audience, thus creating localized “audio spotlights”. 2.6 % of the studies explored active noise barriers, which double as desk dividers in office settings. These systems combine the noise reduction properties of sound-insulating barriers with masking and ANC technologies, utilizing feedback controllers on top and feedforward controllers on the back of the partitions. Finally, 2.6 % of the studies investigated movable sound-absorbing or insulating devices that locally alter the acoustic environment. For example, Zhang et al. [37]’s prototype noise-reducing canopy for classrooms provides individual control by allowing users to open or close the structure above their desks, offering tailored acoustic conditions. Please consider that some of the studies focused on more than one PECS type. Fig. 6 illustrates the percentage of studies that employed each type of PECS. One study included both headphones and earmuffs in its evaluation, resulting in a total exceeding 100 %.

Table 1
- Summary of the 38 studies included in the literature review.

Study	Country	Year	Building type	Type of work*	Type of PECS**	Sample size
[13]	USA	1991	Industry	FSS, LS	Earplugs, Earmuffs, Combination of earmuff with earplugs	40
[14]	USA	1995	Office	FSS	HP + Masking	256
[15]	Finland	2002	Industry	FSM	Earmuffs	10
[16]	Taiwan	2006	Not described	LS	HP + ANC	30
[17]	Australia	2010	Club	OS	Earplugs	20
[18]	Canada	2012	Industry	FSM	Earmuffs, Earplugs	24
[19]	Republic of Korea	2013	Not described	S	Sound masking system	Not applicable
[20]	Japan	2014	Waiting room	LS	Sound masking system	7 and 12
[12]	Australia, Germany	2014	Transportation	LS	HP, HP + ANC	32
[21]	Japan	2015	Care setting	LS, FSS	Sound masking system	6 and 12
[22]	Japan	2016	Office	FSMS	Active noise barrier	8 and 10
[9]	Sweden	2016	Office	LS	HP, HP + Masking	30
[23]	USA	2016	Transportation	FSS	Active sound zoning systems	12
[24]	UK	2017	Office	FSMS, FSS	HP, HP + Masking	28 and 12
[25]	Iran	2017	Industry	LSNS	Earmuffs	30
[26]	Poland	2017	Industry	LSNS	Earmuffs	10
[27]	The Netherlands	2017	Care setting	FSMS	Sound masking system	3
[28]	Sweden	2017	Office	LS, FSS	Chair with integrated loudspeakers	Not described
[29]	Germany	2018	Office	LS	HP + Masking	24
[30]	Germany	2018	Not described	LS	HP, HP + ANC, Earplugs	10, 194
				OS	Different types	10, 194
[31]	Germany	2018	Office	FSMS	Sound masking system	24
[32]	Hungary	2018	Office	S, FSM	Chair with integrated loudspeakers	Not applicable
[33]	Denmark	2019	Residential	W	Active sound zoning systems	6
[34]	Denmark	2019	Residential	FSS	Active sound zoning systems	7
[35]	UK	2019	Not described	LSNS, S	Metamaterial lens	Not applicable
[36]	Taiwan	2020	Industry	FSM	Earmuffs, Earplugs	50
[37]	The Netherlands	2021	School	LS	Passive sound absorbing/insulating devices (installed in the room)	201
[38]	Finland	2021	Office	LS	HP, HP + ANC, HP + Masking, HP + ANC + Masking	55
[39]	Germany	2021	Office	LS	HP + Masking	33
[40]	USA	2021	Not described	S	Active sound zoning systems	Not applicable
[11]	USA	2021	Not described	LS	Earmuffs	30
[41]	Denmark	2022	Office	S	HP + ANC	Not applicable
[42]	India	2022	Care setting	FSMS	HP + Masking	54
[43]	USA	2022	Residential	FSS	HP + Masking	62
[44]	England	2022	Not described	LS	HP + ANC + Masking	15
[45]	USA	2022	Care setting	FSS	HP + ANC + Masking	97
[10]	Germany	2022	Office	LS	HP, HP + ANC	21 and 57
[46]	Denmark	2023	Residential	FSS	Active sound zoning systems	5 households (up to 19 people)

* Type or work: LS – Lab Study; LSNS – Lab Study without Subjects; S – Simulation; FSS – Field Study Survey; FSM – Field Study with Measurements; FSMS – Field Study with Measurements and Survey; OS – Online Survey; W – Workshop.
** Type of PECS: HP – Headphones without noise cancelling; HP + ANC – Headphones with noise cancelling; HP + Masking – Headphones without noise cancelling and with masking; HP + ANC + Masking – Headphones with noise cancelling and masking.

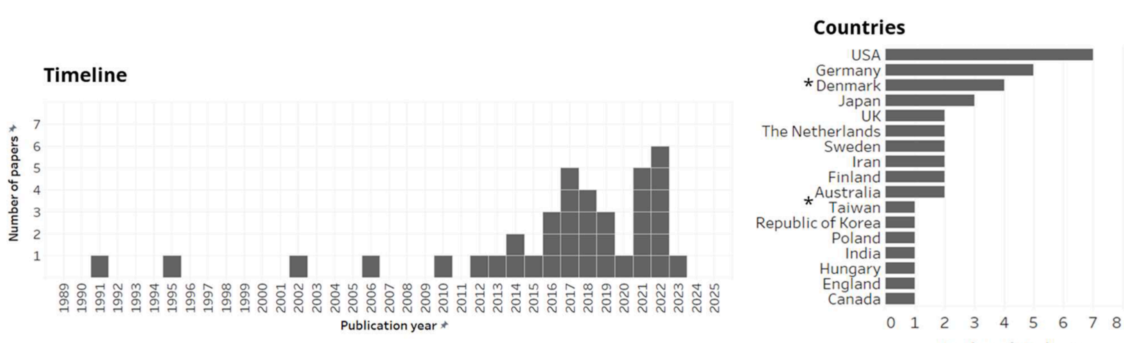

Fig. 4. – Distribution of papers by year and country.
*One study in both Germany and Australia

3.3.2. Categorization

The identified types of Acoustic PECS can be categorized based on two key principles, as initially discussed in [6]. The first distinction is between active and passive systems. Passive systems, by definition, lack electronic components for altering the acoustic field (e.g., loudspeakers, microphones) and rely solely on physical structures that disrupt sound waves through mechanisms like soundproofing and sound absorption.

The second principle addresses the application mode of the PECS, distinguishing between systems integrated into the surrounding environment—such as walls, ceilings, floors, or office furniture—and those applied directly to the individual (i.e., wearables). The identified Acoustic PECS are categorized according to these principles in Fig. 7.

Wearable passive Acoustic PECS include earplugs and earmuffs. Earplugs are simple devices made from foam or polymer that are inserted into the ear canal to block sound. They are often used in noisy environments such as industrial settings, but more and more frequently,

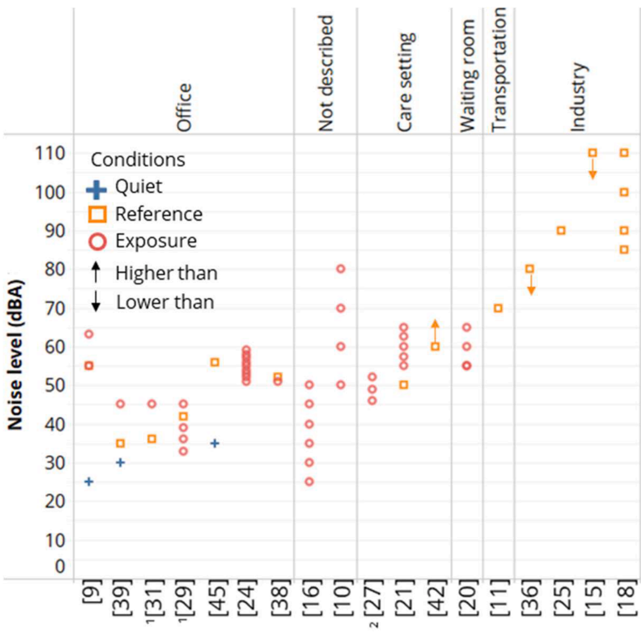

Fig. 5. – Noise levels for quiet conditions (cross), reference (square), and exposure (circle) conditions, by building type. For terminology, see Fig. 3. When only a minimum or maximum value is provided in the studies, this is indicated with an upward or downward arrow, where the upper or lower end of the arrow corresponds to the maximum or minimum level reported in the studies.

[1] Studies also providing a quiet condition, but not specifying its noise level. [2] Studies also providing a reference condition, but not specifying its noise level.

they are being proposed for personal comfort in public or residential spaces. Earmuffs cover the entire ear and are often used as protective equipment in industrial or construction settings. They provide passive noise reduction by forming a physical barrier around the ears.

Building-attached passive Acoustic PECS, although less common, include prototypes of sound-absorbing or insulating structures positioned around the individual, independently adjusted, or prototypes of metamaterial-based acoustic lenses that could potentially direct different sounds to specific areas within a space, thus creating personalized soundscapes.

Wearable active Acoustic PECS include headphones, whether equipped with ANC or sound masking, or both. These devices are perhaps the most popular of the Acoustic PECS.

At the room level, examples of active Acoustic PECS include loudspeaker systems integrated into the headrests of chairs, such as the noise-cancelling office chair prototype developed by Sujbert and Szarvas [32], or active noise barriers with embedded sound masking systems designed to safeguard speech privacy and speech distraction in open-plan offices. Another example includes active sound zoning systems, which empower individuals to control the sound environment in specific areas of a room while leaving other areas unaffected. This technology enables the creation of “acoustic bubbles” within the same space, without the need for wearable devices.

3.4. RQ2.1 impact of acoustic PECS on occupants’ subjective evaluation

The selected studies examined participants’ subjective responses across various dimensions, including emotional (or affective) response, perceived loudness, communication and privacy, PECS usage, sleep quality, and work or study performance (see Fig. 8).

The studies explored emotional and affective responses, focusing on factors such as annoyance, relaxation, stress reduction, comfort, disturbance, overall satisfaction, and preference. When examining perceived loudness and noise reduction, the studies addressed aspects such as perceived loudness, hearing protection, and perceived sound exposure. For perceived privacy and communication, the focus included speech intelligibility, privacy, and interpersonal communication and interaction. Specific aspects related to the use of PECS were also explored, such as ease and frequency of use, willingness to use, ergonomics, perceived control, and the quality of the listening experience. Lastly, in evaluating self-reported performance, the studies investigated areas like concentration, distraction, perceived workload, work or study performance, workplace and job satisfaction, and turnover intention. Appendix A provides an overview of each study investigating

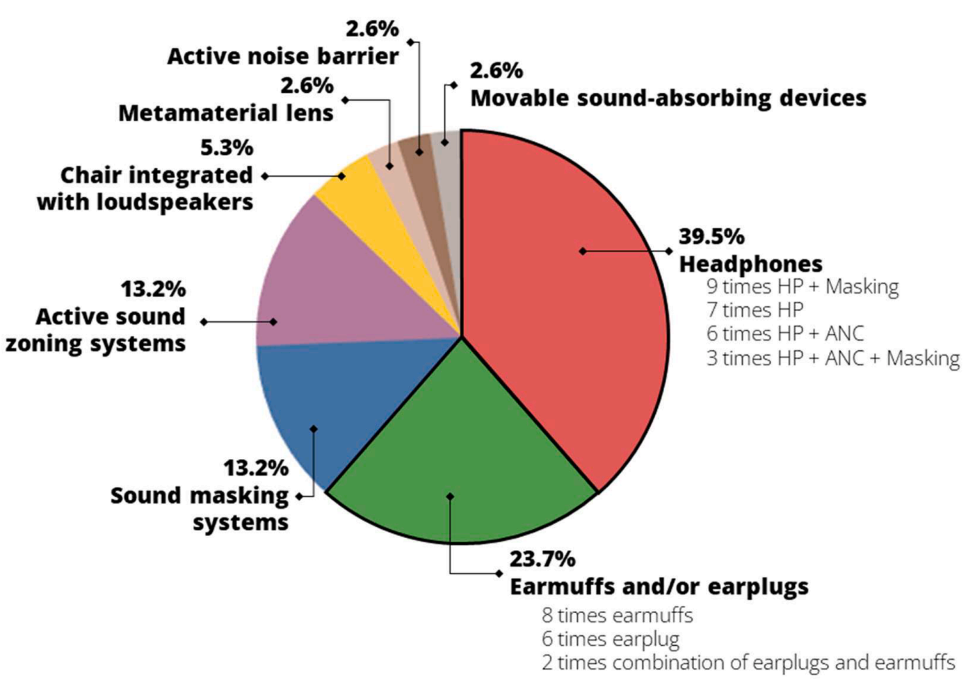

Fig. 6. – Frequency of investigation for different types of acoustic PECS across the selected studies (N = 38). Note that a single study may have examined multiple types.

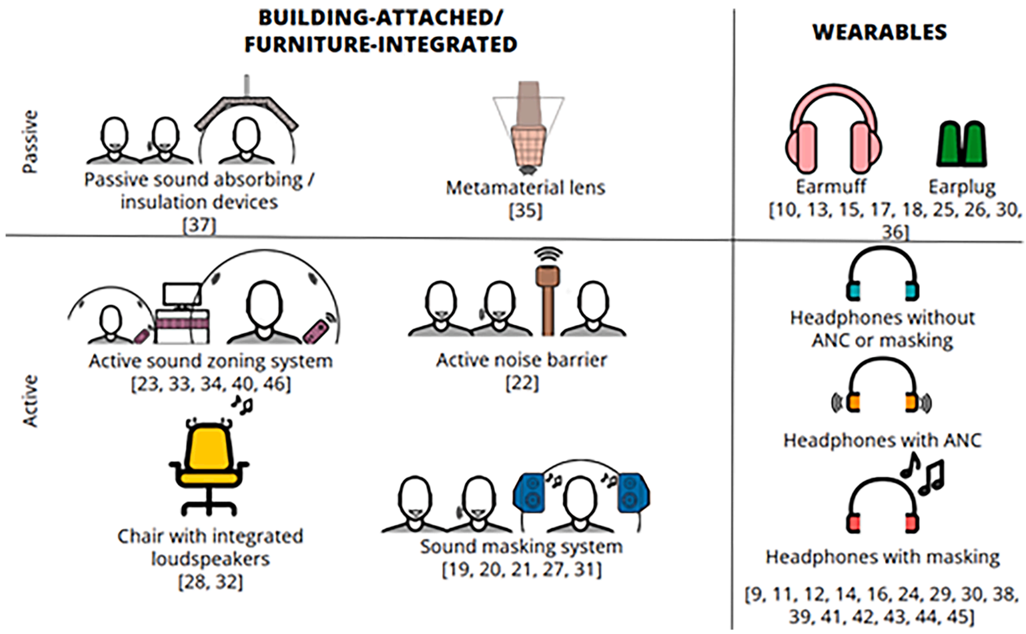

Fig. 7. – Acoustic PECS categorization into active and passive systems, and further differentiated based on whether they are directly worn by the occupant (wearables) or installed in the environment where the occupant is situated (building-attached/furniture-integrated).

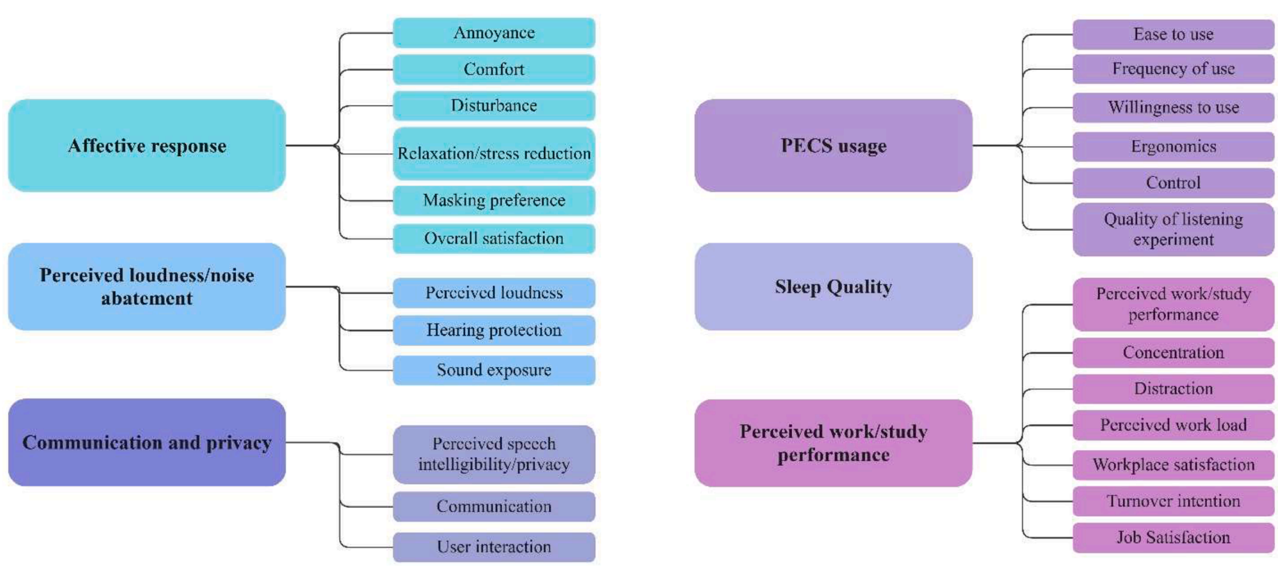

Fig. 8. - Categories investigated regarding participants' subjective responses to the use of PECS.

participants' subjective responses, highlighting the key outcomes for each category examined. It includes details on the study type (sample size, availability of control over the PECS by study participants, typology of experiment and PECS under investigation), evaluation methods (e.g., scales used for the different attributes), exposure conditions, and the baseline condition used for comparison.

Notably, in most studies, participants were not allowed to use the devices freely but were constrained by predefined experimental conditions. In cases where participants had control over the use of PECS [14,24,27,28,37,45,46], no negative effects were generally observed on the subjective categories investigated. Conversely, when participants did not have control over PECS usage [9,10,11,21,22,29,31,38,39,42,44], the effects on subjective responses were more varied, with some negative outcomes observed. In detail, when the baseline involved quiet conditions, PECS usage was often evaluated negatively [9,29,31,10]. However, under more challenging baseline conditions, PECS usage was generally perceived positively, and subjective evaluations were rated negatively in only two studies compared to the reference condition [21,39]. Study [39] reported increased perceived loudness levels with masking noise, while study [21] noted heightened annoyance ratings, albeit described as low discomfort, with masking systems still being recommended. The impacts on users' subjective evaluations are detailed below for the different technologies.

3.4.1. *Headphones*

Studies involving headphones (without masking or ANC) [9,10,24,38] mostly showed non-significant effects compared to the reference condition (office noise or speech between 52 and 56 dB(A)) in the evaluations of annoyance [10,38], concentration [10,24], communication [24], perceived work or study performance [10,24]. Improvements were observed in perceived workload, as participants reported lower workloads in the headphone-only condition compared to the reference (speech noise at 55 dB(A)) [9], and in reduced perceived loudness compared to the reference condition (office conversation 56 dB(A)) [10].

When headphones were combined with sound masking [9,14,24,29,38,39,42], general improvements were observed in subjective assessments compared to the reference condition in terms of annoyance [29,38,39], disturbance, perceived speech intelligibility, overall satisfaction [39], concentration [24,39], perceived work performance [14,24,39], sleep quality [42], workplace satisfaction, turnover intention, distraction, relaxation [14], and perceived work load [9]. However, one study reported an increase in perceived loudness with masking [39], while two studies showed no significant effects on communication [24] and on job satisfaction [14] compared to the baseline. In the study by Vassie and Richardson [24], focus group outcomes highlighted that the use of masking noise (a modified brown noise) reduced their ability to hear nearby colleagues' conversations, causing them to avoid using masking, and they perceived the modified masking noise headphones as too irritating and uncomfortable. In the study by Warjri et al. [42], improvements from using masking sounds through a mobile app with headphones were observed in sleep quality among patients in intensive care units [42]. Compared to the control group, patients listening to pink and brown noise twice a day for three days significantly improved their sleep quality, which had an impact on their recovery [42].

Headphones with ANC showed no negative effect compared to reference conditions [10,38]. No significant differences were reported in annoyance when using headphones or headphones with ANC compared to the reference condition [38]. However, improvements were observed in annoyance, concentration, and perceived work performance when ANC was activated in [10].

Three studies [38,44,45] examined the effects of headphones with sound masking and ANC, reporting improvements compared to the baseline in terms of reduced annoyance [38], distraction [44], improved quality of listening experience [44], job satisfaction, ease of use, and relaxation [45]. Radun et al. [38] observed no significant improvements when using headphones (with or without ANC) in presence of irrelevant speech at 52 dBA, but reduced speech annoyance when masking noise was added. For all types of headphones, when the baseline condition was quiet, negative effects were reported, including increased annoyance [10,29], higher perceived workload [9], reduced concentration, and perceived performance [10].

3.4.2. *Active sound zoning systems*

Studies on active sound zoning [23,34,46], typically preliminary in nature, reported beneficial effects of such systems. Jacobsen et al. [46] evaluated the system with household participants, emphasizing that users valued the control it offered and found the reduction in audio exposure among household members to be motivating [46]. Although participants noted that sounds from outside their designated sound zones were audible, they did not perceive this as disruptive and expressed a preference for maintaining awareness of activities occurring in the surroundings [46]. Overall, active sound zones would allow simultaneous exposure to different sound conditions and were positively evaluated for preserving social interactions in shared spaces, while ensuring a level of privacy [23,34].

3.4.3. *Sound masking systems*

Sound masking systems demonstrated the ability to reduce annoyance [27,31], though they occasionally caused minor annoyance or slight reductions in comfort [21,27]. When the baseline was quiet, the masking sound was evaluated as more annoying [31]. However, these drawbacks were in other studies considered acceptable given the enhanced privacy the systems offered [21,27]. When integrated into chairs with built-in speakers, these masking systems proved beneficial for most individuals, especially in terms of overall satisfaction, concentration, and occupant interaction [28].Wang et al. [22] tested an active noise barrier under different masking conditions and signals, with energetic masking (where the target sound is covered by another sound), informational masking (where the target and masker sounds are audible but not separable for comprehension), and mixed-type masking. Stationary energetic random noises were found to be relatively acceptable, while informational noises (time-reversed masker) and mixed-type noises (artificially synthesized non-stationary masker) were perceived as the most annoying [22].

3.4.4. *Canopies*

Regarding passive sound absorbing and insulating devices, the prototype developed by Zhang et al. [37]—a ceiling-mounted canopy for classrooms, designed to be individually controllable and adjustable—was found to be beneficial, particularly in terms of ease of use, user satisfaction, willingness to use, and perceived performance [37]. Participants reported that they would interact with the system and change its mode several times a day if it were installed in their classroom [37].

3.4.5. *Earplugs and earmuffs*

Two studies investigated the effects of earplugs [17] and earmuffs [11] in noisy environments. Beach et al. [17] reported improvements in hearing protection, communication, reduced disturbance, and enhanced ergonomics when earplugs were used by nightclub attendees. Rudin et al. [11] found no significant effects on communication, disturbance or comfort with unilateral ear occlusion using earmuffs but observed benefits in presence of background noise, such as a reduced tendency to raise one's voice due to the Lombard effect, while still being able to hear others and communicate effectively.

Fig. 9 summarizes the effects of PECS on various participants' subjective responses, on affect, work or study performance, sleep quality, and Fig. 10 the effects of PECS on perceived loudness, speech intelligibility and privacy, and PECS usage. In Figs. 9–11, when multiple Acoustic PECS are examined within the same study, and/or under different baseline conditions, and/or in relation to different outcome measures, the study is shown multiple times across the relevant figures. Colours are used to indicate the type of PECS, while distinct sections of the figures reflect the specific outcome assessed (e.g., affective response) and the condition under which it was evaluated (e.g., quiet with PECS). At the bottom of the figure, the percentages are shown—separately for the different baseline conditions—of the times an improvement, neutral effect, or negative effect was assigned in the evaluation category within a given study of a specific PECS. For example, it is interesting to note how, in terms of affective response and perceived work performance, acoustic PECS may be beneficial in the presence of background noise (improvements in 67 to 77 % of cases) but not in the presence of a quiet background (negative effects observed in 100 % of cases).

3.5. *RQ2.2 impact of acoustic PECS on occupants' physiological response*

Only one study has explored the link between the use of Acoustic PECS and individuals' physiological responses. In an EEG-based investigation by Haruvi et al. [43], researchers assessed the impact of audio content played through headphones on focus levels by decoding brain signals recorded during various tasks (e.g., working, reading, solving puzzles, playing Tetris, performing math calculations, and tackling word problems). Compared to a quiet condition, three types of masking signals were tested: "pure focus" and "focus flow" music playlists, as well as personalized soundscapes. Among these, only personalized soundscapes significantly enhanced participants' focus levels, particularly after 2.5 min, while music playlists had no measurable impact. A predictive model of focus and genre analysis indicated that engineered soundscapes and classical music were the most effective at boosting focus, whereas pop and hip-hop music were the least effective. Fig. 11 summarizes the effects of PECS on occupants' physiological, and cognitive response, and speech perception.

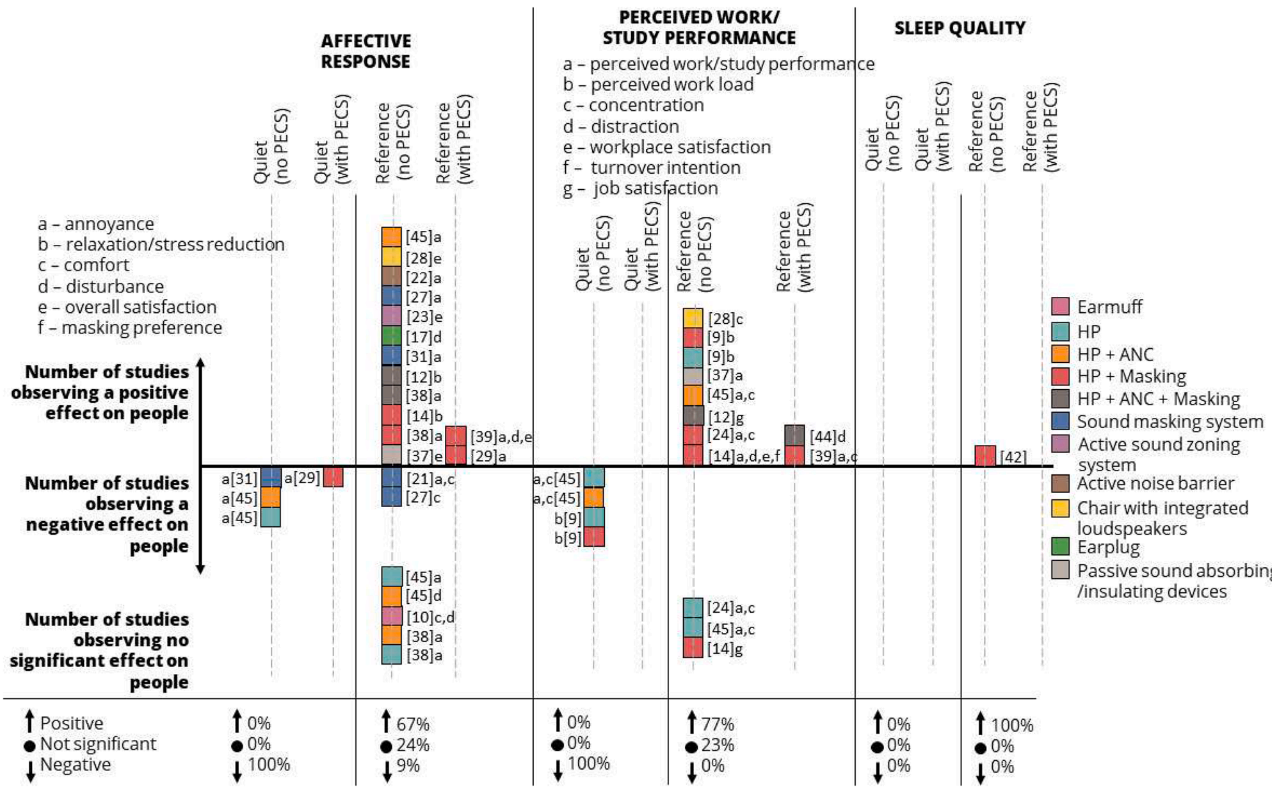

Fig. 9. – Qualitative overview of Acoustic PECS impacts on affective response, perceived work/study performance, and sleep quality.

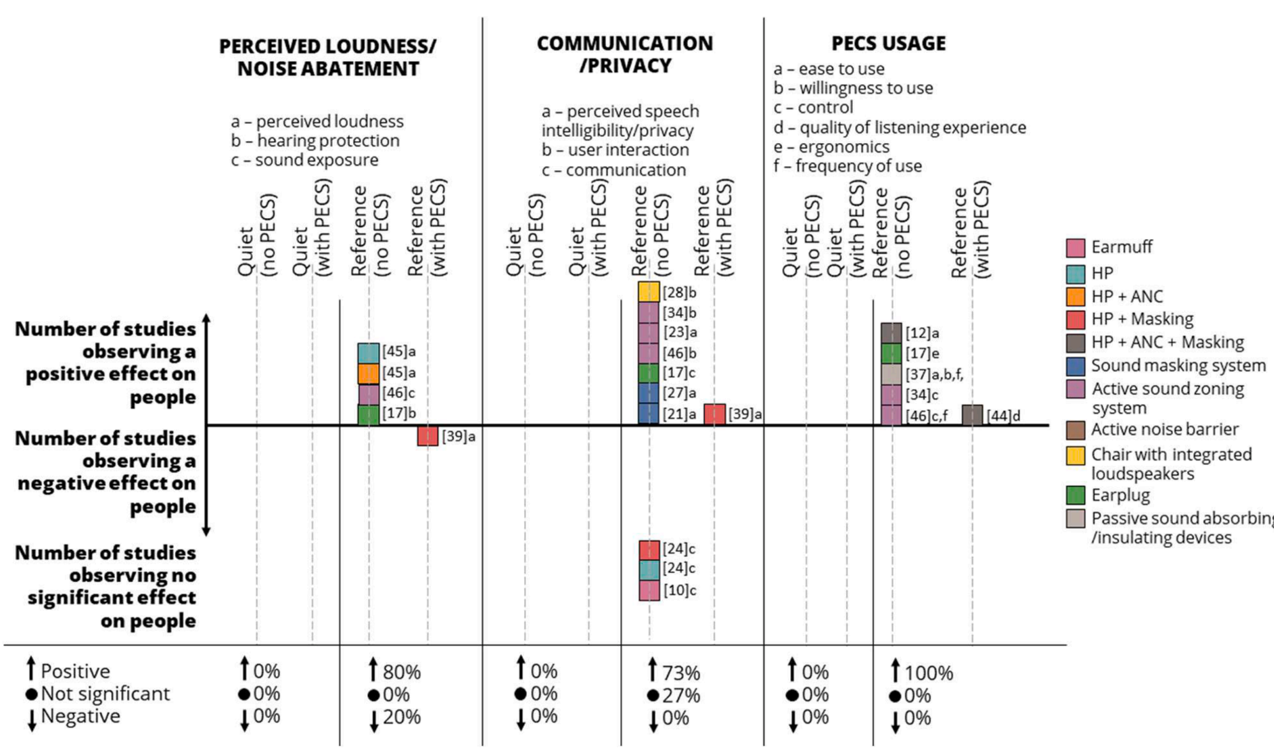

Fig. 10. – Qualitative overview of Acoustic PECS impacts on perceived loudness/noise abatement, communication and privacy, and PECS-related aspect.

3.6. RQ2.3 impact of acoustic PECS on occupants' cognitive response

The cognitive effects of using acoustic PECS were examined in seven studies, all of which employed a serial recall task to assess short-term memory, as summarized in Fig. 11 and Appendix B. Renz et al. [31] investigated the influence of a decentralized sound masking system under 10 masking scenarios, varying the signal-to-noise ratio and loudspeaker location, and compared these to three baseline conditions:

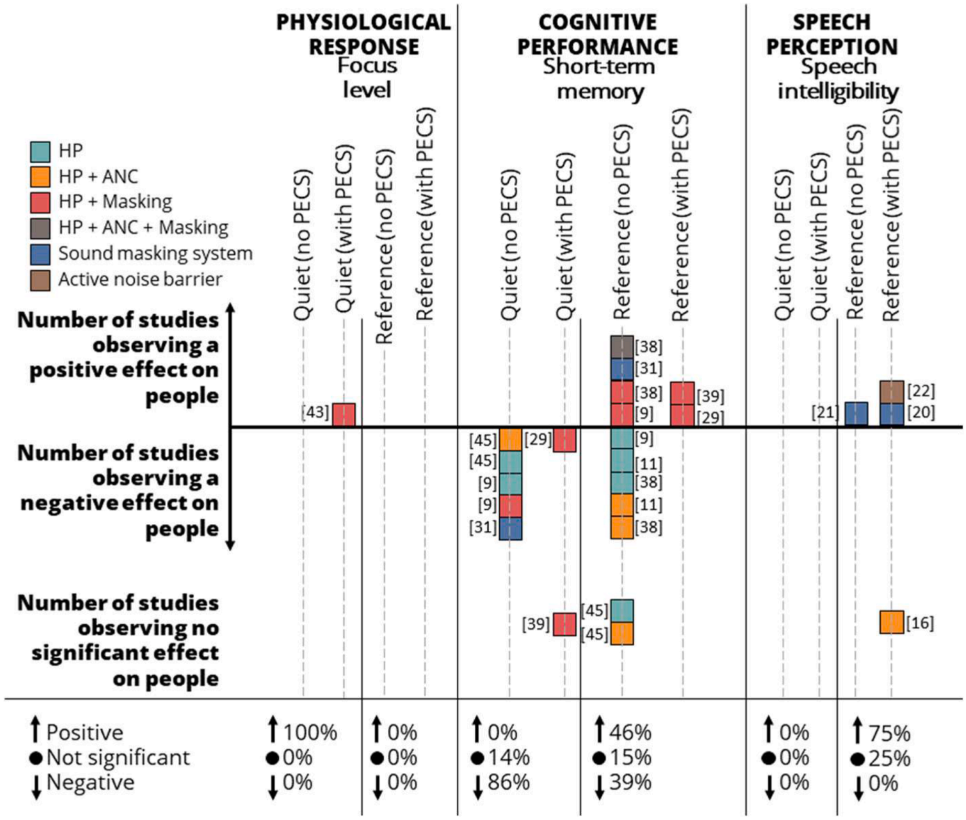

Fig. 11. - Qualitative outcome of physiological response, cognitive performance and speech perception.

quiet and unmasked speech at 33 and 36 dB(A). As expected, the quiet condition yielded the best performance. However, in scenarios with speech noise, all comparisons involving masked speech at −12 dB signal-to-noise ratio (SNR) showed significant improvements in performance compared to unmasked speech. At −9 dB SNR, significant differences were observed only when the masking emitter was positioned in the same direction as the speech source.

Additional studies explored the effects of headphones. While the quiet condition consistently provided the most favourable outcomes (see Fig. 11), positive effects on short-term memory were observed under noisy reference conditions only when a masking signal was applied (either with ANC on or off) [9,29,39]. In contrast, no improvements were detected in other cases [10,12], except among noise-sensitive individuals [38].

3.7. RQ2.4 impact of acoustic PECS on occupants' speech perception

Four studies investigated the impact of acoustic PECS on speech perception, defined as the process by which a listener decodes, and transforms an incoming stream of otherwise meaningless sounds generated by speech production into meaningful information. This is typically assessed through speech intelligibility, which measures the percentage of correctly identified words (target signal). Lower speech intelligibility indicates more effective masking and greater privacy, making it a key metric for evaluating the performance of masking systems. The studies examined a variety of factors, including SNRs, the directional relationship between the signal and masker, and the type of masker (e.g., informational or spectral content). Across all studies, the systems evaluated—such as active noise barriers for offices [22], sound masking systems [20,21], and headphones [16]—proved capable of effectively masking surrounding speech noise under certain conditions. Wang et al. [22] evaluated an active noise barrier for open-plan offices by comparing four masking types: band-limited pink noise, target-spectrum-based random noise (energetic maskers), time-reversed speech (informational masker), and synthesized environmental noise (mixed-type masker). These maskers were tested across target-to-masker (TMR) signals ranging from −15 dB to 0 dB in 5 dB increments. At TMRs below −10 dB, speech intelligibility for all four maskers fell below 10 %, ensuring high speech privacy. Among the maskers, environmental noise had the highest masking performance overall. Pink noise and target-spectrum-based noise outperformed time-reversed speech at low TMRs, especially at −15 dB. Mochizuki et al. [20] tested a sound masking system by varying speaker positions around the listener's head. When the masker was played at 55 or 60 dB(A), the masking effect on a 55 dB(A) speech signal was minimal, regardless of speaker layout. However, at a masker level of 65 dB(A), word intelligibility scores dropped to about 35 %, irrespective of the speaker arrangement. Arimitsu et al. [21] assessed the masking potential of pink noise, air conditioning sounds, and nature sounds against a speech signal at 50 dB(A). At an SNR of −15 dB(A), word recognition scores approached zero for all three maskers. Among them, nature sounds provided the best masking performance, outperforming air conditioning and pink noise, though all maskers effectively reduced word recognition. Lin et al. [16] investigated noise-cancelling (NC) headphones compared to standard headphones in terms of reducing speech intelligibility at 25 dB hearing level (dBHL), combined with transformer noise across levels ranging from 25 to 50 dBHL. At SNRs between 0 dB and −5 dB, speech intelligibility with headphones plus ANC was 6–8 % lower than with standard headphones alone. However, at lower SNRs, ANC did not provide additional reductions in intelligibility.

In summary, Fig. 11 qualitatively presents positive (in 75 % of cases), or neutral effect (in 25 % of cases) of Acoustic PECS on speech perception, while Appendix B provides an overview of each study, highlighting the key outcomes.

3.8. RQ2.5 impact of acoustic PECS on objective acoustic parameters

Ten studies focused on evaluating the impact of Acoustic PECS on the acoustic field, employing instrumental measurements or simulations rather than directly involving participants [15,18,19,25,26,32,35,36,40,41]. Among these, two studies combined simulations and experimental testing to develop innovative PECS, such as a chair with integrated loudspeakers for noise cancellation [32] and a conceptualized metamaterial lens to direct sound [35].

Seven studies assessed the effectiveness of Acoustic PECS in reducing noise entering the ear canal [15,25,26,32,35,36,46]. These evaluations commonly investigated either the noise attenuation properties of earmuffs and earplugs or the noise suppression capabilities of chairs equipped with integrated loudspeakers and reference microphones for active noise control. The studies utilized the Microphone in Real Ear (MIRE) method for experimental characterization of earmuffs [15,18,25,26,36] and earplugs [18,36]. However, background conditions varied: three studies measured noise levels exceeding 85 dB [15,18,25], one evaluated levels below 80 dB [36], and others did not specify background noise conditions [26]. High noise levels were recorded in real-world industrial environments by monitoring workers over a workday.

Two studies compared the performance of earmuffs and earplugs, using fit tests to assess proper usage by measuring noise reduction in both ear canals. Additionally, two studies compared manufacturer-reported noise reduction values for earmuffs with those measured on-site, revealing lower performance in real-world conditions [15,25]. Another study [26] evaluated the noise attenuation of 27 different earmuff models, reporting reductions ranging from 24.7 to 42.8 dB at high frequencies. Fig. 12 presents a graphical summary of the noise reduction provided by earplugs and earmuffs across the reviewed studies.

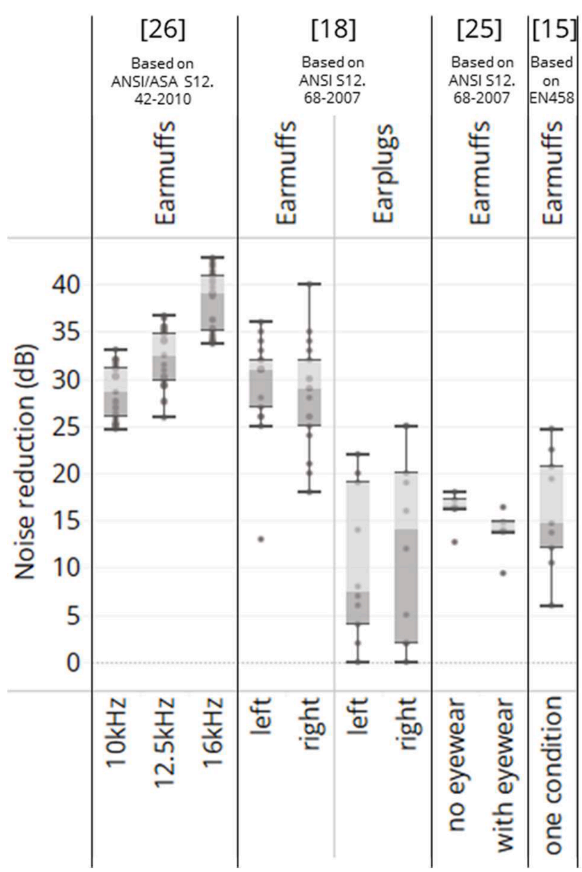

Fig. 12. – Noise reduction of earmuffs and earplugs per study.

The noise-cancelling office chair, equipped with multiple reference microphones, demonstrated noise suppression exceeding 16 dB(A) for broadband and sine noise, with a maximum reduction of 29.7 dB for tonal noise at 500 Hz. The study on the metamaterial lens prototype [35] highlighted its potential to direct sound to specific areas, enabling the creation of audio spotlights for personalized soundscapes in shared environments. Detailed findings from these studies are summarized in Appendix C.

The five simulation-based studies differed in the type of PECS investigated, the analytical models, and/or the software employed. Park et al. [19] conducted an analytical study to evaluate the error sensitivity of a personal audio system, which focuses acoustic energy into a specific zone of interest using multiple loudspeakers [19]. The system's performance is defined as the energy ratio between the zone of interest and the surrounding area. The study formulates the relationship between this energy ratio and various types of errors. Iotov et al. [41] used an analytical approach to improve the noise attenuation of ANC headphones in the presence of speech noise [41]. The study proposed a feedforward ANC system based on a fixed filter with integrated long-term linear prediction and demonstrated, through simulation, the effectiveness of the proposed system. Using 12 speech signals, the study achieved an average attenuation gain of 8 dB for voiced speech compared to conventional systems. ANC was also the focus of the study by Kaneko and Roy [40], this time in open-space applications, where ANC could cause noise amplification in areas outside the target zone. This issue was investigated in a simulated reverberant room, demonstrating that the proposed method can create a zone of silence while keeping noise amplification in the rest of the room moderate. Simulations often complemented experimental tests. For example, they were used to optimize the placement of reference microphones in the development of the noise-canceling office chair by Sujbert and Szarvas [32] or to simulate focal lengths in Memoli et al. [35]'s study of lenses based on acoustic metamaterials.

3.9. RQ3 limitations of current acoustic PECS

Many categories of Acoustic PECS identified in the literature face technological and practical limitations, as highlighted by the authors of the reviewed studies. While a detailed analysis of each technology falls outside the scope of this work, some key insights are summarized below.

Passive sound-absorbing and insulating canopies suspended from ceilings [37] are limited by their "boring appearance" and the noise generated by the linear motors used to open and close them. This highlights the need for designers and architects to develop solutions that are both functional and visually appealing.

Earplugs often raise issues related to comfort and performance, which are highly sensitive to fitting procedures. In contrast, earmuffs and ear canal cap devices tend to be less affected by improper fitting [13,26,36]. Individuals with smaller ear canals may find partially compressible foam earplugs difficult to insert, increasing the likelihood of them falling out during extended use [36]. Custom-made earplugs can improve comfort but require an adaptation period, and their high cost often discourages widespread adoption [17]. Proper training on how to wear earplugs can significantly enhance their effectiveness [36]. Some users have reported challenges in adjusting their voices while wearing earplugs in environments with loud music, feeling as though they are shouting [17]. However, unilateral occlusion—leaving one ear open—can mitigate this issue by reducing the tendency to raise one's voice, thereby enabling more effective communication. Earmuffs, on the other hand, may have varying levels of effectiveness depending on their fit relative to the size of the wearer's ears [25].

In sound masking systems, speaker placement relative to listeners and surrounding noise sources are critical. For example, sound attenuation over short distances may be insufficient to effectively mask disturbing speech sounds, and masking may not be desired in close proximity because communication needs to be maintained between adjacent workstations [31].

Metamaterials lenses are limited by their maximum size relative to the bandwidth they can cover. While current capabilities are sufficient for applications such as delivering alarms or personal audio messages, larger bandwidths are highly desirable for consumer audio systems [35].

The exploration of wearable devices and furniture-integrated solutions that generate masking signals has sparked broader discussions about which types of signals are best suited for promoting concentration and well-being. However, the use and testing of such systems as PECS might partly overcome these limitations, as the occupant can choose the masker that best suits their needs and preferences in real time.

Using barriers that directly cover the ears—such as headphones, earplugs, or earmuffs—may lead to antisocial behaviours or even unsafe situations. This is because these devices can make it difficult to hear verbal warnings, alarm signals, telephones, or instructions from supervisors and coworkers [14]. Additionally, wearing headphones can hinder collaboration and, in some work environments, be perceived as impolite. Delegating the prioritization of auditory information to others may also result in missed opportunities, such as social interactions or professional events [30].

A promising alternative, although not yet commercially available, is represented by “active sound zoning system”. By creating acoustic “bubbles” in shared spaces, active sound zoning eliminates the need for physical or visual barriers like headphones. One major limitation is the low level of sound separation between zones. However, while sound leakage outside the zones may be perceived as a disturbance, it also offers opportunities for informal collaboration, easy information sharing, or maintaining a connection with others in the shared environment. This partially addresses some of the drawbacks associated with headphones.

3.10. Study limitations

The results presented in this study should be interpreted in light of several limitations. First, although the literature review followed a systematic approach, the search string was specifically tailored to the research focus and the need to limit the number of retrieved items to ensure that the review process remained manageable for the working group. As a result, studies that investigated Acoustic PECS without explicit references to the built environment, or that used alternative keywords to describe the built environment, may not have been identified and included. Second, only a qualitative analysis of the impacts of the identified technologies on occupants was feasible. This was due to: (i) the relatively small number of selected studies compared to the number of technologies analysed, resulting in a limited number of studies per category; and (ii) the considerable methodological heterogeneity among studies, both in terms of sound field characterization and questionnaire-based assessments, which precluded the possibility of conducting a meta-analysis. Despite these limitations, we hope that the framework for defining Acoustic PECS and the research directions proposed herein will contribute to the harmonization of methodologies and, ultimately, support the generation of higher-quality scientific evidence regarding the impacts of Acoustic PECS.

4. Discussion

4.1. Acoustic PECS within the PECS framework

The present study explored existing technologies from the literature that align with the proposed definition of Acoustic Personalised Environmental Control Systems (Acoustic PECS). These systems provide individually controlled acoustic environments within the immediate vicinity of an occupant, without impacting the entire space or the surroundings of other individuals. The identified technologies have been categorized based on two key dimensions: the first relates to their spatial integration (whether they are building-attached, furniture-integrated, or wearable devices), and the second concerns the passivity of the device (i.e., whether or not it contains electronic components). Interestingly, these dimensions are also evident in other comfort domains.

Active Acoustic PECS, such as sound masking or active sound zoning systems, are building-attached because they require loudspeakers to be installed within the environment. Sometimes, these systems are integrated into furniture elements, occasionally combined with error microphones, as seen in noise-cancelling office chairs or active noise barriers. In other comfort domains, building-attached PECS include personalized ventilation systems for managing thermal and air quality [47–49], or smart projectors and adaptive lighting [50], which are building-integrated fixtures that can be controlled or automated to illuminate specific workspaces or desks, addressing individual visual preferences. Furniture-integrated PECS include devices like thermal chairs [51], leg warmers, desk mats [52], and personalized exhaust systems for air quality management [53].

Active and wearable PECS include headphones, which are among the most common means of controlling personal acoustic environments (in this case, from the ear canal to the eardrum) without disturbing others. Research has examined their use in conjunction with various maskers and/or ANC technology. Wearable PECS are also available for thermal [54,55] and air quality control [56,57], as well as for personal lighting [58], allowing the occupant to regulate environmental factors around them.

Less common are passive devices installed at the room level, such as prototypes of sound-absorbing canopies that hang from the ceiling and are operable individually (openable or closable) [37,59], and metamaterial lenses [35] designed to direct sound to specific points within the room, potentially creating distinct audio spotlights in shared spaces.

Finally, earplugs and earmuffs represent passive wearable devices, primarily studied in noisy environments (e.g., clubs or industrial settings) but increasingly marketed for use in residential or office settings. These devices can be compared to clothing for thermal comfort, with the development of innovative materials for personalized thermal management [60]. Similarly, for air quality, we can mention face masks or glasses for personal adjustment in the visual domain.

These examples highlight how Acoustic PECS share several similarities with PECS in other comfort domains, such as thermal, air quality, and lighting control. Categorizing them under the umbrella concept of personalised environmental control systems can provide valuable insights for future devices—whether building-attached, furniture-integrated, or wearable, whether passive or active—that could enable the control of multiple comfort domains. This approach could allow in future for personalised management of the local thermal environment, soundscape, smellscape, and air quality, aligning with a multi-domain approach to indoor environmental quality management [3].

4.2. Impacts of acoustic PECS on building occupants

The present study evaluated the benefits of acoustic PECS after identifying their types and categories in the literature. Under specific usage scenarios and boundary conditions, acoustic PECS have shown potential advantages in several areas. As reported through self-assessments, these include improving occupants’ affective responses, reducing perceived noise, altering privacy and communication conditions in work environments, enhancing sleep quality, and boosting performance in work or study contexts. The study also explored factors influencing their use, such as ergonomics and ease of use. Additional areas of investigation included objectively assessed physiological responses (albeit in one study), cognitive responses, and speech perception.

It is important to note that conclusive evidence regarding the benefits of acoustic PECS cannot yet be drawn due to the limited number of selected studies, the wide variety of devices studied, the diversity of methodologies employed, and certain methodological limitations. These issues will likely be addressed as these devices will be recognized and studied as acoustic PECS, following the guidelines outlined in Section 4.3.

Generally, based on the currently available evidence, it can be observed that while acoustic PECS may not be beneficial in quiet conditions, their adoption can yield positive effects in more challenging acoustic environments (e.g., in the presence of background speech noise) across one or more of the identified areas. For example, despite occasional comfort issues (e.g., with earplugs or masking systems introducing new masking noises), these systems can still be advantageous due to noise reduction, decreased intelligibility of surrounding speakers, and subsequent improvements in privacy and concentration. The performance of systems employing maskers can vary significantly depending on the type of signal used. Beyond their performance in terms of energetic or informational content relative to the target being masked, individual preference plays a critical role, and this aspect is key to evaluating the benefits of using PECS. As highlighted in Table 2, most studies imposed fixed experimental conditions on participants, without allowing them control. As noted in Section 3.4, when participants were allowed control over the conditions of acoustic PECS usage, the effects on the subjective aspects assessed through self-reports were predominantly positive. This observation, which will lead to recommendations for future research on acoustic PECS in the next section, finds strong justification in the literature on the role of environmental control in individual satisfaction [61]. When devices designed for user control are studied under fixed and non-modifiable conditions, the benefits of control might not be observed or quantified.

The importance of personalising the acoustic environment can be especially critical in multi-user spaces such as open-plan offices. This is primarily due to two factors. First, the same physical acoustic environment can be perceived differently by various occupants depending on personal and contextual factors, resulting in distinct soundscapes—acoustic environments perceived within a given context [62]. The availability of Acoustic PECS can partly address issues related to aural diversity [63], differing noise sensitivities (which may be particularly pronounced in neuroatypical populations), and the varying adaptive capacities of individuals to acoustic environments [64].

Second, in open-plan spaces, different users may engage in tasks requiring vastly different acoustic conditions, ranging from concentration to privacy for confidential conversations or collaboration requiring clear communication [65]. While the spatial layout is critical, the use of Acoustic PECS could help customize the acoustic environment in suboptimal acoustic conditions. The recommendations provided in the following section for the future research agenda on Acoustic PECS will therefore further clarify the benefits for occupants.

4.3. Pathways for future research

Current Acoustic PECS, while offering valuable solutions for personalised sound environments, face notable limitations across various categories, as outlined in Section 3.9. Technologies such as headphones, earplugs, earmuffs, and sound masking systems—whether building-attached or furniture-integrated—are relatively mature and well-documented in the literature. In contrast, other systems, such as suspended sound-absorbing canopies and metamaterial lenses, remain in the prototype phase. Active sound zoning has emerged as a promising avenue of research, though it is not yet developed enough for commercial use. However, the concept of independent, customizable acoustic bubbles without the physical constraints of headphones is particularly compelling.

Overall, research on Acoustic PECS aims to address several key challenges: enhancing noise reduction (or cancellation) across broader frequency ranges and sound pressure levels, optimizing masking signals to prevent intrusive or annoying background noise, and improving ease of use and long-term comfort for wearable systems. Although not explicitly discussed in the reviewed studies, the integration of artificial intelligence (AI) into Acoustic PECS presents a significant opportunity. AI could enable dynamic monitoring and control of acoustic conditions, automated source recognition, and personalised adaptations based on users' evolving preferences.

Passive or hybrid systems, such as building-attached or furniture-integrated devices (e.g., office dividers), offer simplicity but are limited in their acoustic impact due to dimensional constraints (e.g., thickness). Moreover, their implementation is often restricted by design and space requirements within rooms and buildings, presenting a significant challenge for future research and development.

In light of the proposed framework for Acoustic PECS and insights from the current literature, several recommendations for future research emerge. First, future studies must establish baseline conditions to rigorously compare the impact of Acoustic PECS. Specifically, a baseline should isolate the experimental condition by ensuring that the absence of the PECS device is the only variable (see Fig. 1). Second, it is crucial to evaluate Acoustic PECS in scenarios where participants have the autonomy to use the devices according to their preferences and needs, as imposed usage conditions undermine the essential principle of individual control, a defining feature of Acoustic PECS.

Additionally, most current studies fail to assess the localized effectiveness of Acoustic PECS—i.e., their ability to create targeted acoustic improvements without directly affecting the entire space or other occupants' environments. Therefore, future research should assess the impacts not only on the PECS user but also at a distance that could represent, for instance, a co-worker or a family member in the case of residential applications.

Moreover, future research should explore a wider range of subjective, cognitive, and physiological responses. The assessment of affective responses in the use of Acoustic PECS remains strongly tied to evaluations of annoyance and disturbance, overlooking recent literature on indoor soundscapes [66]. This body of work provides tools to characterize the impact—whether negative or positive—of acoustic stimuli on the emotions of building occupants, enabling a more comprehensive assessment of the impact of Acoustic PECS on affective responses in indoor environments [67,68]. While one reviewed study investigated physiological responses using EEG, cognitive assessments were largely limited to short-term memory performance. There is substantial room to expand the understanding of how Acoustic PECS influence broader cognitive functions and physiological outcomes.

Crucially, further exploration is needed to examine the relationship between building energy consumption and the deployment of Acoustic PECS. A defining feature of PECS, particularly in thermal and IAQ domains, is their potential to reduce energy consumption by optimizing environmental conditions in occupied areas while leaving unoccupied spaces in suboptimal states. This connection, however, remains largely unexplored for Acoustic PECS. Energy implications may arise directly from the operation of active systems (e.g., sound masking or noise-cancelling devices) or indirectly through their influence on user behaviour and interaction with other energy-intensive building systems. For example, Acoustic PECS could enable passive ventilation strategies (e.g., window openings) under less-than-ideal acoustic conditions, potentially contributing to energy savings in cooling and ventilation.

Finally, as emphasized earlier, developing a comprehensive framework for PECS that integrates thermal, visual, acoustic, and indoor air quality domains is vital for advancing multi-domain optimization of environmental parameters. Such an approach should also recognize the inherently multisensory nature of occupants' experiences. This integrated perspective will be pivotal in guiding future research on multi-domain PECS.

5. Conclusions

This study explores the application of the Personalised Environmental Control Systems (PECS) concept to the acoustic domain, as part of the activities conducted within the IEA EBC Annex 87. Following the proposal of a definition for Acoustic PECS, a systematic literature review was conducted to investigate (1) technologies aligned with this concept, (2) their impact on building occupants, and (3) their current limitations. The literature search, carried out using Scopus, Web of Science, APA, and PubMed, focused on field and laboratory studies that assessed systems enabling localized acoustic control in office-relevant settings. Studies such as review papers, those focused on medical devices, and articles without insights into occupant impacts were excluded, resulting in the selection and analysis of thirty-eight studies. Main outcomes are:

(1) The findings reveal a variety of technologies that align with the Acoustic PECS concept, which can be categorized into active or passive systems, as well as building-attached, furniture-integrated, or wearable devices. Passive wearable devices include earplugs and earmuffs, while active wearables primarily consist of headphones. Building-attached or furniture-integrated PECS range from passive sound-absorbing or insulating devices to metamaterial lenses. Active solutions include technologies such as active sound zoning systems, chairs with integrated loudspeakers, active noise barriers, and sound masking systems.

(2) The qualitative analysis highlights the potential benefits of these systems for occupants in acoustically challenging environments. These benefits include reductions in annoyance, improved work performance, the masking or cancellation of intrusive noises, and enhancements in short-term memory, among others. However, due to the limited number of studies and methodological constraints in assessing these technologies as PECS, a definitive quantification of their benefits remains elusive.

(3) The review also identifies technological limitations, including issues related to comfort during use, dimensional constraints in implementation, limited effectiveness in reducing sound pressure levels or frequency ranges, and acoustic leakage beyond the intended area of individual control.

Crucially, the study establishes research guidelines for advancing Acoustic PECS. Future research should evaluate the benefits of these systems when used under conditions where occupants have control over their operation, assess their impact on surrounding areas where other users may be present, and investigate a broader spectrum of outcomes, including subjective, cognitive, and physiological responses. Additionally, while the connection between Acoustic PECS and building energy consumption has not yet been explored, this presents a significant opportunity for future research. Incorporating Acoustic PECS into the broader framework of PECS—alongside domains such as thermal, indoor air quality, and visual control—is essential for developing multi-domain PECS for simultaneous control of multiple environmental factors at the individual scale.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT by OpenAI in order to improve readability and language of the work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2025.113243.

Appendix A. Overview of studies investigating participants' affective response

Study	Sample size	User Control	Experiment type	Type of PECS	Baseline condition	Exposure (with PECS)	Category	Evaluation	Outcome
[37]	201	Yes	LS	Passive sound absorbing/ insulating devices (installed in the room)	Reference without PECS: Background noise from participants	Same as the reference condition	Ease of Use	Multiple choice, Open question	82 % of participants evaluated the device as easy to use.
							Frequency of use		56 % of participants indicated they would change the device mode multiple times a day if they owned one.

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Study	Sample size	User Control	Experiment type	Type of PECS	Baseline condition	Exposure (with PECS)	Category	Evaluation	Outcome
							Overall Satisfaction		83 % of participants expressed a positive overall impression of the device.
							Willingness to use		61 % of participants desired to have the device in their classroom.
							Perceived work/ study performance		49 % of children believed the device could create a quieter learning environment and improve school performance by reducing noise.
[29]	24	No	LS	HP + Masking	Quiet with PECS, Reference with PECS: Unmasked speech (42 dBA)	Same as the quiet/ reference condition. Masking noise: Speech-shaped steady-state noise, and steady state noise with −5 dB per octave slope (45dBA)	Annoyance	Likert scale, Rating scale	HP + Masking was rated as more annoying than the quiet condition but less annoying than the reference condition.
[38]	55	No	LS	HP, HP+ANC, HP + Masking, HP+ANC + Masking	Reference without PECS: Irrelevant speech (52 dBA)	Same as the reference condition. Masking noise: wideband noise 5 dB reduction per octave within 250−8000 Hz (51 dBA)	Annoyance	Rating scale	No significant difference in annoyance was observed with HP, HP + ANC compared to the reference; however, HP + Masking (with or without ANC) significantly reduced speech annoyance.
[39]	33	No	LS	HP + Masking	Reference with PECS: Irrelevant speech (35 dBA)	Same as the reference condition. Masking noise: "Traditional" masking noise (Pink noise with speech spectrum) and harmonic masking noise (mixture of technical, water-based and slowly fluctuating sounds) (45 dBA)	Annoyance	Likert scale	Both HP + Masking conditions significantly reduced annoyance compared to the reference, with harmonic masking being less annoying than "traditional" masking.
							Disturbance		Harmonic masking noise significantly reduced long-term disturbance compared to the reference, while "traditional" masking showed no significant difference.
							Perceived Speech Intelligibility / Privacy		"Traditional" masking reduced speech intelligibility from strong to moderate, whereas harmonic masking reduced it further to slight intelligible.
							Perceived Loudness		Both masking conditions were perceived as louder than the reference, with no significant difference in loudness between the masking types.
							Concentration		Both masking conditions improved concentration compared to the reference, with harmonic masking being more effective

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Study	Sample size	User Control	Experiment type	Type of PECS	Baseline condition	Exposure (with PECS)	Category	Evaluation	Outcome
									than traditional masking.
							Perceived work/ study performance		Both masking conditions significantly increased perceived performance.
							Overall Satisfaction		Harmonic masking provided a significantly better overall sound environment, whereas "traditional" masking showed no significant improvement.
[21]	6	No	LS, FSS	Sound masking system	Reference without PECS: Background conversation (45 dBA)	Same as the reference condition. Masking noise: multiple voices and environmental sound (55 dBA)	Annoyance	Rating scale	Annoyance increased in both experiments, rated at 1.6 point in the non-masked area (reference) and 2 points in the masked area in the lab study, and 1 point in the non-masked area (reference) and 1.6 point in the masked in the field study.
							Perceived Speech Intelligibility / Privacy, Comfort		Both conditions caused low discomfort, and the addition of masking noise was positively evaluated for enhancing privacy while maintaining discomfort.
[24]	28	Yes	FSMS	HP + Masking	Reference without PECS: Office background noise (51 - 59 dBA)	Same as the reference condition. Masking noise: Modified brown noise (personal masking level choice)	Concentration Perceived work/ study performance, Communication	Likert scale	HP + Masking significantly reduced the disturbance to concentration and overall task performance caused by office noises but had no impact on worker interaction.
				HP					HP-only condition had no significant effect on the disturbance to concentration, overall task performance, and worker interaction caused by office noise.
	12	–	FSS (Focus group discussion)	HP + Masking, HP	–	–	Communication, Annoyance, Comfort	Interview	The masking noise made nearby conversations harder to hear, and modified masking noise was perceived as too irritating and uncomfortable.
[31]	24	No	FSMS	Sound Masking System	Quiet without PECS, Reference without PECS: Unmasked speech (36 dBA at the subject's head position)	Same as the quiet/ reference condition. Masking noise: Ten filtered pink noise adjusted to a spectrum contour that declined by 5 dB, SNRs from −12 ve −3 dB (45 dBA at the subject's head position)	Annoyance	Likert scale, Rating scale	The masked environment was significantly more annoying than the quiet condition but less annoying than the reference (except from the sound masking condition with a difference in horizontal direction of 90° at−9 dB SNR). No clear advantage

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Study	Sample size	User Control	Experiment type	Type of PECS	Baseline condition	Exposure (with PECS)	Category	Evaluation	Outcome
									was found in reducing annoyance when speech and masking sounds came from the same direction versus different directions.
[17]	20	–	OS (telephone interview)	Earplugs	–	–	Hearing Protection	Interview	Earplugs were reported to be effective for hearing protection, with any discomfort experienced while wearing them considered manageable.
							Disturbance		Earplugs reduced the negative effects observed after exposure to loud music.
							Communication		Communication was found to be easier for most interviewees with earplugs in noisy environments.
							Ergonomics		Earplugs were found to be comfortable unless worn for long durations and were considered discreet.
[22]	10	No	FSMS	Active noise barrier	Informational masker: a time-reversed masker	Masking noise: Energetic maskers: a band limited pink noise, a target spectrum based random noise, Mixed-type masker: a synthesized environmental noise	Annoyance	Likert Scale	Annoyance increased with higher masker power levels. However, subjects reported feeling annoyed even at low masker power levels of the time-reversed masker. Time-reversed maskers were rated as the most annoying, while stationary energetic random noises were relatively acceptable.
[42]	54	No	FSMS	HP + Masking	Reference without PECS: Care units background noise (>60 dB)	Same as the reference condition. Masking noise: white, pink and brown noise	Sleep quality	Likert scale	Playback of masking noise via app was perceived by most patients as effective in improving sleep quality by masking unwanted sounds.
[14]	256	Yes	FSS	HP + Masking	Reference without PECS: Office background conditions	Same as the reference condition. Masking noise: Personal choice (music)	Workplace Satisfaction, Job Satisfaction		HP + Masking users experienced increased organizational satisfaction but no change in job or coworker satisfaction.
							Turnover intention		Turnover intentions decreased significantly with HP + Masking, regardless of the type or duration of music.
							Perceived work/ study performance	Likert scale	Performance significantly improved with HP + Masking, independent of music type or listening time, while the control group (not using headphones) maintained stable performance.

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Study	Sample size	User Control	Experiment type	Type of PECS	Baseline condition	Exposure (with PECS)	Category	Evaluation	Outcome
							Distraction		HP + Masking use effectively reduced environmental interference.
							Relaxation/ Stress reduction		HP + Masking users showed the lowest “nervousness scores” along with the highest relaxation levels.
[46]	5 household (up to 19 members)	Yes	FSS	Active sound zoning systems	Reference without PECS: Background noise	Same as the reference condition.	Frequency of use	Interview, soundwalk	Participants adjusted sound zone systems more frequently at the beginning, with adjustments stabilizing over time.
							User Interaction		Sound zone systems enabled families to hear others’ media while creating new opportunities for spending time together, though full isolation was not achieved. Participants enjoyed hearing what others were listening to.
							Sound Exposure		Sound zones reduced perceived sound exposure outside the zones compared to conventional systems.
							Control		Personalized sound zones with an active sound zoning system allowed family members to adjust volume levels individually without disturbing others.
[9]	30	No	LS	HP, HP + Masking,	Quiet without PECS (25dBA), Reference without PECS: Speech (55 dBA)	Same as the quiet/ reference condition. Masking noise: nature sound masking (55 dBA), 7 -voices masking (63.1 dBA)	Perceived workload	Rating scale	Workload was rated lower in quiet condition compared to both the HP and HP + Masking and was rated lower in the HP and HP + Masking compared to the reference condition.
[23]	12	–	FSS (Focus group discussion)	Active sound zoning systems	–	–	Overall Satisfaction, Perceived Speech Intelligibility / Privacy	Interview	The personalized audio zones with an active sound zoning system were positively evaluated for effectively creating distinct sound zones and providing privacy in shared spaces.
[34]	7	–	FSS	Active sound zoning systems	Reference without PECS: Background condition at homes	Same as the reference condition	User Interaction	Interview Soundwalk	The sound zoning system was positively valued for its ability to balance social and private needs, as well as separated and connected conditions, enabling individuals to engage in personal activities while enhancing social connection.
							Control		Participants appreciated the ability to control and adjust sound

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Study	Sample size	User Control	Experiment type	Type of PECS	Baseline condition	Exposure (with PECS)	Category	Evaluation	Outcome
									characteristics to suit individual preferences, even within shared environments.
[44]	15	No	LS	HP + ANC + Masking	Reference with PECS: Quiet and Busy- street, home, and train sound recordings	Same as the reference condition	Quality of Listening Experience	Rating Scale	Listening experience scores were rated higher in conditions with ANC, particularly in noisy environments, while the benefit was less pronounced in quieter condition.
							Distraction		Distraction levels were rated lower with ANC, which negatively correlated with quality of listening experience scores.
[45]	97	Yes	FSS	HP+ANC+ Masking	Reference without PECS: Background condition	Same as the reference condition. Masking noise: Restorative, soothing, inspirational, meditation categories	Job Satisfaction	Free-text response questions	Job satisfaction increased with the use of PECS.
							Ease of use	Likert scale	PECS was rated as "very easy" or "easy" to use by most participants; however, over 50 % did not use it, likely due to time constraints among nurses.
							Relaxation/ Stress reduction	Yes/No question	Relaxation and restoration levels increased with the use of PECS and were highest for soothing sounds (31.6 %), followed by meditation (28.1 %) and restorative movement sound categories (22.8 %).
[27]	3	Yes	FSMS	Sound masking system	Reference without PECS Reference: Patient Room background conditions	Same as the reference condition. Masking noise: Combination of white and pink noise (46,49,52 dBA)	Annoyance	Interview	Noise produced by the sound masking system was not perceived as disturbing or annoying by participants.
							Perceived Speech Intelligibility/ Privacy, Comfort		PECS reduced speech intelligibility during conversations with doctors, enhancing patient privacy. Patients recommended higher masking levels, valuing improved privacy over temporary reductions in comfort.
[11]	30	No	LS	Earmuffs	Reference without PECS: Multitalker conversation (50,60, 70, 80 dBA)	Same as the reference condition	Communication	Yes/No question	Unilateral earmuff usage, defined as wearing an earmuff on one ear, significantly reduced the tendency to raise voice volume in noisy environments.
							Disturbance, Comfort	Rating scale,	Communication disturbance and discomfort remained unaffected though

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Study	Sample size	User Control	Experiment type	Type of PECS	Baseline condition	Exposure (with PECS)	Category	Evaluation	Outcome
									unilateral earmuff usage.
[28]	NA	Yes	FSS	Chair with integrated loudspeakers	Reference without PECS: Office background conditions	Same as the reference condition. Masking noise:Two monotonous, two dynamic masking noises and one placebo noise (recording of empty office)	Masking Preference	Rating scale, Interview	Users prioritized selecting pleasant, peaceful sounds, followed by those that were least disturbing, supported concentration, and effectively blocked external noise while avoiding monotony.
							Overall Satisfaction		74.4 % of participants rated the sound environment in the bubble created with PECS as an improvement, while 16.3 % noticed no difference and 9.3 % found it worse.
							Concentration, Occupants Interaction		The sound bubble created with PECS enhanced focus and concentration by masking unwanted noise while maintaining awareness of the surroundings.
[10]	Exp 1: 21 Exp 2: 57	No	LS	HP+ANC	Quiet without PECS (35 dBA)	Same as the quiet condition	Annoyance, Concentration, Perceived work/ study performance	Likert scale	Annoyance levels were significantly higher, while concentration and performance were lower compared to quiet condition.
				HP+ANC	Reference without PECS: Office conversation (56 dBA at listening Position) Exp 1: three speaker positions Exp 2: one speaker position	Same as the reference condition.	Annoyance		Perceived annoyance was reduced compared to the reference condition in both experiments.
							Disturbance		No significant differences in long-term disturbance were observed compared to reference condition.
							Concentration		The ability to concentrate was rated significantly higher compared to the reference condition.
							Perceived work/ study performance		No significant performance differences were observed compared to the reference condition in Experiment 1, but performance was higher in Experiment 2.
							Perceived loudness		Headphones reduced the perceived loudness of the speaker in both experiments compared the reference condition, with no significant difference between ANCon and ANCoff.

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Study	Sample size	User Control	Experiment type	Type of PECS	Baseline condition	Exposure (with PECS)	Category	Evaluation	Outcome
	Exp 1: 21			HP	Quiet without PECS (35 dBA)	Same as the quiet condition	Annoyance, Concentration, Perceived work/ study performance		Annoyance increased while concentration and performance decreased with headphones compared to quiet condition.
				HP	Without PECS Reference: Office conversation (56 dBA at the listening position) Exp 1: three speaker positions Exp 2: one speaker position	Same as the reference condition	Annoyance, Concentration, Perceived work/ study performance		No significant differences in annoyance, concentration, or performance were found compared to the reference condition.
							Perceived loudness		Headphones reduced perceived loudness of the speaker and increased perceived speaker distance due to the insertion loss effect.

*Type or work: LS – Lab Study; S – Simulation; FSS – Field Study Survey; FSM – Field Study with Measurements; FSMS – Field Study with Measurements and Survey; OS – Online Survey

**Type of PECS: HP – Headphones without noise cancelling; HP + ANC – Headphones with noise cancelling; HP + Masking – Headphones without noise cancelling and with masking; HP + ANC + Masking – Headphones with noise cancelling and masking.

Appendix B. Occupants' physiological response, cognitive response and speech perception

Study	Evaluation type	Sample size	Type of PECS*	Background condition	Exposure condition	Outcome
[29]	Short-term memory	24	HP + Masking	Quiet with PECS (no information), Reference with PECS (Speech varied between 33 dBA and 42 dBA to result in SNRs from −12 dB to 3 dB)	Ten mixed signals as maskers (Steady-state noise with −5 dB per octave slope and Speech-shaped steady-state noise), all 45 dBA (only the speech in the background varied)	The mean error rates with the stationary masking sound with −5 dB per octave spectrum were lower compared to unmasked speech (SNRs of −6, −9, and −12 dB).
[38]	Short-term memory	55	HP, HP + ANC, HP + Masking, HP+ANC+Masking	Reference without PECS (No headphones, Speech 52 dBA),	HP, HP+ANC, HP + masking (51 dBA), HP+ANC+masking (51 dBA).	PECS use did not influence the serial recall accuracy in general. However, the noise sensitive group had better accuracy in conditions 4 and 5 than the reference.
[39]	Short-term memory	33	HP + Masking	Quiet with PECS (below 30 dBA), Reference with PECS (Speech 35 dBA)	HP + masking (45 dBA - technical noise and water-based noise; harmonic, slowly fluctuations sounds)	Not statistically significant reduction in cognitive performance compared to the quiet condition. Statistically significant improvement in cognitive performance compared to the reference.
[31]	Short-term memory	24	Sound masking systems	Quiet without PECS (no information), Reference without PECS (36 dBA)	Pink noise masker at 45 dBA (varied the masker placement in the office).	Only −12 SNR (speech 33 dB masker 45 dB) scenarios performed better than the reference (statistically), while the quiet condition was significantly better than all other conditions.
[9]	Short-term memory	30	HP, HP + Masking	Quiet without PECS (25 dBA), Reference without PECS(Speech 55 dBA)	HP, HP + sound masking with natural content (55 dBA), HP + 7 sound masking signals with speech content (63.1 dBA)	No difference between the nature sound masking condition and the quiet condition,. However, the participants performed better in quiet compared to all other sound conditions. The participants were less distracted by background speech when it was masked by nature sound through headphones.
[12]	Short-term memory	32	HP, HP + ANC	Reference without PECS (Speech 70 dBA and Aircraft noise 65 dBA)	HP, HP + ANC	No improvement.
[10]	Short-term memory	21 and 57	HP, HP + ANC	Quiet without PECS (35 dBA), Reference without PECS (Speech 56 dBA)	HP, HP+ANC	No statistically significant effects of the ANC headphones on cognitive performance. The error rate in the

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Study	Evaluation type	Sample size	Type of PECS*	Background condition	Exposure condition	Outcome
						headphone conditions was neither statistically significantly lower in the condition HP nor in HP + ANC than the reference.
[21]	Speech perception	6 and 12	Sound masking system	Reference without PECS (Speech 50 dBA)	Three types of maskers (+ 5 dBA, + 7.5 dBA, + 10 dBA, + 12.5 dBA, + 15 dBA added to the reference for all maskers) (maskers: 1 - nature sounds and voices, 2 - air conditioning, and 3- pink noise)	Nature sounds provide the highest masking level. Speech intelligibility decreses by 20 % with SNR= −10 dBA, and is close to 0 % with SNR= −15 dBA.
[16]	Speech perception	30	HP, HP + ANC	Reference with PECS (Speech 25 dBHL) added equipment noise (25, 30, 35, 40, 45 and 50 dBHL); HL - hearing level	HP + ANC	The aim was to evaluate the ability to atenuate background noise (industrial) while maintaining communication between workers. - with SNR around −10 dB, HP and HP + ANC have similiar speech intelligibility scores (around 80 %); when SNR 0 dB and −5 dB, speech intelligibility with HP + ANC is 6–8 % lower than with just HP; with SNR −15, −20 and −25 dB, speech intelligibility 13 % to 32 % greater with HP + ANC compared to just HP.
[22]	Speech perception	8 and 10	Active noise barrier	Four maskers: pink noise, x time-reversed masker, target spectrum based masker, environmental noise (target-to-masker signals TMRs from −15 to 0 in steps of 5)	Four maskers: pink noise, x time-reversed masker, target spectrum based masker, environmental noise (target-to-masker signals TMRs 0, 5 dB, 10 dB, 15 dB)	Speech intelligibility is less than 10 % for all maskers when TMR is −10 and −15 dB; the time-reversed masker decreases speech perception with TMRs of −5 and 0 dB compared to the other maskers, and the environmental noise achieves similar results compared to the time-reversed masker when TMR is −5 dB (both below 20 %).
[20]	Speech perception	7 and 12	Sound masking systems	Speech at 55 dBA masked by white noise at 55, 60 and 65 dBA around participants ears. Different positions of the speakers were tested around the ears.	Different positions of the speakers were tested around the listeneŕs head	The masker at 55 or 60 dB(A), speech intelligibility is higher than 35 % (categorized as weak masking effect by the authors) and no significant influence of speaker positions around the ear; when the masker is played at 65 dB(A), speech intelligibility is about 35 % at most, regardless of the layout.
[43]	Focus level	62	HP + Masking (music)	Quiet with PECS (no information)	Two music playlists, One personalized soundscape	Personalized soundscapes significantly increased focus compared to the quiet condition, while music playlists did not show a significant effect on focus levels.

*Type of PECS: HP – Headphones without noise cancelling; HP + ANC – Headphones with noise cancelling; HP + Masking – Headphones without noise cancelling and with masking; HP + ANC + Masking – Headphones with noise cancelling and masking.

Appendix C. Monitoring studies

Study	Building	Type of PECS	Background condition	Method	Test	Product	Outcome
[25]	Industry	Earmuffs (five models)	Pink noise as continuous test signal in 90 dB	Insertion loss (IL) collected through microphone in the real ear (MIRE)	Personal attenuation rating (PAR): difference between the overall A-weighted unprotected exposure level and the overall A-weighted protected level. Compared the labelled and actual ILs in octave bands for the earmuffs.	No specification (Model A NR=20 dB, Model B NR=25 dB, Model C NR=25 dB, Model D NR=26 dB, Model E NR=30 dB); The variability in PAR values between individuals was not statistically significant ($p > 0.05$); The PAR values of earmuffs when a typical eyewear was worn differed statistically ($p < 0.05$).	Model A: PAR with eyewear 13.8 dB; without 16.5 dB. Model B: PAR with eyewear 9.4 dB; without 12.7 dB. Model C: PAR with eyewear 14.8 dB; without 17.2 dB. Model D: PAR with eyewear 16.4 dB; without 18.0 dB. Model E: PAR with eyewear 14.0 dB; without 16.2 dB.

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Study	Building	Type of PECS	Background condition	Method	Test	Product	Outcome
[36]	Industry	Earmuffs (one type), Earplugs (three types)	Less than 80 dB in the three tested settings	Noise Reduction (NR) collected through field microphone in the real ear (F-MIRE)	Workday monitoring - Personal attenuation rating (PAR) - Test if the participants were wearing the PECS properly by differences in attenuation from one ear to another. (If the sum of the binaural PAR dB and the statutory noise value in the workplace exceeded the setting standard for participating research factories, the result was a pass; otherwise, the result was a fail). Did not report attenuation values.	Classic roll-down foam earplugs.	Wearing it properly: test 1 - 78 % of 111 people; test 2 - 20 % of 29 people.
						Push-ins stemmed-style pod plugs.	Wearing it properly: 70 % of 23 people.
						Ultrafit pre-molded Earplugs.	Wearing it properly: 0 % of 7 people.
						Peltor X4A Earmuff	Wearing it properly: 100 % of 7 people.
[26]	Industry	Earmuffs (27 models)	Pink noise, no description of noise level	Real ear at threshold (REAT) method with subjects	Noise reduction	27 models of the commonly used earmuffs from five manufacturers: 3 M Peltor, Howard Leight, MSA, Hellberg, and JSP. Twentyfour models of earmuffs were available in a version with a head band, whereas three other models were attached to an industrial safety helmet	the mean values of the measured attenuation fall within the range from 24.7 to 33.1 dB for the 10 kHz frequency band, from 25.9 to 36.7 dB for the 12.5 kHz frequency band, and from 33.7 to 42.8 dB for the 16 kHz frequency band. The standard deviation of the measured sound attenuation was values within the range from 1.9 to 6.7 dB. insertion loss values measured using the acoustic test fixture are close to the results obtained with subjects in a restricted manner. In the case of the 10 kHz frequency band, for each of 27 earmuffs considered in the tests, the results obtained using the test fixture are never lower than the results obtained with subjects.
[18]	Industry	Earmuffs (used in four companies), Earplugs (used in four companies)	Different ambient noise over 8 companies. Company 8 - "severe noise levels, above 110 dBA"; Company 6 "from 90 dBA to > 100 dbA". Company 4 "ambient noise > 85 dBA".	Noise Reduction (NR) collected through field microphone in the real ear (F-MIRE)	Workday monitoring - Attenuation index (AI) from left and right ear	Peltor H7A Earmuff (companies 6 and 7)	company 6: "AI is different from the left to the right ear and is constantly below the range of values (…) and generally inversely proportional to the spectral balance." AI between 7–10 dB from 10:00 to 12:00.
						Sonomax molded earplugs (companies 1, 2, 4, 5)	company 4: Low attenuation values in the right ear before lunch break. it almost doubles after lunch, suggesting better earplug insertion in the afternoon. The first few minutes of the afternoon shift show high values of AI rapidly declining toward a more constant value. poor fit of the earplug causing the plug to 'lose' gradually its seal.

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Study	Building	Type of PECS	Background condition	Method	Test	Product	Outcome
						Oris Mustang EM-4155 Earmuff (company 3)	No specific results, just graphically comparing with all the others.
						Bilsom Thunder T3 and T3H Earmuff (company 8)	Evaluated the use of the earmuff combined with safety glasses. AI values increased to 5–8 dB after the glasses were removed. Much more AI fluctuations when the safety glasses were worn.
[15]	Industry	Earmuffs (Plastic foam cushion rings, metal or plastic head bands. Changed cupvolume: small, medium, large)	A-level (104.3–110.1) C-level (103.6–114.4); Three different companies	Predicted Noise Reduction (PNR) collected through microphone in the real ear (MIRE)	Workday moniroting - Predicted Noise Reduction	Small; From manufacturers: Attenuation by frequency: high f 26 dB; medium f 17 dB; low f 11 dB.	Company 1: 10.5 dB; Company 2: 6 dB; Company 3: 12.1 dB.
						Medium; From manufacturers: Attenuation by frequency: high f 30 dB; medium f 27 dB; low f 18 dB.	Company 1: 14.7 dB; Company 2: 13.7 dB; Company 3: 20.7 dB.
						Large; From manufacturers: Attenuation by frequency: high f 30 dB; medium f 26 dB; low f 17 dB.	Company 1: 22.5 dB; Company 2: 19.4 dB; Company 3: 24.7 dB.
[32]	Office	Chair with integrated loudspeakers	Chair with ANC on and off for four conditions: sine at 3 frequencies (200 Hz, 500 Hz, 800 Hz) and broadband noise (200 Hz)	Suppression in dBA	Placed a sound level meter on a dummy head in the chair, four microphones around the chair (out of the noise cancelling zone as the reference condition) and a sound source in a distance of around 3.2 m to measure the suppression	The authors developed the chair with integrated loudspeakers	Sine 200 Hz: 20.4 dBA; Sine 500 Hz: 29.7 dBA; Sine 28.2 dBA; broadband noise was 29.2 dBA, cancelling noise even above 1 kHz, but no suppresion under 300 Hz.
[35]	Not described	Metamaterial lens	With and without the metamaterial lens, no sound pressure level specified	Differences in Sound Pressure Level with and without the metamaterial lens	Lens type ($f = 150$ mm) positioning it in different distances (from around 1 to around 11 m) and different angles related to the source ($d = 4.34$ m tested from 50° to −70°)	The authors developed the metamaterial lens	The aim was to add sound with the metamaterial (i.e. auditorium). The sound pressure level is consistently larger with the metamaterial than without at every distance tested. The angle of divergence of the speaker (10 dB below the peak) was reduced from 60° to 27°

Data availability

Data will be made available on request.

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