



# Indoor soundscape, speech perception, and cognition in classrooms: A systematic review on the effects of ventilation-related sounds on students

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## ARTICLE INFO

### Keywords:

Classroom acoustic  
Classroom soundscape  
Ventilation  
Speech perception  
Cognition  
Indoor comfort

## ABSTRACT

Good air quality in classrooms, achieved through natural or mechanical ventilation, is necessary for students' health and cognition, but might simultaneously expose them to challenging sound environments, affecting learning and well-being. In this work we focused on the interaction between acoustics and ventilation modality and systematically reviewed the effects of sound stimuli related to ventilation on students' speech perception, cognition, and acoustic comfort.

Adopting the PRISMA guidelines, we selected 37 studies published after 1990, including students from primary school to university and assessing the impacts either of fan noise from mechanical ventilation or of sounds intruding into the classroom when windows are opened (i.e. traffic noise, aircraft noise, railway noise, human noise, sirens and construction noise, natural sounds). By comparison with a quiet baseline condition (no noise or low sound level), the effects were categorized as positive, null or negative.

Our systematic review showed a negative effect of fan noise. However, future research should better frame the result by including an integrated approach between acoustical and ventilation requirements. Concerning anthropogenic sounds entering the classroom in natural ventilation conditions, negative or no effects were generally observed, depending on the specific task and noise characteristics. On the contrary, natural sounds from open windows were found to consistently yield a positive effect on students' learning and comfort. Therefore, ventilation can sometimes improve the indoor soundscape depending on the context. The limitations of the currently available knowledge and under-investigated areas were outlined through the systematic review, which should be addressed in future studies.

## 1. Introduction

Good indoor air quality (IAQ) is essential in learning environments, as it can impact students' cognition [1], affecting both low-level [2] and high-level [3] cognitive functions, and health [4]. Proper IAQ is usually achieved through adequate ventilation, either by opening windows or through mechanical ventilation systems. The CO<sub>2</sub> concentration is generally used as a good proxy for assessing the effectiveness of ventilation [5,6], being an indicator for other bioeffluents and occupant-related contaminants, and also relatively easier to measure compared with most indoor air contaminants. Good IAQ is achieved in classrooms (for children) when the difference between outdoor and

indoor CO<sub>2</sub> concentration is less than 550 ppm [7]. Assuming a 400 ppm outdoor average CO<sub>2</sub> concentration, this means the indoor concentration should not exceed 950 ppm. This level prevents also detrimental impacts on students' cognition since impairments were observed for concentrations above 1000 ppm [8].

The role of ventilation in schools has become even more evident since the Covid-19 outbreak, as the improvement of ventilation was essential to prevent the spread of the virus. Guidelines have been issued by all the major associations working on IAQ (such as ASHRAE [9], REHVA [10], AICARR [11]), recommending achieving the number of air changes per hour expressed in standards [12] and guidelines [10]. This target can be obtained by increasing either the window opening time in

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<https://doi.org/10.1016/j.buildenv.2023.110194>

Received 5 January 2023; Received in revised form 22 February 2023; Accepted 7 March 2023

Available online 8 March 2023

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“naturally ventilated buildings” or the external air flow rates for “mechanically ventilated” ones. The distinction between natural ventilation (NV) and mechanical ventilation (MV) was made according to the definition in ANSI/ASHRAE STANDARD 62.2-2016 [13], where NV is defined as “ventilation occurring as a result of only natural forces, such as wind pressure or differences in air density, through intentional openings such as open windows and doors” and MV as “the active process of supplying air to or removing air from an indoor space by powered equipment such as motor-driven fans and blowers but not by devices such as wind-driven turbine ventilators and mechanically operated windows”.

The provision of NV and MV could change the acoustic environment of the classroom [14]. Indeed, either opening windows or equipping learning environments with ventilation units may lead students to greater exposure to louder and more frequent task-irrelevant sounds (TIS), which may affect learning and well-being. Nevertheless, the interrelationship between the different domains and requirements of indoor environmental quality is an aspect that is often overlooked by research, practice, and policy makers [15,16]. For instance, acoustic requirements for schools frequently assume that windows are closed when assessing indoor noise levels [17,18], while mechanical engineers assume windows are open when designing NV. As already highlighted in the literature for residential buildings [19,20], this lack of integration at the policy and design level leaves end-users with the burden of choosing which domain to prioritize at the expense of others, thus inadvertently forcing trade-offs which may lead to potential risks for health, well-being, and cognition.

Moreover, when investigating the acoustic impacts of ventilation in buildings (e.g., dwellings), the focus has traditionally been on the negative outcomes produced by noises [19]. A different perspective has recently been enlightened by research on indoor soundscapes [21] to investigate whether the presence of favourable sounds can improve the indoor acoustic environment [19] and students’ performance and cognition [22–24]. According to indoor soundscape research and practice, sounds are valued as meaningful events, characterized according to people perception in context, and employed as a design resource to mask noise, and to shape acoustically pleasurable environments [23]. However, given the negative impacts of sub-optimal acoustic conditions on pupils’ spoken language processing [25] and cognition [26] there might be the possibility that the use of positive sounds would jeopardize communication and learning in educational settings. Research is called to identify what are the students’ desired sounds [24] and to unravel their potential role to lead to positive outcomes in students’ performance and cognition.

Given the limitations resulting from the fragmented research and practice on acoustics and ventilation, and the perspectives set forth by indoor soundscape research on the use of positive sounds, a systematic literature review was conducted to answer the question: how do sound stimuli related to the ventilation of the classroom (positively and negatively) influence students’ learning and comfort?

In keeping with soundscape research, the literature review was conducted recognising the importance of the type of sounds that make up the acoustic environment and that determine the perceived acoustic quality of a place together with people’s affective response to it. Sound types were studied according to the type of ventilation, thus explicitly intersecting the domains of acoustics and ventilation. All sound stimuli generated by the fan of the ventilation unit or emitted by ducts, air outlets or intake terminals were categorized as belonging to MV (fan noise). Sound stimuli of NV, on the other hand, were defined as natural or anthropogenic sound stimuli that originate outside the school building and are brought inside through façade ventilation openings.

Regarding the impacts on students, the domains investigated were speech perception and cognition, both crucial for students’ learning but at the same time especially vulnerable to the negative effects of TIS [27]. In addition, comfort results were analysed to consider students’ perception of the environment, which is often investigated by research on indoor environmental quality and, more recently, soundscape. The

domains that have been included in the review are briefly introduced below.

### 1.1. Speech perception

The American Psychological Association (APA) Dictionary of Psychology [28] defines speech perception as: “the process in which a listener decodes, combines, and converts an incoming stream of otherwise meaningless sound created by the speech production process into a meaningful sequence and phonological representation”. Speech perception is the lowest level of spoken language processing, and it is supported by perceptual, linguistic, cognitive, and neurophysiological mechanisms [29]. As learning in schools occurs primarily through oral communication, it is vital that the sound environment is designed to allow students to accurately discriminate what the teacher or other classmates are saying amongst the other TIS. Research has been focused on this issue since long, and three main factors leading to a decrease in the outcome of speech intelligibility (i.e., percentage of words correctly perceived, that reflects the accuracy reached in the task) have been identified: 1) the transmission channel between the speaker and the listener [25,29], mainly influenced by the signal-to-noise ratio (SNR, difference between the sound level of the talker and the noise) and the reverberation time [30]; 2) the characteristics of the talker (e.g., presence of speech disorders [31], voice amplification systems [32]); and 3) the characteristics of the listener (e.g., presence of hearing impairments [33], non-native listener [34]).

It should be noticed that, even when the speech is highly intelligible, listeners might need to draw upon *effortful* cognitive processes, relying upon compensation strategies (i.e., allocate more attention, isolate the information) in order to complete the task [35]. Given the limited capacity of the human cognitive resources, this greater reliance on top-down processes will come at a cost of information processing and memorization [36]. The *listening effort* was defined in the Framework for Understanding Effortful Listening (FUEL) as the “deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a [listening] task” [37] and it is increasingly used besides accuracy in order to get insights into the mechanisms applied by the listeners to accomplish a speech perception task [38].

### 1.2. Cognitive abilities

In addition to negative effects on speech perception, suboptimal acoustic conditions have a major impact also on cognition and learning. A growing body of evidence over the last two decades [27,39] has led the World Health Organization (WHO) to list reduced well-being and quality of life, and cognitive impairment among the non-auditory effects of noise exposure [40]. Especially for school-age children, these effects can have lifelong consequences as the development of cognitive abilities is crucial not only for academic achievements but also for subsequent life chances [39].

On the one hand, suboptimal acoustic conditions hamper low-level cognitive functions (e.g., attention, memory), that are critical for academic foundation and significantly associated with students’ educational attainments and learning process [41,42]. On the other hand, excessive noise and/or prolonged reverberation were found to impact the performance in complex cognitive tasks (i.e., tasks that are underpinned by lower-level cognitive functions), like those usually performed by students at school (e.g., mental arithmetic, reading, writing). In the following, the impact of sound stimuli on both low-level cognitive functions and complex cognitive tasks will be considered.

### 1.3. Acoustic comfort

The study of the impact of environmental stressors on comfort has been traditionally at the centre of indoor environmental quality (IEQ) research. The very concept of comfort can be defined as “indoor

environment conditions that facilitate a state of satisfaction of bodily wants in occupants, based on their individual preferences and their given activity, and that limit physical stressors causing annoyance" [43]. If the traditional definition of comfort is linked to the absence of annoyance in building occupants, interpreted as passive receptors of steady environmental stimuli, recent research has moved to include aspects related to the dynamic exposure to (multi)sensory stimuli, and the active building-user interactions to target sensory pleasure, beyond sensory neutrality [21,24,44–46]. In the context of indoor soundscape research, 'comfort' resulted one of the two main dimensions explaining affective responses to indoor acoustic environments in residential buildings [23]. According to this model, affective responses to soundscapes can be analysed and represented in a comfort-content perceptual space, in which annoyance represents only the negative side of the comfort axis, and thus a very limited sub-area in a larger perceptual space to be investigated. In the following, the comfort construct will be intended in a broader sense, including aspects related to annoyance, satisfaction, single-domain and overall comfort, and sensory pleasure.

#### 1.4. Structure of the paper

Section 2 describes the search strategy for systematically identifying and selecting articles, and the criteria to process the retrieved information. In Section 3 the reader will find the results of this review and, in particular, a descriptive analysis of the papers identified (participants, domain and tasks, sound types and sound levels) and an analysis of how each type of sound stimulus might affect speech perception, cognition, and comfort. Finally, Section 4 provides a discussion of the effects of sounds related to natural and mechanical ventilation, including reference to previous literature, illustrates the limitations of the review process, gaps in the research analysed, and possible implications for the future research agenda.

## 2. Methods

A literature search was carried out to investigate the effects of sound stimuli related to MV and NV on students. The three domains of speech perception, cognition, and acoustic comfort were targeted.

The literature review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [47–49] to ensure a systematic approach to literature collection, analysis, and reporting. The statement is referred to as an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses and involves the use of a flow diagram and a checklist. Due to the heterogeneity of the studies, we conducted a systematic review but not a meta-analysis.

### 2.1. Eligibility criteria

The review includes: I1) Studies based on field campaigns carried out in school or university classrooms, or laboratory campaigns. As regards the latter, only studies recreating the 'physical' space of a classroom inside a laboratory or in virtual reality were considered. I2) Papers investigating the impact of sound stimuli on *speech perception*, *cognition*, and/or *acoustic comfort*. Studies investigating the students' listening effort were considered within the domain of *speech perception*. Among the broad set of *cognitive abilities*, the low-level functions of attention and memory, and the complex cognitive skills related to language and calculation were selected. Concerning the *comfort* category, all studies in which participants were asked to rate the perceived quality of the acoustic environment (e.g., global comfort, annoyance, pleasantness) were included. I3) With reference to the domain of *cognition*, tasks presented either in a visual or auditory modality. Both modalities were deemed eligible, as equally representative of the teaching/learning methodologies inside the classroom. I4) Studies investigating the impact on students of at least one TIS related to ventilation. Concerning NV, only those stimuli that are likely to be present in an urban environment

and therefore audible inside the classroom when opening the windows were considered. Notably, traffic noise (TN), aircraft noise (AN), railway noise (RN), human noise (HN), sirens and construction noise (SCN), and natural sounds (NS) were included. I5) Both studies investigating chronic and acute noise exposures, as the impact of noise on learning might depending on the interaction between type of exposure and task [50]. Studies focusing on chronic exposure consider TIS continuously and repeatedly listened to every day over a long period (i.e., months or years), and usually compare students attending schools in noisy areas (e.g., close to airports) and students going to schools in quieter areas. Studies focusing on acute exposure place the students in a highly controlled situation in which they have to perform a specific task while listening to TIS played-back through headphones or loudspeakers. I6) Peer-reviewed journal articles published in English after 1990.

We excluded: E1) Studies on the impact of the acoustic environment on pre-schoolers (children younger than five). E2) Papers investigating the effects of the classroom acoustic environment on students with hearing impairments. E3) Papers reporting only the results of acoustic measurement without performing subjective tests on at least one of the domains of interest (*speech perception*, *acoustic comfort*, and *cognition*). E4) Studies whose manuscript was not available. E5) Literature reviews were not included but investigated to avoid duplications.

All the inclusion and exclusion criteria are summarized in Table 1.

### 2.2. Literature search

A literature search was performed on the "Scopus" database in December 2021 to identify studies in the field of acoustics investigating the effect of sound stimuli ("nois\*" or "natural sound\*" or acoustic\*) on the different domains of interest ("ventilation" or "intelligibility" or "comfort" or "perception" or "listening effort" or "cognitive" or "student's performance") in a classroom environment ("school\*" or "university"). The complete research query was as follows: TITLE-ABS-KEY (("nois\*" or "natural sound\*" or acoustic\*) and ("ventilation" or "Intelligibility" or "comfort" or "perception" or "Listening Effort" or "cognitive" or "student's performance") and ("School\*" or "University")). Keywords such as "natural sound\*" and "ventilation" were chosen and placed in a specific group to avoid obtaining too many irrelevant results.

The selection procedure was based on title, abstract and eligibility criteria, according to the flow diagram depicted in Fig. 1.

**Table 1**  
Eligibility criteria used in the selection process of the articles.

INCLUSION CRITERIA	EXCLUSION CRITERIA
I1 – Field studies conducted in schools and universities, or laboratory tests recreating a classroom (in virtual reality or through school furniture).	E1 - Studies involving pre-schoolers (children younger than five).
I2 – Studies investigating the effect of sound events on the domains of <i>speech perception</i> , <i>cognitive abilities</i> , and <i>acoustic comfort</i> .	E2 – Papers investigating the effects of sound stimuli on students with hearing impairments.
I3 – Studies on cognition, in which the tasks were either auditory or visual.	E3 - Studies not including subjective tests on at least one domain between <i>speech perception</i> , <i>cognitive abilities</i> , and <i>acoustic comfort</i> (i.e., studies carrying out only objective measurements of the acoustic environment).
I4 – Studies assessing the impact on students of at least one ventilation-related sound stimulus.	E4 - Studies whose manuscript was not available.
I5 – Papers investigating the effect of either chronic or acute noise exposure.	E5 – Literature reviews.
I6 – Journal articles published after 1990 in English language	

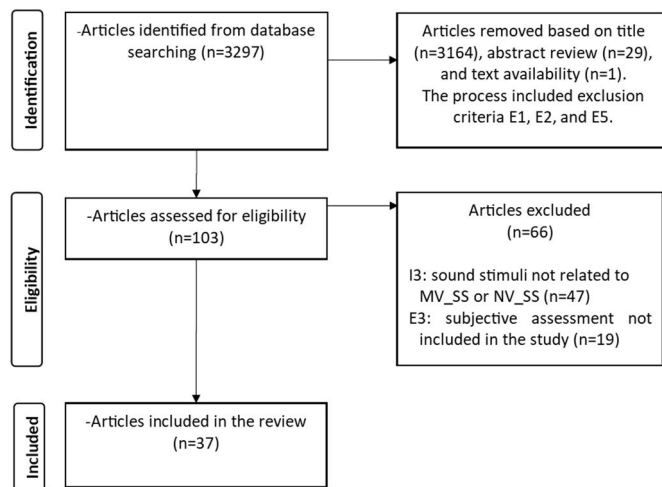


Fig. 1. PRISMA flow diagram for the identification of the studies via database.

### 2.3. Data extraction

The following information was extracted from the selected articles: 1) The modality of task administration (auditory or visual, only with reference to the domain of cognition). 2) The investigated TIS (e.g., TN, NS). 3) The TIS sound level or, for tasks presented in the auditory modality, the SNR. 4) The type of exposure (chronic or acute). 5) The specific task used in the experiment (e.g., with reference to speech perception, single-word repetition). 6) The outcome being assessed for each task (e.g., accuracy, response time) and the perceptual attribute investigated for the comfort domain (e.g., pleasantness, annoyance). A spreadsheet was compiled manually by the corresponding author. In case of uncertainty in the interpretation of data included in the original articles, the other authors were involved for collegial discussion.

### 2.4. Data analysis

In this review, we investigated how ventilation-related sounds affect speech perception, cognition, and comfort, by distinguishing between *positive*, *negative*, and *null effects*. The analysis procedure is described in the following.

In the first step, all the results referring to sounds not related to MV and NV were filtered out of the dataset. This is the case of studies assessing the impact of sound stimuli generated inside the classroom (e.g., children chatting) or inside the school building but outside the classroom (e.g., voices from adjacent classrooms).

After filtering the results, a baseline condition was identified for all the papers investigating speech perception and cognition. Depending on the study, we defined as “baseline” the condition with no sound stimuli added (for example, in laboratory studies), or the condition with the lowest sound level (for studies comparing the effect of the same TIS presented at different dB levels). By comparing the outcomes in a given listening condition against the baseline, it was possible to define the presence of a negative, positive, or null effect based on the statistical significance of tests reported in the reviewed studies (level of statistical significance:  $\alpha = 0.05$ ). For instance, a positive effect of TIS on speech perception was reported only when the improvement with respect to the baseline condition was confirmed by a statistical test in the original study; if the comparison was not significant, the effect of TIS was described as null.

Regarding comfort assessments, a comparative evaluation was not always possible, as several studies were missing a baseline condition. In these cases, the evaluation of the effect of a TIS on the comfort domain was carried out based on the appraisal given by the participants by the means of Likert scales (i.e., a negative effect was related to a negative

assessment on the Likert scale).

It should be noted that the effect of a TIS on one domain (e.g., speech perception) could differ depending on the specific outcome being investigated. For instance, exposure to a specific sound stimulus could simultaneously yield a positive effect on task accuracy and a null effect on response time. In the following, studies reporting at least one negative effect on a task outcome are classified as negative. Similarly, articles reporting at least one improved outcome, although the others were unchanged, are classified as positive. When all outcomes were unchanged, the study is classified as null effect.

## 3. Results

The literature search through the SCOPUS database returned 3297 papers. Based on titles and abstracts, a total of 3193 records was removed (3164 and 29, respectively). The removed items included review studies, and studies focusing on pre-schoolers or students with hearing impairment. One additional article was removed due to the unavailability of the text. After screening the full text, 66 out of 103 articles were further removed, due to the absence of subjective measurements in at least one of the three domains here considered ( $n = 19$ ) or the use of TIS not related to MV and NV ( $n = 47$ ). Thirty-seven studies published in the period from 1992 to 2021 were finally included in the review (see Table 2).

### 3.1. Qualitative summary of the extracted data

#### 3.1.1. Participants

The reviewed studies comprised listeners between the age of 5 and 58. The number of participants involved in each study ranged from 30 to 2844, with the larger sample sizes found in epidemiological studies such as the RANCH project [50–52].

#### 3.1.2. Domains and tasks

The studies that investigated the effect of sound stimuli on the three domains of speech perception, cognition, and acoustic comfort were 8, 23 and 15 respectively. Following the inclusion criteria I2, the domain of the cognition was further divided into the four subdomains of memory ( $n = 12$  studies), attention ( $n = 8$ ), language skills ( $n = 16$ ) and mathematical skills ( $n = 6$ ). Please notice that each study might have addressed several sub-domains, so that the number of studies reported for a specific domain might be higher than the number of reviewed studies (i.e.,  $N = 37$ ).

A variety of tasks was used to assess each domain (e.g., single-word repetition, phonological awareness, and sentence recognition in the case of speech perception). Tasks were presented in the auditory modality in all the studies on speech perception, in five studies on language skills and two studies on math skills. In the remaining studies, tasks were always presented in the visual modality. Concerning outcome measures, accuracy was assessed in 22 studies, while response time was assessed in 12 studies.

#### 3.1.3. Sound stimuli: types and levels

Traffic noise was the most studied stimulus ( $n = 25$ ), followed by aircraft noise ( $n = 11$ ) and fan noise ( $n = 9$ ). The least studied sound stimuli were human noise ( $n = 4$ ) and railway noise ( $n = 2$ ).

Overall, sound stimuli levels ranged from 30 dBA to 89 dB (the maximum measured level in dBA was 79). In the studies using an auditory presentation of the task, SNRs ranged from 0 to +10 dB, while the speech level ranged from 55 to 75 dBA (measured at 1 m distance from the source).

Finally, regarding the type of exposure, 13 papers analysed the effect of sound events during chronic exposure, while the remaining 24 analysed the effect during acute exposure. Notably, all but one of the studies on aircraft noise involved a chronic exposure, by comparing schools located in a quiet area with those located closer to an airport [51–59].

**Table 2**

Characteristics of the 37 studies included in this systematic review. The following information is given: 1) baseline number [Ref], 2) study population, including sample size (number of students or classes or schools), 3) task-irrelevant sound stimuli (TIS) used in the article, 4) listening condition, expressed as sound level, SNR or STI value. The condition used as baseline in the analysis is marked with an (r). If the sound level is measured outdoors (o), 5) type of students' exposure to background noise (acute or chronic), 6) domain and cognitive abilities analysed in the study, 7) task used to analyse a domain, 8) results of the task, 9) mode of task presentation (visual or auditory). Each task was performed in all listening conditions and sounds irrelevant to the task were expressed. In case of uncertainty between the listening conditions used for each TIS, the same superscript indicates the listening condition - TIS combination used in the article.

Study	Population (sample size)	Task-irrelevant sound stimulus	Listening condition	Type of exposure	Domain	Task	Outcome	Task presentation modality
Matheson et al., 2010 [50]	2276	Aircraft noise		Chronic	Memory	Recognition, conceptual recall, informational recall (Episodic memory)	Accuracy	Visual
		Traffic noise				Initial on specific points (Prospective memory)	Accuracy	Visual
Clark et al., 2006 [51]	2010	Aircraft noise <sup>a</sup>	Quiet area far from airport (r) <sup>a,b</sup>	Chronic	Language skills	Sentence comprehension	Accuracy	Visual
		Traffic noise <sup>b</sup>	30 ÷ 77 dBA (o) <sup>a</sup> 32 ÷ 71 dBA (o) <sup>b</sup>					
Clark et al., 2012 [52]	719	Aircraft noise <sup>a</sup>	Quiet area far from airport (r) <sup>a,b</sup>	Chronic	Language skills	Sentence comprehension	Accuracy	Visual
		Traffic noise <sup>b</sup>	34 ÷ 61 dBA (o) <sup>a,b</sup>		Memory	Recognition, conceptual recall, informational recall (Episodic memory)	Accuracy	Visual
Seabi et al., 2010 [53]	174	Aircraft noise	57 (r) (o)	Chronic	Language skills	Reading comprehension	Accuracy	Visual
					Attention	Toulouse Pieron (Attention)	Accuracy (overall, number of omission and commission error)	Visual
					Memory	Recognition, conceptual and informational recall (Episodic memory)	Accuracy	Visual
Haines et al., 2001 [54]	340	Aircraft noise	<57 dBA (r) (o) >66 dBA (o)	Chronic	Language skills	Reading comprehension	Accuracy	Visual
					Memory	Word recall after a week (Long term memory)	Accuracy	Visual
					Memory	Digit recall (Short term memory)	Number of digits	Visual
Stansfeld et al., 2005 [55]	2844	Aircraft noise <sup>a</sup>	<57 dBA (r) (o) <sup>a,b,c</sup>	Chronic	Comfort	Annoyance	Participant assessment (Likert)	Visual
		Traffic noise <sup>b</sup>	>66 dBA (o) <sup>a,b,c</sup>		Language skills	Reading comprehension	Accuracy	Visual
		Aircraft noise <sup>a</sup>	Quiet area far from airport (r) <sup>a,b</sup>		Attention	Toulouse Pieron (Attention)	Accuracy (overall, number of omission and commission error)	Visual
van Kempen et al., 2010 [56]	2844	Aircraft noise <sup>a</sup>	Quiet area far from airport (r) <sup>a,b</sup>	Chronic	Attention	Simple digit substitution (Attention)	Latency	Visual
					Attention	Simple reaction time (Attention)	Reaction time	Visual
					Memory	Switching attention	Accuracy (arrow and switching condition)	Visual
					Memory	Digit span test (Short term memory)	Span length	Visual

(continued on next page)

Table 2 (continued)

Study	Population (sample size)	Task-irrelevant sound stimulus	Listening condition	Type of exposure	Domain	Task	Outcome	Task presentation modality
van Kempen et al., 2012 [57]	553	Aircraft noise <sup>a</sup>	Quiet area far from airport (r) <sup>a,b</sup>	Chronic	Attention	Simple digit substitution (Attention)	Latency	Visual
		Traffic noise <sup>b</sup>	30 ÷ 77 dBA (o) <sup>a,b</sup>			Simple reaction time (Attention)	Reaction time	Visual
						Switching attention	Accuracy (arrow and switching condition)	Visual
				Memory	Digit span test (Short term memory)	Span length	Visual	
van Kempen et al., 2009 [58]	2844	Aircraft noise <sup>a</sup> Traffic noise <sup>b</sup>	Quiet area far from airport (r) <sup>a,b</sup> 32 ÷ 62.8 dBA (o) <sup>a,b</sup>	Chronic	Comfort	Annoyance	Participant assessment (Likert)	Visual
de Olivera Nunes and Sattler 2006 [59]	57 Schools	Aircraft noise		Chronic	Comfort	Annoyance	Participant assessment (Likert)	Visual
Prodi et al., 2013 [60]	47 Classrooms	Traffic noise	STI 0.1 ÷ 0.7 [0.7 r(O)]	Acute	Speech perception	Word recognition	Accuracy Response time	Auditory
Peng et al., 2016 [61]	60	Fan noise <sup>a</sup>	SNR 10 dB (level 60 dBA) (r) <sup>a,b,c</sup>	Acute	Speech perception	Mandarin Chinese test word list	Accuracy	Auditory
		Syrens and construction noise <sup>b</sup>	SNR 0 dB (level 70 dBA) <sup>a,b,c</sup>					
		Traffic noise <sup>c</sup>						
Klatte et al., 2007 [62]	23	Railway noise	SNR 26 dB (level 34 dBA: low-level continous noise) (r)	Acute	Speech perception	Word Identification	Accuracy	Auditory
			SNR 0 dB (59 dBA: unfiltered train)		Language skills	Sentence comprehension	Accuracy	Auditory
			SNR 26 dB (level 34 dBA: low-level continous noise) (r)	Acute	Language skills	Phonological Awareness	Accuracy	Auditory
			SNR 0 dB (59 dBA: unfiltered train) SNR 0 dB (61 dBA: filtered train)		Memory	Digit span test (Short term memory)	Span length	Visual
Lee and Khew 1992 [63]	105	Traffic noise	55 dBA (r) 60 dBA 65 dBA	Acute	Speech perception	Word identification	Accuracy	Auditory
Valente et al., 2012 [64]	90	Fan noise	SNR+10 dB (50 dBA) (r)	Acute	Speech perception Language skills	Sentence recognition	Accuracy	Auditory
			SNR+7 dB (53 dBA)			Classroom learning	Accuracy	Auditory
Visentin and Prodi 2021 [65]	159	Traffic noise	No added TIS (r)	Acute	Speech perception	Subjective assessment of effort in a speech intelligibility task	Effort	Auditory
			SNR 0 dB (60 dBA)		Language skills	Subjective assessment of effort in a sentence comprehension	Effort	Auditory
					Mathematical skills	Subjective assessment of effort in a calculation task	Effort	Auditory
Prodi et al., 2019 [66]	159	Traffic noise	No added TIS (r)	Acute	Speech perception	Low predictability sentence repetition	Accuracy Response time	Auditory
			SNR 0 dB (60 dBA)		Language skills	Sentence comprehension	Accuracy Response time	Auditory
Astolfi et al., 2012 [67]	983	Fan noise <sup>a</sup> Traffic noise <sup>b</sup>	STI 0.1 ÷ 0.8 [0.8 (r)] <sup>a,b</sup>	Acute	Speech perception	Diagnostic rhyme test	Accuracy	Auditory
Ljung et al., 2009 [68]	187	Traffic noise	No added TIS (r)	Acute	Language skills	Reading comprehension	Accuracy Reading time	Visual
			62 dBA		Mathematical skills	Mathematical Calculation	Accuracy	Visual
						Mathematical reasoning	Accuracy	Visual
Ding 2020 [69]	18	Traffic noise	30 dBA (r)	Acute	Language skills	Reading comprehension	Accuracy Reading time	Visual
			50 dBA 70 dBA		Comfort	Annoyance	Participant assessment	Visual
Papanikolaou et al., 2015 [70]	676	Traffic noise	55 ÷ 66 dBA (r) (o)	Chronic	Language skills	Reading comprehension	Accuracy	Visual

(continued on next page)

Table 2 (continued)

Study	Population (sample size)	Task-irrelevant sound stimulus	Listening condition	Type of exposure	Domain	Task	Outcome	Task presentation modality	
Chen and Ou 2021 [71]	42	Traffic noise	67 ÷ 77 dBA (o)	Acute	Mathematical skills	Mathematical Calculation	Accuracy	Visual	
			72 ÷ 80 dBA (o)		Language skills	Sentence comprehension	Accuracy	Auditory	
			40 dBA (r)		Comfort	Disturbance	Response time	Visual	
Evans et al., 1995 [72]	135	Aircraft noise <sup>a</sup>	No added TIS (r) <sup>a,b</sup>	Acute	Attention	Simple reaction time	Participant assessment	Visual	
		Traffic noise <sup>b</sup>	80 dBA <sup>a,b</sup>		Comfort	Annoyance	Reaction time	Visual	
			42 dBA (r) <sup>a,b</sup>				Participant assessment (Likert)	Visual	
Ronsse and Wang 2013 [73]	67 Classrooms	Fan noise	66 dBA <sup>a,b</sup>	Chronic	Language skills	Reading comprehension	Accuracy	Visual	
			78 dBA <sup>a,b</sup>			Mathematical skills	Mathematical Calculation	Accuracy	Visual
			90 dBA <sup>a,b</sup>			Language skills	Sentence comprehension	Accuracy	Auditory
Prodi et al., 2021 [74]	171	Traffic noise	33 ÷ 54 dB						
Proverbio et al., 2018 [75]	50	Natural sounds	[33 (r)]	Acute	Mathematical skills	Calculation	Accuracy	Visual	
Caviola et al., 2021 [76]	162	Traffic noise	No added TIS (r)	Acute	Mathematical skills	Calculation	Accuracy	Auditory	
Sepehri et al., 2019 [77]	24	Fan noise	SNR 0 dB (60 dBA)	Acute	Memory	2 back (Working Memory)	Accuracy	Visual	
			55 dBA (r)		Attention	Simple reaction time (Attention)	Response time	Visual	
Shu and Ma 2019 [78]	95	Natural sounds	65 dBA	Acute		Sustained attention	Accuracy (overall, number of commission and omission error)	Visual	
			75 dBA		Attention	Sustained attention	Response time	Visual	
			No added TIS 45 dBA (r)		Memory	Digit span test (Short term memory)	Span length	Visual	
Lee and Jeon 2013 [79]	20	Fan noise <sup>a</sup>	50 dBA	Acute	Memory	Word comprehension (Semantic memory)	Accuracy	Visual	
			Traffic noise level 35 dBA (r) <sup>a,b</sup>		Memory	Free recall (Episodic memory)	Accuracy	Visual	
			Traffic noise level 35 dBA+30 dBA <sup>a,b</sup>		Comfort	Annoyance	Participant assessment (Likert)	Visual	
Yang and Moon 2018 [80]	60	Syrens and construction noise <sup>b</sup>	Traffic noise level 35 dBA+40 dBA <sup>a,b</sup>	Acute	Comfort	Disturbance	Participant assessment (Likert)	Visual	
			Traffic noise level 35 dBA+50 dBA <sup>a,b</sup>				Participant assessment (Likert)	Visual	
			45 dBA (r) <sup>a,b</sup>				Participant assessment (Likert)	Visual	
Wen et al., 2019 [81]	120	Fan noise <sup>a</sup>	55 dBA <sup>a,b</sup>	Chronic	Comfort	Pleasantness	Participant assessment (Likert)	Visual	
		Natural sounds <sup>b</sup>	65 dBA <sup>a,b</sup>				Annoyance	Participant assessment (Likert)	Visual
		Traffic noise	75 dBA <sup>a,b</sup>				Annoyance	Participant assessment (Likert)	Visual
Silva et al., 2016 [82]	213	Syrens and construction noise		Chronic	Comfort	Annoyance	Participant assessment (Likert)	Visual	
		Human noise							
		Traffic noise							
Adbullah et al., 2021 [83]	96	Syrens and construction noise		Acute	Comfort	Annoyance	Participant assessment (Likert)	Visual	
		Human noise							
		Traffic noise							
Astolfi et al., 2019 [84]	367	Syrens and construction noise		Chronic	Comfort	Annoyance	Participant assessment (Likert)	Visual	
		Human noise							
		Traffic noise							
Yang and Moon 2019 [85]	60	Fan noise <sup>a</sup>		Acute	Comfort	Overall acoustic comfort	Participant assessment (Likert)	Visual	
		Natural sounds <sup>b</sup>	45 dBA (r) <sup>a,b</sup>						
			55 dBA <sup>a,b</sup>						
Chan et al., 2021 [86]	209	Fan noise <sup>a</sup>	85 dBA <sup>a,b</sup>	Chronic	Comfort	Pleasantness	Participant assessment (Likert)	Visual	
		Natural sounds <sup>b</sup>	75 dBA <sup>a,b</sup>						
			55.2 ÷ 73.55 dBA <sup>a,b,c,d,e</sup>						

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Table 2 (continued)

Study	Population (sample size)	Task-irrelevant sound stimulus	Listening condition	Type of exposure	Domain	Task	Outcome	Task presentation modality
		Traffic noise <sup>c</sup> Sirens and construction noise <sup>d</sup> Human noise <sup>e</sup>						

3.2. Effects of sound stimuli on speech perception

The domain of speech perception includes findings from listening tasks designed to assess reception and decoding of the auditory information. We found eight papers [60–67] assessing the effect of sound stimuli on student’s performance across different speech perception tasks, including sentence repetition (meaningful [64]; with low-predictability [65,66]), single-word repetition [60–63,67], and phonological discrimination [62]. The primary outcome for these studies was task accuracy (e.g., number of words repeated correctly). Three studies also addressed listening effort, either measured through the response time [60,66] or self-rated [65].

The majority of these studies focused on TN (n = 5), followed by fan (n = 3), SCN (n = 1), and RN (n = 1). Notably, no study investigated the effect of AN, NS and HN on students’ speech perception.

All the identified studies reported at least one negative effect on speech perception (Fig. 2).

3.2.1. Fan noise

Three studies explored the impact of noise from MV on the domain of speech perception. Valente et al. [64] and Peng et al. [61] analysed the effect of fan noise at two different SNR (7–10 dB and 0–10 dB, respectively), while Astolfi et al. [67] investigated the relationship between STI (range 0.1–0.8) and intelligibility. A worsening in students’ performance was consistently found as SNRs and STI decrease. Additionally, Valente et al. [64] and Peng et al. [61] investigated the combined effect of fan noise and classroom reverberation, showing that the effect of noise is stronger the longest the reverberation time of the classroom.

3.2.2. Traffic noise

Six studies [60,61,63,65–67] dealt with TN, reporting a significantly negative effect on students’ speech perception. Two studies [61,63], examined the effect of TN at different SNRs while both Prodi et al. [60]

and Astolfi et al. [67] investigated accuracy for different STI values. Prodi et al. [60] studied also how the response time was affected. In all of the studies a drop in student’s speech perception accuracy was reported as SNR and STI decreased [60,61,63]. Exposure to TN in comparison to a quiet condition was found to yield significantly lower accuracy [66] and higher self-ratings of effort [65] but did not impact response times [66]. Differently, a significant effect of TN on listening effort was found in Prodi et al. [60] where the combined change of classroom reverberation and noise level yielded significantly longer responses times as STI decreased.

3.2.3. Railway noise

The effect of RN on speech perception has been one of the least investigated, with only one study [62] reporting the effect of this type of noise on the accuracy of a word identification task. The RN was presented via headphones at a level of 59 dBA and compared to low-level continuous noise played at 36 dBA. The Authors found that RN reduced the accuracy of the speech perception task.

3.2.4. Sirens and construction noise

The effect of SCN on speech perception was investigated only in one study. Peng et al. [61] analysed the effect of piling noise (impact noise characterised by a large amount of energy in a short period of time) at two SNRs (0 and 10 dB), while keeping the target stimulus level at 70 dBA. A negative effect on speech perception accuracy was found when switching from +10 to 0 dB SNR, that was stronger for longer reverberation times.

3.3. Effects of sound stimuli on language skills

Within the studies investigating noise effects on cognition, 16 papers [51–55,62,64–66,68–74] addressed the impacts on listening/reading comprehension, intended as the ability to understand complex verbal or written information, and phonological awareness, a pre-reading skill. The tasks used to assess listening comprehension were sentence comprehension [62,65,66,71,74], and classroom learning [64], while for reading comprehension both standardised [51–55,72,73] and non-standardised tests were employed [68–70]. The main outcome was the accuracy of the answers [51–55,62,64,66,68–74], together with the response time for sentence comprehension [66,71,74], the reading time [68,69], and the self-assessment of effort [65]. The TIS investigated in the reviewed studies were traffic (n = 10), aircraft (n = 6), fan (n = 2), and railway noise (n = 1). As concern the effects of TIS on language skills, Fig. 3 show the number of the papers reporting a positive, negative, or no effect. The majority of the papers reported at least one negative effect for a specific TIS (n = 11), while in the remaining ones (n = 7) only null effects have been identified. In the following lines a more accurate description of the effect is provided for each TIS.

3.3.1. Fan noise

Two studies [64,73] investigated the effect of fan noise on language skills finding a negative effect on the students’ performance. Valente et al. [64] used a classroom-learning task, in which participants listen to a teacher and some students reading a story and then are asked to answer some questions. The experiment was conducted under two different SNRs (+10 and +7 dB). The Authors found a negative effect of

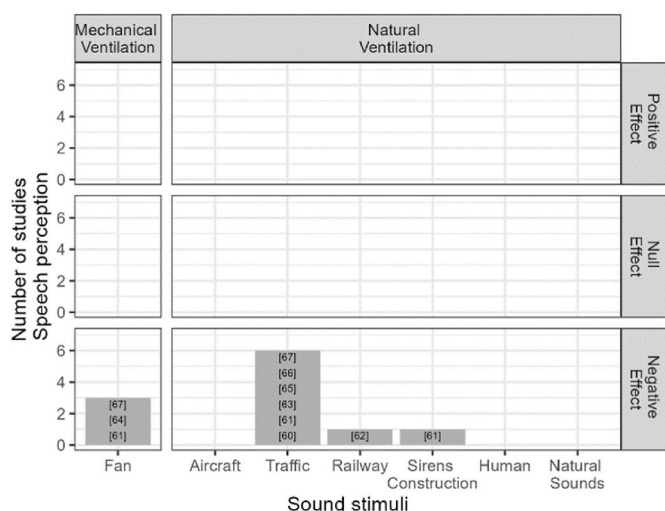


Fig. 2. Distribution of the studies investigating the effect of sound stimuli on speech perception. The Y-axis shows the number of studies reporting positive, null and negative effects. Numbers indicate the reference of the study.



SNR on task accuracy, with a significant drop in the number of correct answers when increasing the noise level. The second record [73] investigated how the chronic exposure to the noise generated by a HVAC system affects reading comprehension and found a negative correlation between the noise level (range: 33–54 dBA) and the students' score in a standardised test (State Accountability test).

### 3.3.2. Aircraft noise

Five studies focused on the impact of AN on reading comprehension [51–55], evaluated by means of standardised tests (i.e., Suffolk reading scale 2). The highest measured noise level was 77dBA [51,55] while, in the other works, it reached 66–68dBA. Chronic exposure to AN prompted a significant decrease in test scores according to four of the reviewed studies [51–53,55] whereas Haines et al. [54] found no significant differences between children attending schools next to airports and the ones in quieter areas.

### 3.3.3. Traffic noise

TN was the most studied sound stimulus, with ten articles investigating its effect on language skills [51,52,55,65,66,68–71,74].

Six studies focused on a reading comprehension task, using as outcome only accuracy [51,52,55,70] or both accuracy and reading time [68,69]. The former group investigated the effects during chronic exposure to traffic noise (levels ranging between 30 and 80dBA). The latter examined acute exposure, playing back recorded TN at different levels during the task (66dBA measured 2 m away from the speaker [68]; 30, 50 and 70dBA [69]). A decrease in comprehension performance with increasing TN level was found in Ding [69] and in Papanikolaou et al. [70], but not in the other studies [51,52,55,68]. Inconsistent results were also found regarding the effects of TN on reading time, which was found to increase [68] or not change [69] with the worsening of the listening conditions.

Four studies examined the effect of TN on listening comprehension [66,71,74] and self-reported effort [65]. The TN level was between 40 and 55dBA in Chen and Ou [71] and 60 dBA in the rest of the identified papers. Both negative [71] and null [66,74] effects of the noise on task accuracy were found, whereas as concern the response time, no effect was identified [66,74]. Finally, TN exposure was found to increase self-reported effort [65] when compared to a quiet condition.

### 3.3.4. Railway noise

One study [62] investigated the impact of RN on speech comprehension and phonological awareness. A train recording with a level of 59

dBA was played during sentence comprehension, while in the phonological task the authors used RN both as recorded and in a filtered version (frequency <200Hz lowered by 12 dB). In the filtered RN, the level was raised to 61 dBA. In both tasks, the accuracy results were compared with those obtained by the students in a reference condition (low-level continuous noise at 36 dBA). No differences emerged between the listening conditions in either task.

### 3.4. Effects of sound stimuli on mathematical skills

Six studies investigated the effect of sound events on mathematical skills [65,68,70,73,75,76]. The studies typically analysed the performance in the mathematical calculation, while Ljung et al. [68] employed also mathematical reasoning and geometrical problems. The main outcome investigated was the accuracy in the task, but findings on the response time in the calculation task [75,76] and the self-reported effort [65] were identified as well.

Regarding the distribution of the sound stimuli, TN was the most frequently analysed (n = 5), followed by fan noise (n = 1) and NS (n = 1). Sound stimuli levels ranged between 54dBA and 89 dB, with most of the studies reporting a level in the range from 54 to 62dBA [65,68,73,76].

All the three types of effect were documented, with one study reporting a positive effect, two stating that TIS does not affect mathematical skills, and three showing a negative effect. The distribution of studies by sound stimuli and their effect on mathematical skills is depicted in Fig. 4.

#### 3.4.1. Fan noise

Only Ronsse and Wang [73] investigated the effect of noise from an HVAC system on calculation. The Authors presented the students with a standardised Terra Nova test while the noise level ranged between 33 and 54 dBA. No effect of the sound stimulus on mathematical abilities was detected.

#### 3.4.2. Traffic noise

Four studies evaluated the impact of TN on mathematical skills, by considering calculation [68,70,76], reasoning and geometrical problems [68], and self-reported effort in calculation [65]. Papanikolaou et al. [70] analysed the effect of chronic outdoor exposure up to 80 dB, while the rest of the studies focused on the effect of acute exposure in the 60–62 dBA range. An auditory presentation of the calculation task was employed by Visentin and Prodi [65] and Caviola et al. [76].

No consensus was found concerning noise effects on calculation accuracy, as both negative effects [68,70] and no effect [76] were reported. Furthermore, exposure to TN did not affect calculation time [76] or reasoning [68], whereas it negatively affected both geometric tasks [68] and the self-ratings of effort [65].

#### 3.4.3. Natural sounds

The effect of the sound of the rain on mathematical calculation was investigated in Proverbio et al. [75]. Participants were presented with a mathematical operation and a possible result, e.g., “7 + 5 = 13”, and had to state if the result was correct or not. During the test, participants listened to silence or rain condition via headphones at 89 dB. Both accuracy and response time improved in presence of rain sound.

### 3.5. Effects of sound stimuli on attention

Seven studies [53,55–57,72,77,78] examined the effect of sound stimuli on attention. Five different standardised tasks were used in the examined studies: *Toulouse Pieron* [53,55], *Simple reaction time* [56,57,72,77], *Digit substitution* [56,57] *Switching attention* [56,57] and *Sustained attention* [77,78]. Depending on the task, the investigated outcomes might be accuracy of the task, expressed as the number of correct answers or the number of errors (commission and omission), reaction

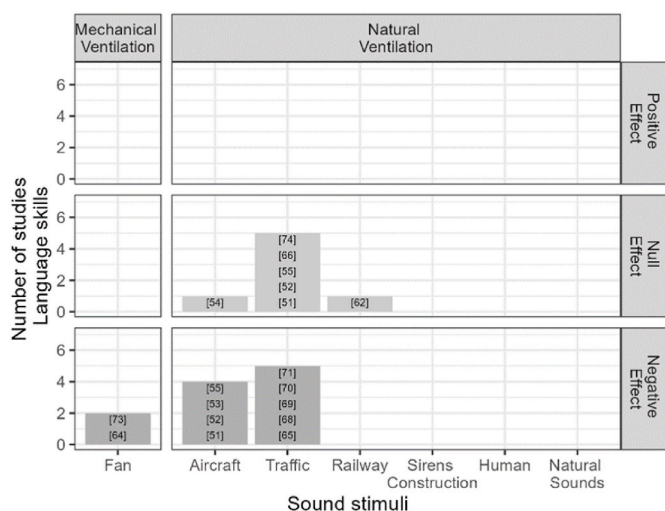


Fig. 3. Distribution of the studies investigating the effect of sound stimuli language skills The Y-axis shows the number of studies reporting positive, null, and negative effects. Numbers indicate the reference of the study.

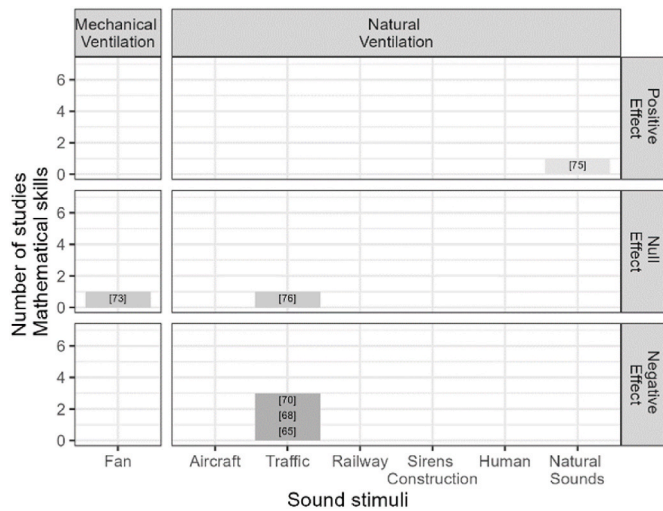


Fig. 4. Distribution of the studies investigating the effect of sound stimuli on mathematical skills. The Y-axis shows the number of studies reporting positive, null, and negative effects. Numbers indicate the reference of the study.

time, or latency. Regarding the types of sound stimuli analysed, the focus was most often on AN (n = 5), followed by TN (n = 4), fan noise (n = 1) and NS (n = 1). Sound levels ranged from 55 to 80dBA with a prevalence of chronic exposure (n = 5). As concerns the TIS effect on attention, a prevalence of studies reporting at least one negative effect (n = 6) were found among the analysed TIS. Evidence was found also for null (n = 4) and positive (n = 1) effects. Fig. 5 show the distribution of the studies among the three effects for the attention.

### 3.5.1. Fan noise

One study [77] focused on the effect of fan noise on students' attention. Participants performed a simple reaction time task and a sustained attention task under nine environmental conditions, resulting from the combination of three noise levels (55, 65, 75dBA) and three temperatures (14, 18, 22 °C). Results showed that as the noise level increased, students' attention decreased, as showed by longer reaction times, lower overall accuracy, and increased commission errors. The effect of the sound stimulus was even stronger when participants were exposed to lower temperatures.

### 3.5.2. Aircraft noise

Five studies [53,55–57,72] analysed the effects of AN on students' attention. *Simple reaction time* [56,57,72], *Attention switching* [56,57] *Toulouse Pieron* [53,55], and *Digit substitution* [56,57] were analysed. Within the reviewed studies, simple reaction times and digit substitution tasks were not affected by AN [56,57,72], whereas the number of errors in attention switching increased [56,57]. Finally, the Toulouse Pieron task was differently affected by AN across the reviewed studies. Seabi et al. [53] reported an increase in the number of omission errors, while Stansfeld et al. [55] did not found any effect on any of the outcomes (global accuracy, omission, and commission error).

### 3.5.3. Traffic noise

Four studies [55–57,72] examined the effects of TN exposure on attention. Similarly to the findings for AN (see 3.5.2), the results showed no effect of TN on simple reaction time, digit substitution, and Toulouse Pieron task [55–57,72] while more errors occurred in the attention switching task [56,57].

### 3.5.4. Natural sounds

One study investigated the effect of NS on sustained attention [78], with a focus on the restorative potential of NS. Students performed the task in silence, then listened to birdsong and water-related sounds

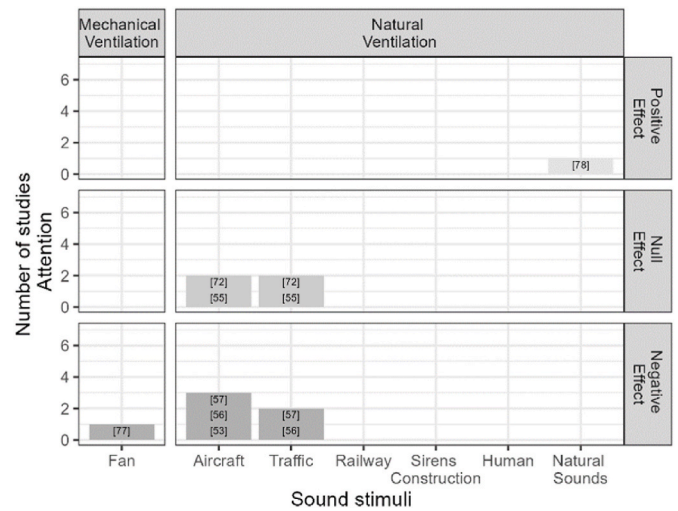


Fig. 5. Distribution of the studies investigating the effect of sound stimuli on attention. The Y-axis shows the number of studies reporting positive, null, and negative effects. Numbers indicate the reference of the study.

(fountain and stream) and performed the task in silence again. After being exposed to NS, the students had shorter response times, whereas no effect was evident on the overall accuracy and the number of errors of omission and commission. Water-related sounds were found to have a greater restorative effect, as they yielded the shortest response times.

### 3.6. Effects of sound stimuli on memory

Fig. 6 shows the distribution of studies reporting positive, no and negative effects on students' memory by sound stimuli. Null effects are the most occurring among the TIS employed in memory tasks with eight studies reporting a null effect, followed by negative effects (n = 6) and positive ones (n = 3).

Six types of memory were investigated in the reviewed studies: *long-term* [54], *short-term* [54,56,57,62,78], *working* [52,53,55,77], *episodic* [50,52,53,55,79] *prospective* [50,55] and *semantic* [79]. Effects on memory were typically assessed in terms of accuracy, either overall accuracy or, in the case of episodic memory, relative to each of its three constituent aspects (recognition, conceptual recall, informational recall). In the case of short-term memory tasks, results were expressed in terms of number of digits recalled in the correct order by the participant.

Within the reviewed papers, most studies focused on AN (n = 7) and TN (n = 5), followed by fan noise (n = 2), and SCN, RN and NS (n = 1), while no study addressed the effects of HN on memory. The sound stimuli level ranged from 30 to 77dBA, with the highest levels found in the studies of the RANCH project [50–52,55–57].

#### 3.6.1. Fan noise

Within the selected studies, one paper addressed noise effects on episodic and semantic memory [79] and one on working memory [77]. Regarding episodic and semantic memory, Lee, and Jeon [79] studied the accuracy of responses when fan noise was added to a reference condition (TN at 30dBA) at three sound levels (30, 40, and 50dBA). Results showed that the addition of fan noise at 40 and 50dBA significantly impaired the accuracy of the episodic memory task, whereas semantic memory was unaffected, regardless of the level. Concerning working memory, Sheperi et al. [77] considered nine environmental conditions obtained by combining fan noise played at three levels (55, 65, 75dBA), and three different temperature conditions (14, 18, 22 °C). They found that increasing the noise level reduced the task accuracy at all temperatures, while longer response times were only found with the highest temperature.

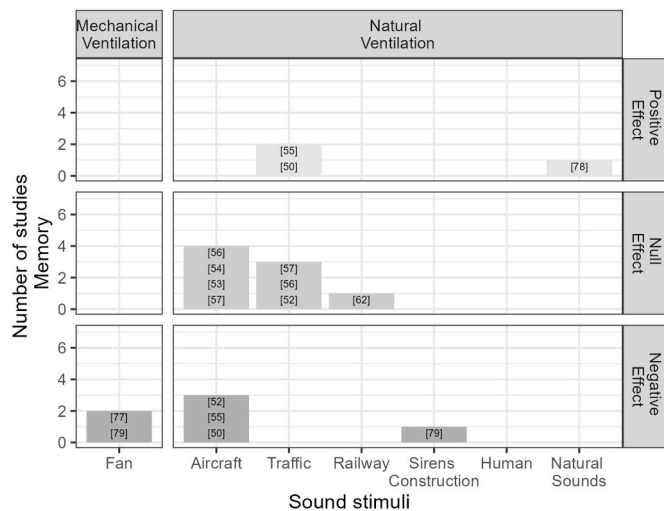


Fig. 6. Distribution of the studies investigating the effect of sound stimuli on memory. The Y-axis shows the number of studies reporting positive, null, and negative effects. Numbers indicate the reference of the study.

### 3.6.2. Aircraft noise

Five types of memory, namely long-term [54] and short-term memory [54,56,57], prospective [50,55], episodic [50,52,53,55], and working memory [52,53,55], were investigated in relation to AN exposure at levels between 30 and 77dBA. Only episodic memory was found to be affected by AN, while no effects were consistently reported for all other memory types [50,53–57]. Concerning the effect of AN on episodic memory, controversial results have been found, with studies reporting either no effect [53], a negative effect on conceptual and information recall, but not on recognition [52], or the opposite [50,55].

### 3.6.3. Traffic noise

Five studies [50,52,55–57] addressed the effect of TN on students' memory with reference to chronic exposure. Four types of memory have been investigated: long-term [54] and short-term memory [56,57], prospective [50,55], episodic [50,52,55] and working memory [52,55]. Noise levels ranged from 30 to 77dBA. None of the selected works showed negative effects due to TN. On the contrary, a positive effect (better accuracy) was found for informational and conceptual recall [50, 55].

### 3.6.4. Railway noise

One work addressed the effects of RN on short-term memory by analysing the number of correct digits in a digit span test [62]. Participants performed the task while listening to filtered and as-recorded RN (see 3.3.4) via headphones at a sound level of 61 and 59dBA respectively. The Authors reported no effects of the sound stimuli on short-term memory.

### 3.6.5. Sirens and construction noise

Lee and Jeon [79] analysed the effect of construction noise on episodic and semantic memory, where SCN was added to a reference condition with TN played at 30dBA. Three levels of SCN (i.e., 30, 40 and 50dBA) were employed for the task. Results showed a negative effect on episodic memory when construction noise was added at a level of 40 and 50dBA, while no effect was found on semantic memory, thus showing similar patterns of influence to those reported for fan noise (see 3.6.1).

### 3.6.6. Natural sounds

Within the reviewed studies, only one paper investigated the restorative effect of NS (bird songs and water-related sounds) on short-term memory [78]. The study showed that students were able to remember correctly longer series of digits when previously exposed to

natural sounds. Longer series occurred with water-related sounds, compared to bird songs.

### 3.7. Effects of sound stimuli on acoustic comfort

Fifteen studies [54,55,58,59,69,71,72,79–86] investigated the effect of sound stimuli on the domain of the acoustic comfort. In six of the 15 studies, participants assessed acoustic comfort after acute exposure to a specific stimulus [69,71,72,79,80,85], while in the rest of the studies [54,55,58,59,81–84,86] the assessment was made based on chronic exposure. Participants' ratings of the acoustic environment were collected through Likert scales built around different perceptual constructs, i.e., *overall acoustic comfort* [85], *pleasantness* [80,86], *annoyance* [54,55,58,59,69,72,79–84], and *disturbance* [71,79].

The most investigated stimulus was TN ( $n = 9$ ), followed by SCN and fan noise ( $n = 6$ ), AN ( $n = 5$ ), HN ( $n = 4$ ), NS ( $n = 3$ ), and RN ( $n = 1$ ). The sound level varied between 30 and 77dBA.

Fig. 7 shows the distribution of studies among the TIS by the type of effect on acoustic comfort. All type of effects were identified. A total of four studies reported positive effects, seven documented null effects, and 21 reported at least one negative effect.

#### 3.7.1. Fan noise

Four studies analysed the effect of fan noise on the comfort domain [79,80,85,86], in terms of overall acoustic comfort, pleasantness, annoyance, and disturbance. Noise levels ranged between 45 and 75dBA in Yang and Moon [80,85], while in Lee and Jeon [79] fan noise was added to a reference condition with traffic noise ( $L_{\text{Traffic}} = 30\text{dBA}$ ) at three different levels ( $L_{\text{Fan}} = 30, 40, 50\text{dBA}$ ). Results showed a decrease in overall acoustic comfort [85] and pleasantness [80], and an increase in annoyance and disturbance [79] in presence of fan noise. A null effect on annoyance was also found, due to the equal distribution between participants who were satisfied with hearing fan noise and those who were dissatisfied [86].

#### 3.7.2. Aircraft noise

Five studies investigated the effect of AN on annoyance [54,55,58, 59,72]. Four papers [54,55,58,59] compared the evaluation given by students near and far from an airport (noise level near the airport  $>66\text{dBA}$ , far  $<55\text{dBA}$ ) using standardised questionnaires, while Evans et al. [72] assessed students' annoyance to an burst played at 80dBA. The studies consistently reported that students are annoyed by AN.

#### 3.7.3. Traffic noise

TN effect on comfort domain was analysed in several papers including both acute [71,72] and chronic exposures [54,55,58,81,82,84, 86]. Consensus among studies was not found, as TN exposure was reported to increase annoyance [55,58,72,81,84], and disturbance [71], to have no effect [54,82], or even to provide a positive effect on the comfort domain [86].

#### 3.7.4. Railway noise

Haines et al. [54] addressed the annoyance rating related to RN exposure. Results showed that RN did not influence students' annoyance, as there was no difference in ratings between students attending schools in noisy areas, located closer to the airport, and those in quieter areas, located further away from the airport.

#### 3.7.5. Sirens and construction noise

Several studies addressed the impacts of urban sound environments including sirens [81–84] and construction noise [79,81,82,86] on the comfort domain. No information is generally available regarding the sound level in papers reporting effects under chronic exposure [81–84, 86]. As regards the study by Lee and Jeon [79] please refer to section 3.7.1. The noise of sirens was found to be detrimental to the acoustic comfort in three out of four studies [81,83,84], resulting in higher

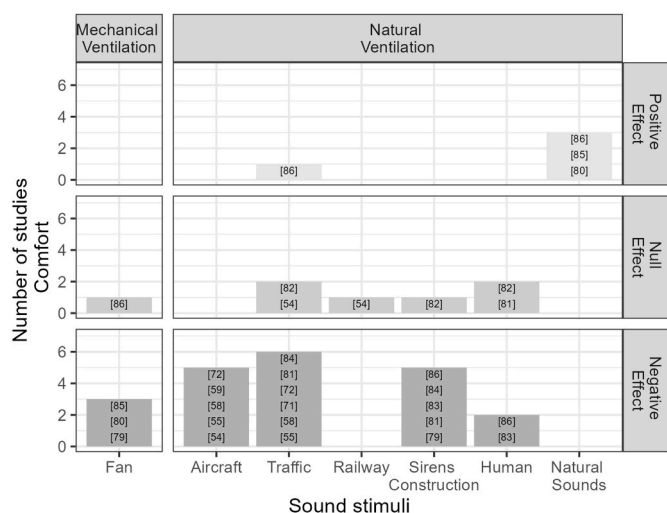


Fig. 7. Distribution of the studies investigating the effect of sound stimuli on comfort. The Y-axis shows the number of studies reporting positive, null, and negative effects. Numbers indicate the reference of the study.

annoyance assessments. Exposure to construction noise was found to increase annoyance [79] and decrease pleasantness [86]. However, studies reporting none or little annoyance (null effect) on construction noise [81] and on construction noise and sirens [82] were also found.

### 3.7.6. Human noise

Four studies [81–83,86] investigated the effect of a chronic exposure to HN on acoustic comfort. Two main types of HN were identified: children playing in the playground [82,86] and noise generated by people in the street [81,83]. As regards the evaluated constructs, the studies mainly investigated annoyance [81–83] and, to a lesser extent, pleasantness [86]. The sound of children playing was found to negatively affect pleasantness [86] but not annoyance [82]. As regards the effect of noise from people in the street on the comfort dimension, either a negative effect [83] or a null effect [81] on noise annoyance was reported.

### 3.7.7. Natural sounds

Three studies addressed the impact of being exposed to natural sounds on acoustics comfort in terms of annoyance [80], pleasantness [80,86] and overall acoustic comfort [85]. Within the reviewed studies, the sound stimuli level ranged from 35 to 75dBA in Yang and Moon. [80, 85], while no information was available in Chan et al. [86]. NS were generally perceived as pleasant [80,86], not annoying [80], and able to provide a well-rated overall acoustic comfort [85]. The ratings of NS were found to depend on their level following a U-shaped relationship, with greater annoyance and lower acoustic comfort being associated with higher sound levels [80,85] and maximum pleasantness reported at 45 dBA [80].

## 4. Discussions

The need to ensure proper ventilation in classrooms has received increasing attention since the outbreak of the COVID pandemic. The issue cannot be tackled in isolation, but needs to be framed into a broader perspective, by considering the interaction between the different domains pertaining to indoor environmental quality. In this work we focused on the interaction between acoustics and ventilation.

Table 3 provides an overview of the types of sound together with their impacts (i.e., negative, null, positive) on the considered domains (i.e., speech perception, language skills, math skills, attention, memory, comfort), thus highlighting the domains most often studied and those on which future research is needed. In the following, the effects of each type

of sound related to the two ventilation strategies (MV and NV) are summarized and discussed, outlining limitations and future research perspectives.

### 4.1. Effects of stimuli generated by MV on students

The results of our systematic review point toward a negative effect of fan noise on the domains here investigated (see Table 3), thus stressing that MV in classrooms is critical from the acoustics point of view. However, these findings should be considered in light of two main limitations. The first relates to the low number of studies addressing each domain, especially regarding the sub-domains of cognition, where, in some cases, results are brought about by only one study. This prevents the generalization of the findings, that might specifically refer to the task and listening conditions selected for the single study. The second limitation concerns the MV-related noise levels tested in the reviewed studies. In half of the cases, the baseline condition referred to a fan noise level of 50dBA or more, and thus well above the limit of 35dBA indicated by standards on the acoustic quality of classrooms [17,87,88]. Lower impacts are likely to be found under listening conditions closer to those recommended by the standards. However, consideration must be given to whether adequate air exchange could still be ensured while meeting the recommended noise levels. For instance, measurement campaigns conducted in university classrooms reported sound levels due to mechanical ventilation between 37.8 and 46dBA [89,90]. In the study by Serpilli et al. [89], these levels were measured in halls for 150 persons at flow rates of 900 and 1200 m<sup>3</sup>/h, thus below the 36 m<sup>3</sup>/h per person (i.e. 10 l/s per person) that are recommended for a good IAQ [12]. This points once again to the urgency to consider the issues of good ventilation and good acoustics in classrooms holistically. While low noise levels generated by HVAC systems are desirable to limit noise-related impacts on students, as recommended by acoustic regulations, technologies must be available and implemented to ensure at the same time proper air exchange, thus preventing negative effects on students due to high pollutant concentrations, as recommended by IAQ standards.

### 4.2. Effects of stimuli related to NV on students

#### 4.2.1. Aircraft noise

Aircraft noise was analysed among the reviewed studies almost exclusively in its chronic exposure effects, comparing schools near airports with those in quieter areas, assessing the impact only for non-auditory tasks. Students chronically exposed to aircraft noise exhibited lower performance in reading comprehension and reported being more annoyed. As regards attention and memory, studies revealed mixed results with a strongly task-dependent effect. Despite the knowledge provided by recent reviews dedicated to noise pollution and human cognition [26], an explanation for this discrepancy is still lacking.

Some limitations can be identified in the reviewed studies concerning the type of tasks investigated and the reported noise levels. Notably, no studies were found on the impact of aircraft noise on mathematical skills and speech perception, and most of the studies reported external and not internal sound levels, thus lacking information on the actual exposure conditions of students in the classroom. These limitations and research gaps will result in suggestions for the future research agenda in the field of classroom acoustics and ventilation, as discussed in section 4.3.

#### 4.2.2. Traffic noise

The impact of traffic noise on students was studied extensively (by 67.5% of the articles reviewed), being one of the most frequent sources of noise in both urban and suburban contexts and one of the main sources of concern by EU policy makers [91].

Among the analysed sound types, traffic noise is the one for which impact data is available on all domains, with several studies for each of them. The nature of effects is highly dependent on the domain studied,

**Table 3**

Effects of the sound stimuli on the different domains, as found in the reviewed studies. The reference of each study is indicated within brackets.

Sound stimulus	Effect	Speech perception	Cognition				Comfort
			Language skills	Math skills	Attention	Memory	
Fan noise	Positive	-	-	-	-	-	-
	Null	-	-	[73]	-	-	[86]
	Negative	[61,64,67]	[64,71]	-	[77]	[77,79]	[79,80,85]
Aircraft noise	Positive	-	-	-	-	-	-
	Null	-	[54]	-	[55,72]	[53,54,56,57]	-
	Negative	-	[51-53,55]	-	[53,56,57]	[50,52,55]	[54,55,58,59,72]
Traffic noise	Positive	-	-	-	-	[50,55]	[86]
	Null	-	[51,52,55,66,74]	[76]	[55,72]	[52,56,57]	[54,82]
	Negative	[60,61,63,65-67]	[65,68-71]	[65,66,70]	[56,57]	-	[55,58,71,72,81,84]
Railway noise	Positive	-	-	-	-	-	-
	Null	-	[62]	-	-	[62]	[54]
	Negative	[62]	-	-	-	-	-
Sirens and construction noise	Positive	-	-	-	-	-	-
	Null	-	-	-	-	-	[82]
	Negative	[61]	-	-	-	[79]	[79,81,83,84,86]
Human noise	Positive	-	-	-	-	-	-
	Null	-	-	-	-	-	[81,82]
	Negative	-	-	-	-	-	[83,86]
Natural sounds	Positive	-	-	[75]	[78]	[78]	[80,85,86]
	Null	-	-	-	-	-	-
	Negative	-	-	-	-	-	-

with a prevalence of negative associations for speech perception, mathematical skills and comfort, as well as perceived effort. As regards language skills, attention and memory, mixed results were found, with even positive effects on memory and comfort. Positive effects could lie in the increased level of arousal provided by traffic noise [92]. However, evaluations of arousal levels are not often carried out nor using standardised instruments, and further data would be needed to investigate the effects of arousal on cognitive functions with reference to different types of sound stimuli.

Moreover, differences in results may be related to the spectro-temporal characteristics of the traffic noise, which vary according to the urban context of the school. In the case of schools located in the city centres, the sound environment may consist mainly of isolated car passages, with salient sound events. In suburban areas, the sound environment could be determined by a continuous flow of vehicles, thus resulting in a more stationary, and somehow pleasant [86], noise. However, information on the spectral characteristics of the noise and a detailed description of the urban context and related sound types is often missing in the reviewed studies.

#### 4.2.3. Railway, sirens and construction, human noise

Railway, construction, and outdoor human noise can often intrude into school environments in urban contexts and their importance in the classroom soundscape is recognised by students [93,94]. However, their specific impact on student performance has rarely been studied (see Table 3), to the point that, due to the paucity of studies, it is not possible to draw conclusions or outline patterns on the effects of railway noise and sirens on the analysed domains.

Regarding construction noise, only two studies observed a negative impact on speech perception and memory, whereas more evidence was found for the domain of comfort. Notably, these studies have shown an increase in annoyance and a decrease in pleasantness for students exposed to construction noise, likely due to its spectro-temporal characteristics and level.

Concerning the effects of outdoor human noise on students, only studies investigating the impact on comfort were identified, focusing on the general assessments of annoyance and pleasantness, and often neglecting details on the levels and the characteristics of the sound stimuli present during the subjective evaluation. Within the reviewed

studies, the effect of noise generated by children playing and people talking in the street was taken into consideration, having negative or no effect on students' comfort. Both types of sound are characterized by the presence of salient events and informational content (e.g., intelligible words or sentences among a babble noise), that previous studies concerning the noise generated by the students themselves within the classroom indicated to be particularly detrimental to performance in verbal tasks [95].

#### 4.2.4. Natural sounds

Few studies have investigated the effect of natural sounds on students, but they consistently report a positive effect on attention ( $n = 1$ ), memory ( $n = 1$ ), mathematics ( $n = 1$ ) and comfort ( $n = 3$ ). With regard to comfort, natural sounds were perceived as pleasant or unpleasant, depending on the sound level (see 3.7.7). The results are in line with literature indicating that the visual and sound immersion in the natural environment can provide physical and physiological restoration [96,97] and well-being [98,99], and positive learning outcomes [100]. It could therefore be hypothesised that exposure to natural sounds helps students recover their attention span, with knock-on effects on their academic performance, but since comfort depends on sound level, the restorative and beneficial effect could also be influenced by sound level. Notably, the acceptance and positive effects of natural sounds may pave the way to a more systematic usage of natural sounds as design elements in shaping the classroom soundscape, for instance with the aim of restoring from or masking the negative impacts of other types of noises.

#### 4.3. Limitations and implications for future research agenda

The systematic review must be interpreted by considering three main limitations. The review was based on the use of Scopus as database and, therefore, some articles may have not been detected as not covered by the database. In any case, the vast majority of high-quality journals are indexed in Scopus and it has also often been used in reviews in the same field [101]. At the article selection stage, checks were made to assess whether certain studies we had found from other sources were actually included in Scopus and identifiable for review purposes, and this check was successful. Therefore, we expect that the likelihood of missing out key studies is very limited. The second limitation is related to the lack of

a meta-analysis of the reviewed studies, due to the heterogeneity of tasks and listening conditions found among them. Moreover, the reported data are often incomplete (e.g., not all the studies reported the sound levels during the task/assessment, the urban context and the acoustic characteristics of the classroom were not systematically specified) or derived from different methodological assumptions (e.g., measurements performed either indoor or outdoor). Above all, the baseline condition used to determine the effect of the sound stimuli on the task was not fixed or comparable among the studies. Finally, the last limitation regards the population under study. This review focused only on students with normo-typical development and normal hearing, and so the findings cannot be generalized to more vulnerable and diverse categories of students (e.g., L2 students, students with hearing impairments). Future research should include a more aurally diverse population and allow for the characterization of potential differences across aural sensitivities [102].

As regards the suggestions for future research, in order to derive meaningful information from IAQ investigations in educational settings, studies on MV must include a characterisation of the acoustic environment associated with a certain ventilation strategy. Similarly, studies in acoustics shall report MV systems layout and not simply refer to “fan noise”. Moreover, threshold limits provided by acoustics and IAQ regulations should be used as a reference in the design of experiments and in discussing results. A non-integrated approach between ventilation and acoustics in schools could lead to the risk that standards only set benchmarks based on the respective literature, making them difficult to meet when combined in practice.

A multi-domain assessment (soundscape and ventilation) should form the basis of future research on the effects of the combined ventilation strategy and sound exposure on speech perception, cognitive abilities and comfort, thus improving the cost-benefit analysis of the available ventilation strategies and updating, if necessary, acoustics and IAQ limits within international standards in a coordinated fashion. For instance, pioneering UK regulations for schools already take into account tolerance parameters on the indoor background noise level based on the type of ventilation and specific conditions (e.g., overheating). This approach intends to blend air quality, overheating and soundscape assessment in policy and regulations [103–105].

However, integrated design requirements shall be based on a comprehensive analysis of the combined effects of ventilation-related sound events on speech perception, different cognitive abilities, and comfort. As regards comfort assessments, the selected studies mainly relied on the evaluation of noise annoyance/disturbance and, to a lesser extent, pleasantness. Perceptual aspects triggered by the sound environment inherent in students’ emotions, such as arousal, have not been considered in the reviewed studies, although they may affect students’ cognitive abilities [106]. Future research should aim to characterize the dimensions underlying the affective response to classroom soundscape, in order to explore the relationships between emotional and cognitive responses based on a reference “measuring” system, similarly to what has already been done in the outdoor [107,108] and indoor [23,24] soundscape literature.

Moreover, future research both in laboratory settings and in situ should increasingly take into account the multisensory nature of pupils’ experience in school [16,109,110]. Laboratory evaluations will need to be multi-domain and accompanied by an accurate description of test conditions to allow for subsequent meta-analyses and aggregations between different studies [111]. Testing activities in real school environments should possibly involve a continuous monitoring and description of the different sound sources in occupied conditions [112,113] as well as a characterization of other domains of environmental quality (i.e., visual, IAQ, thermal), to have more comprehensive information on possible confounding factors and covariates, along with information on controlled factors.

Studies should analyse in detail the different technological solutions in the field of mechanical ventilation, both those that can be employed

in new school buildings (e.g., centralized system) and those that can be more easily integrated into the existing building stock (e.g., decentralized ventilation units). As far as natural ventilation is concerned, the balance between ventilation efficiency and indoor noise levels is often delicate and context-dependent, with values that can easily be higher than those recommended by school regulations [114] (e.g., 35dBA for ANSI [87], 40dBA for BB93 [88]). While the past research has focused extensively on TN exposure to limit the negative outcomes on students, future research will have to cover a wide range of sound types and urban contexts, in order to obtain a wider information on the spectrum of potential negative and positive effects. If information on the beneficial effects of natural sounds already seems promising, more research is needed to assess the potential positive effect of sounds more commonly found in urban contexts, such as light traffic or distant voices, while characterising if and under what conditions of level and spectro-temporal characteristics these conditions occur for the different domains of interest (speech perception, cognitive abilities and comfort). This soundscape-based knowledge could lead to a revision (or raising) of reference background noise level limits, based, for instance, on specific acoustic contexts or the interaction with other environmental factors and duration of exposure (e.g., under overheating conditions). Future research might then be employed to leverage urban planning and building design decisions towards the adoption of natural ventilation, alone or in combination with active ventilation strategies, in order to achieve both occupant well-being and sustainability objectives [115].

It should be noted that in the context of an evolving school environment in terms of both teaching methods and related architectural design strategies, the discussion on acoustics and ventilation needs to be adapted to a set of spaces with varied characteristics and which have to meet different functional (and acoustic) requirements. This may lead to an activity-based acoustic design of schools similar to that already employed in open-plan office design [116,117], thus providing acousticians and architectural designers with a palette of different materials and target sounds and ventilation strategies for the different activities and related spaces.

## 5. Concluding remarks

In this systematic review we aimed to assess the impact of sound stimuli related to natural and mechanical ventilation in the classrooms on students’ speech perception, cognition and perceived comfort. The systematic review showed a negative effect of fan noise in the conditions addressed by the reviewed studies. Regarding anthropogenic sounds entering the classroom under natural ventilation conditions, negative or no effect was generally observed, depending on the specific task and noise characteristics. In contrast, natural sounds from open windows had a positive effect on students’ learning and comfort. Therefore, ventilation can sometimes improve the classroom soundscape, depending on the outdoor context. The domains most often studied and the areas where research is still lacking were identified, together with limitations of previous studies and future research perspectives. In particular, future studies are advocated to: 1) explore the potential beneficial effect of exposure to certain types and levels of sound stimuli on student’s comfort and cognition, which could be delivered by passive ventilation strategies, depending on the urban context; 2) assess the combined effects of different domains of environmental quality (e.g., sound, ventilation, air quality) on students’ learning through laboratory and field investigations; 3) target an integrated approach between acoustic and ventilation for the design of the educational spaces, which can be then translated into multi-disciplinary standards for the design of educational buildings.

## CRedit authorship contribution statement

**Matteo Pellegatti:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Simone Torresin:** Writing –

review & editing, Supervision, Conceptualization. **Chiara Visentin:** Writing – review & editing, Supervision, Conceptualization. **Francesco Babich:** Writing – review & editing, Supervision. **Nicola Prodi:** Writing – review & editing, Supervision, Conceptualization.

### 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.

### Data availability

No data was used for the research described in the article.

### Acknowledgments

This work was supported by the Eurac Research – Institute for Renewable Energy internal funding.

Furthermore, the authors thank the Department of Innovation, Research and University of the Autonomous Province of Bozen/Bolzano for covering the Open Access publication costs.

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