Research Paper

The Impact of HVAC Systems on Speech Intelligibility in University Classrooms

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Received November 15, 2024; revised February 3, 2025; accepted April 4, 2025; published online May 16, 2025.

Good speech intelligibility in university classrooms is crucial to the learning process, ensuring that students can clearly hear all conversations taking place in the classroom. While it is well known that speech intelligibility depends on the geometrical characteristics of a space and the properties of its surfaces, other factors need also to be considered. Among the most important are: the heating, ventilation, and air conditioning (HVAC) systems used in classrooms. Fan noise from HVAC systems increases the background noise level (BNL), negatively affecting speech intelligibility. In addition, the movement of air caused by these systems alters room acoustic variables. Although this dynamic situation is often overlooked in the early design stages, HVAC systems are often active during lectures and influence acoustics variables, especially the speech transmission index (STI). In this study, the impact of HVAC systems on the STI was measured in five different unoccupied classrooms in the Rafet Kayış Faculty of Engineering at Alanya Alaaddin Keykubat University. The results were evaluated according to relevant standards. The results of these evaluations offer insights for researchers, architects, and engineers working in the field of acoustics.

Keywords: speech intelligibility; speech transmission index (STI); room acoustic variables; room impulse response (RIR); acoustic performance.

1. Introduction

The act of learning is a process influenced by and related to a number of factors, including the environment, infrastructure, the student, and the instructor. The acoustic performance of a space is an important factor that affects students' learning outcomes. Educational institutions should provide well-designed and appropriate spaces in order to improve the quality of education. Speech intelligibility plays an important role in educational settings by directly affecting the quality of communication between students and instructors. Several studies suggest that poor room acoustic performance have a negative impact on speech intelligibility and affects verbal communication between students and instructors (Yang, Mak, 2018; Choi, 2020; Engel *et al.*, 2020; Kawata *et al.*, 2023; Di Loreto *et al.*, 2023).

For effective communication, it is not enough to simply hear what the instructor says, as hearing and understanding what is said without loss is an important component of communication. In the field of education, an area where communication is actively used, the quality of communication (information exchange) between instructors and students is closely related to speech intelligibility. Acoustic conditions have been shown to directly affect students' ability to understand speech, often leading to inefficient communication in the classroom (Rabelo *et al.*, 2014). When speech intelligibility is inadequate, instructors may have to raise their voice, students may have problems to maintain focus, and key information may not be conveyed accurately. This situation negatively affects communication between instructors and students and undermines the realization of the learning outcomes intended for the course.

In the courses offered at Alanya Alaaddin Keykubat University (ALKU) Rafet Kayış Faculty of Engineering, lecturers support the educational process by using various visual communication tools, such as slides, graphics, and videos, to teach course material more effectively. While visual aids are commonly used, the primary communication remains verbal. The language of instruction in most departments at this faculty is English. For students whose first language is not English, challenges related to pronunciation, vocabulary, and grammatical structure can hinder proper understanding. These linguistic barriers make it even more difficult for non-native speakers to follow the courses. Non-native speakers require a 4 dB to 5 dB improvement in the signal-to-noise ratio (SNR) to achieve equivalent level of speech intelligibility as native speakers (International Organization for Standardization [ISO], 2003).

Speech intelligibility is related to several objective acoustic metrics such as reverberation time (RT), background noise level (BNL), useful energy (first 50 ms), the early-to-total energy ratio (D50), and the SNR. Some studies have shown that RT has a significant effect on speech transmission index (STI). Payton and Shrestha (2008) showed that STI measures the extent to which speech envelope modulations are preserved in degraded listening environments. Recently, Chinese speech intelligibility scores has been examined in university classrooms using a hybrid method (Huang *et al.*, 2023). The results show that to achieve better speech intelligibility, RT at all frequencies should be shorter, and it is better when an RT is flat at low frequencies. The STI is an objective metric that correlates well with the intelligibility of speech, a subjective metric, which is degraded by additive noise and reverberation.

While it is common to categorize students into age groups, typically under 12 and over 12 years old, there are additional factors to be considered in university classrooms (Minelli *et al.*, 2022). In many universities around the world, students are taught in a second language, different from their mother tongue in education settings. It is important to take this language barrier into account when assessing speech intelligibility. Moreover, there is not enough information on how the speech intelligibility parameter is affected by HVAC systems, particularly through their impact on BNL and SNR. It has been shown that these systems, which are actively used in the educational process, negatively affect SNR ratio, which is one of the acoustic parameters, as well as speech intelligibility (Di Loreto *et al.*, 2023; Zhu *et al.*, 2024). Considering the possible effects of various factors, studies on speech intelligibility in university classrooms remain relatively scarce.

In this study, acoustic measurements were conducted in five different spaces, both with HVAC systems inactive and operating at different fan speed levels. From the raw acoustic data measured, parameters, including: RT, center time (Ts), D50, STI, strength (G), and SNR, were obtained across seven octave bands (125 Hz–8000 Hz). The results presented are compared for the five different spaces. The acoustic performance of each space is evaluated according to relevant standards. The results of these evaluations are then utilized to draw conclusions of interest to researchers, architects and engineers working in the field of acoustics.

2. Methods and data

2.1. Descriptors of room acoustics for speech intelligibility

The RT, specifically T30, is defined according to Schroeder curves (SC) obtained from the impulse response ($g(t)$) (Rossing *et al.*, 2014):

$$T_{30} = 2[t(\mathrm{SC} = -35\,\mathrm{dB}) - t(\mathrm{SC} = -5\,\mathrm{dB})], \tag{1}$$

where

$$\mathrm{SC} = 10\log_{10}\left(\frac{\int_0^t g^2(\tau)\,\mathrm{d}\tau}{\int_0^\infty g^2(\tau)\,\mathrm{d}\tau}\right). \tag{2}$$

Ts is the ratio of early energy to late energy, defined as

$$\mathrm{Ts} = \frac{\int_0^\infty \tau g^2(\tau)\,\mathrm{d}\tau}{\int_0^\infty g^2(\tau)\,\mathrm{d}\tau}. \tag{3}$$

D50 is the ratio of useful energy (the first 50 ms) to total energy, and it is expressed as

$$D_{50} = \frac{\int_0^{50\mathrm{ms}} g^2(\tau)\,\mathrm{d}\tau}{\int_0^\infty g^2(\tau)\,\mathrm{d}\tau} \leq 1. \tag{4}$$

G is the energy gain in a reverberant room compared to a free field with a 10 m distance, where theoretically no reverberation occurs, and it is defined as

$$G = 10\log_{10}\left(\frac{\int_0^\infty g^2(\tau)\,\mathrm{d}\tau}{\int_0^{t_{\mathrm{dir}}} g^2_{10\,\mathrm{m}}(\tau)\,\mathrm{d}\tau}\right), \tag{5}$$

where t_{dir} refers to the direct sound. SNR is

$$\text{SNR}(\omega) = 10\log_{10}\left(\frac{m(\omega)}{1 - m(\omega)}\right), \tag{6}$$

where $m(\omega)$, the complex modulation transfer function, is given by International Electrotechnical Commission [IEC] (2020):

$$m(\omega) = \frac{\int_0^\infty g^2(\tau)e^{-j\omega\tau}\,\mathrm{d}\tau}{\int_0^\infty g^2(\tau)\,\mathrm{d}\tau}. \tag{7}$$

STI is given by Mejdi *et al.* (2019):

$$\text{STI} = \min\left(1.0,\ \sum_{k=q}^{7}\alpha_k \text{MTI}_k - \sum_{k=q}^{6}\beta_k\sqrt{\text{MTI}_k\text{MTI}_{k+1}}\right), \tag{8}$$

where MTI is the modulation transfer index; 6 and 7 are octave bands, α and β are weighting and redundancy factors, respectively; $q = 1$ for male speakers and $q = 2$ for female speakers, which correspond to 125 Hz and 250 Hz, respectively.

2.2. Spaces

Acoustic measurements were conducted in five educational spaces, each with different dimensions, at ALKU Rafet Kayış Engineering Faculty. Three of these spaces – classrooms A203, D107, and T206 – are used for theoretical courses. The other two spaces where measurements were conducted serve as laboratories: A208 is a computer laboratory and D110 is the Vibration and Acoustics Laboratory. Due to concerns about variations in background noise and for operational reasons, acoustic data were collected during the summer, when there were no students at the university.

The selected spaces represent different types of educational rooms within the faculty. The dimensions of each space are shown on the scaled plans shown in Figs. 1–5. The number of seats in each space is as follows: 99 seats in A203, 64 seats in D107, 60 seats in T206, 58 seats in A208, and space and seats for 8 researchers in D110. Each space, except D110, is equipped with a lectern located 2 meters in front of the whiteboard. The HVAC system employed in these spaces is a Daikin FXFQ125 round flow cassette model. There are two units installed in A203, A208, and T206, while one unit is located in D107 and D110. The locations of the HVAC systems are shown in Figs. 1–5, as well. The HVAC system can operate at three different fan levels (L, H, HH), with corresponding fan flow rates of $33.0\,\text{m}^3/\text{min}$, $26.5\,\text{m}^3/\text{min}$, and $19.9\,\text{m}^3/\text{min}$, respectively.

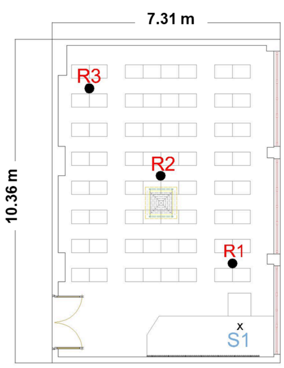

Fig. 1. Scaled plan of classroom D107.

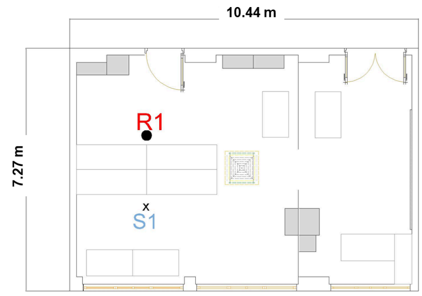

Fig. 2. Scaled plan of Vibration and Acoustics Laboratory, D110.

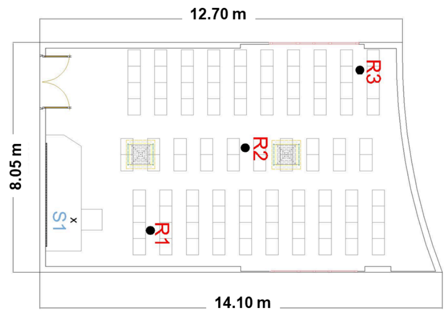

Fig. 3. Scaled plan of classroom A203.

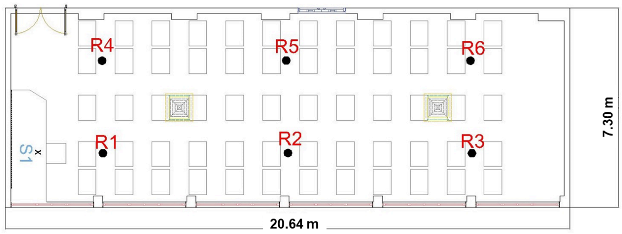

Fig. 4. Scaled plan of classroom T206.

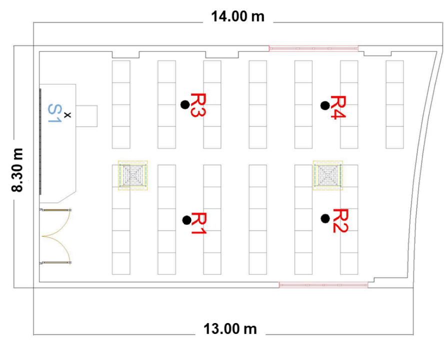

Fig. 5. Scaled plan of classroom A208.

The materials used in the design of the spaces are as follows. Stoneware tiles were selected for the floor covering. The side walls are constructed with brick, finished with basic plaster and thin plaster layers. The windows have double-glazed window systems, while solid wood doors are used throughout. To improve acoustics, micro-perforated acoustic panels were installed on the ceiling. The tables and chairs are made of wood, and ceramic-enameled whiteboards are used as writing surfaces. In addition, roll curtains made of polyester material were installed to cover the windows.

2.3. Measurements

The indirect method used in this study to determine acoustic parameters consists of measuring the response of an enclosed space to an impulse signal. The Sinus Qohm QS12 sound source is suitable for measurements between 50 Hz–16 000 Hz with a level of 122 dB across a uniform broadband spectrum. The required omnidirectionality for the measurements is in compliance with the relevant standards (ISO, 2014; 2021). In addition, the sound source meets directivity values as it meets the maximum permissible deviation values in the octave bands of pink noise specified by the relevant standard (ISO, 2009). During the measurements, the height of the sound source was set to 1.5 m from the ground.

Exponential sine sweeps (ESS) are used for impulse stimulation in the measurements due to their ability to separate harmonic distortion and yield higher impulse-to-noise ratios under typical test conditions (Meng *et al.*, 2008; Guidorzi *et al.*, 2015; Antoniadou *et al.*, 2018). A Focusrite Scarlett 18i20 external sound card is used as the audio interface to transmit the sound source and microphone signals to the computer. The response of the space is recorded using omnidirectional GRAS 46AE microphones. The software used to record the raw audio signals and process the data is Dirac v7. Prior to measurements, the microphones are calibrated.

The BNL values of the classrooms were determined prior to the measurement survey. According to the relevant standard (American National Standard, 2010), the BNL values in classrooms are expected to be lower than 35 dBA. This standard value applies to unoccupied classrooms and includes environmental noise and HVAC-related noise. The measured BNL values (L_{A90}) for classrooms D107, D110, A203, T206, and A208 are presented in Table 1. Upon analyzing the values in the table, it is evident that in most cases, the BNL values exceed the recommended standard value. These values are shown in bold in the table. The measurements were conducted during the summer period when there were no students on campus and environmental noise levels were minimal. It is clear that the most important contributor to the elevated BNL values is the HVAC system. As the fan speed increases, the noise level also increases, which leads to higher BNL values. As will be explained in the next section, HVAC noise also has a significant impact on the SNR. HVAC noise reduces the SNR, which, in turn, has a negative impact on speech intelligibility.

Classroom D110 is an actively used research laboratory. There are two uninterruptible power supplies (UPS) running 24 hours a day in this space. As shown in the values in Table 1, these devices increase the background noise and have a negative impact on speech intelligibility.

The sound source, representing the instructor, is located behind the lectern. A distance of at least 1 m was maintained between the sound source and the side walls. Microphones, representing the students, were positioned 1.2 m above the ground and at least 1 m away from the walls in accordance with ISO (2009). The distance between the sound source and the microphone is an important variable for speech intelligibility. Therefore, microphones were positioned at different distances from the sound source. The locations of microphones and the sound source are shown in Figs. 1–5 for the studied spaces. During the measurement survey, the temperature and relative humidity were continuously monitored and recorded.

The spaces were stimulated with a 21.8 s ESS signal, in the frequency range 20 Hz–20 000 Hz. During the measurements, the polyester roll curtains, windows and doors were closed. The measurements were repeated with the HVAC system off and operating at three different fan levels, as indicated in Table 1. To account for measurement uncertainty, all measurements were repeated three times, and the average of the processed values was considered for analysis. The photographs taken during the measurement survey are shown in Figs. 6–10.

Table 1. Measured BNLs in dBA.

Space	No fan 0 m^3/min	Fan level I (L), 19.9 m^3/min	Fan level II (H), 26.5 m^3/min	Fan level III (HH), 33.0 m^3/min
D107	29.0	34.7	**41.3**	**47.2**
D110	**40.2**	**41.2**	**43.3**	**47.4**
A203	29.7	**38.5**	**44.0**	**49.5**
T206	31.0	**36.5**	**42.7**	**47.9**
A208	33.6	**37.3**	**43.0**	**48.2**

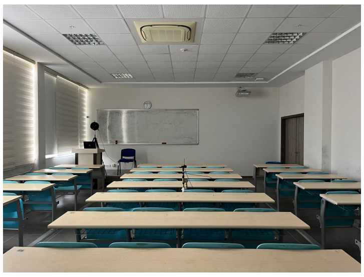

Fig. 6. Experimental study conducted in classroom D107, microphone position: R2, temperature: 26.5 °C.

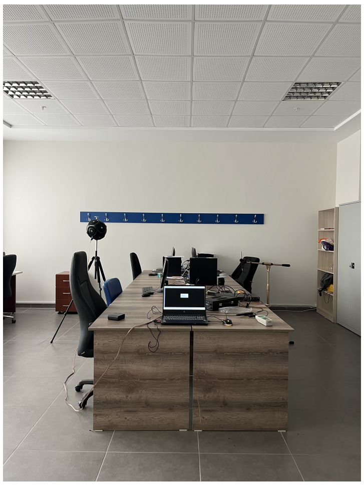

Fig. 7. Experimental study conducted in laboratory D110, microphone position: R1, temperature: 25.0 °C.

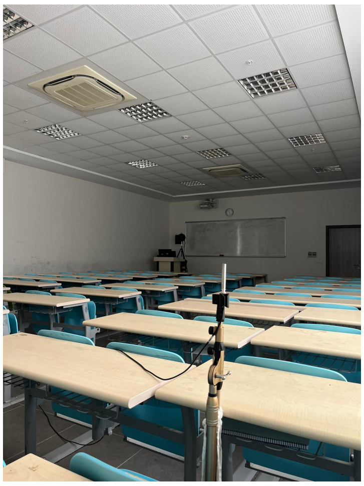

Fig. 8. Experimental study conducted in classroom A203, microphone position: R3, temperature: 26.5 °C.

Fig. 9. Experimental study conducted in classroom T206, microphone position: R1, temperature: 26.5 °C.

Fig. 10. Experimental study conducted in laboratory A208, microphone position: R2, temperature: 26.5 °C.

3. Results and discussion

The intelligibility of speech in an enclosed space depends on the BNL, the distance between the speaker and the listener, the directivity of the speech, the signal strength of the speech, the sound spectrum of the speech, and reverberation characteristics of the space. While the audio signal of speech spans a wide range of frequencies across 7-octave bands, the 500 Hz–4000 Hz range is critical for speech intelligibility. According to the relevant standard (IEC, 2020), STI is calculated as the weighted sum of the MTI, one for each octave frequency band in the 7-octave band; each MTI value is obtained from modulation transfer function (MTF) values over 14 different modulation frequencies (Elliott, Theunissen, 2009).

The SNR values in 7-octave bands are shown in Fig. 11 for the various spaces. BNL can be neglected if the SNR exceeds 15 dB in each octave frequency band of interest (in this case, the 7-octave band). However, the strength of the sound source may need to be increased for this to occur. In practice, this means that the instructor needs to raise their voice. Average vocal effort levels are usually measured in anechoic chambers for classification (Cushing *et al.*, 2011). Average vocal effort levels in anechoic conditions, measured at 1 m, are presented in Table 2. During the measurement survey, the generated sound was adjusted to be at least 15 dB above the BNL.

Table 2. Average vocal effort and sound level in dBA.

	Normal	Raised	Loud	Shouting
Male	58	67	76	89
Female	56	64	70	82

The SNR results clearly show the negative impact of HVAC systems: as the fan speed increases the SNR values decrease, which, in turn, affects speech intelligibility. The variation in SNR is sensitive to frequency, and although the trends are similar, the geometry of

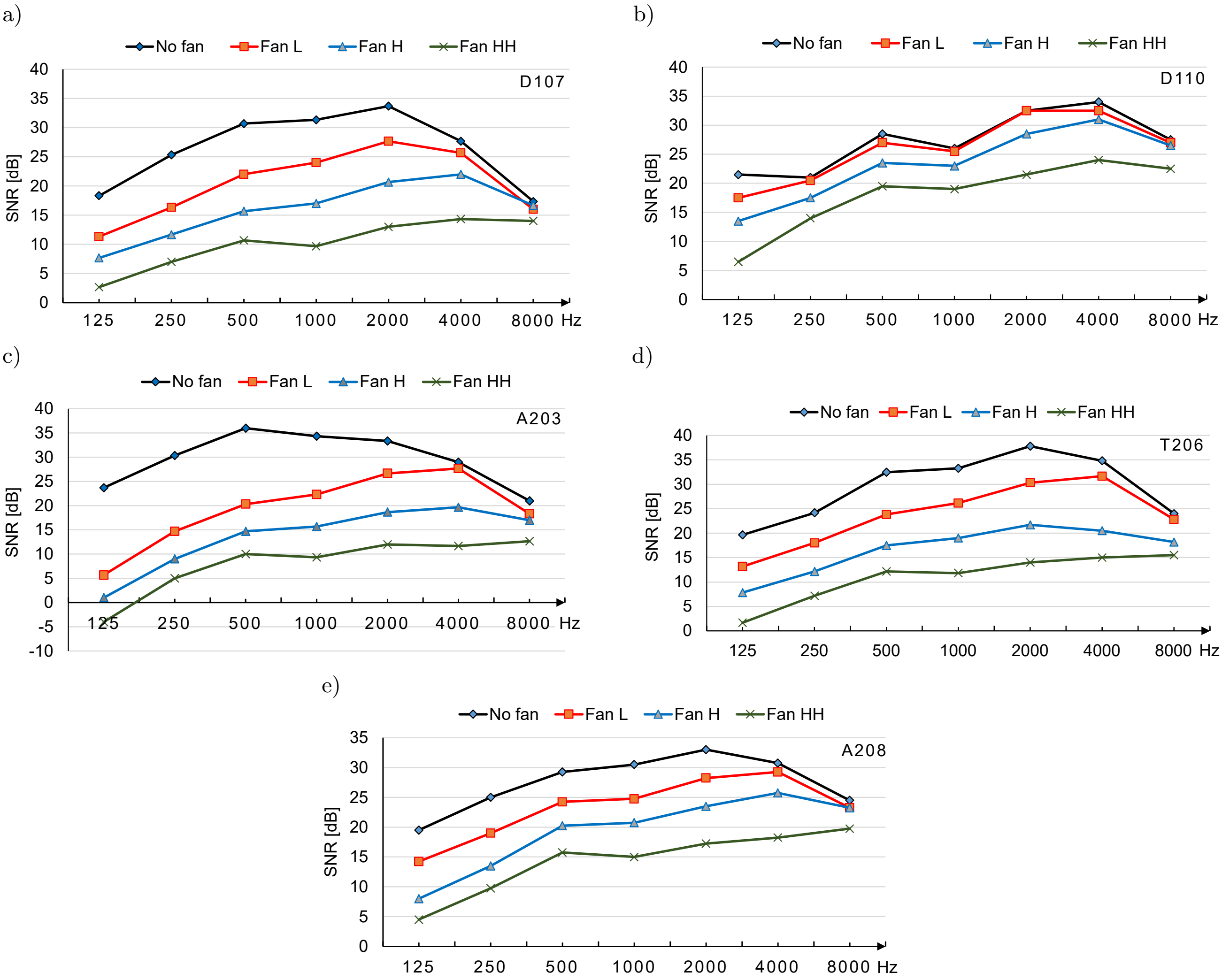

Fig. 11. Variation of SNR in the spaces: a) D107; b) D110; c) A203; d) T206; e) A208.

the space also affects the changes. One way to compensate for the drop in SNR values is for the instructor to raise their voice. The values presented in Table 2 give an idea of the vocal effort required. SNR values in the spaces tend to decrease after 4000 Hz. However, the frequency range 500 Hz–4000 Hz is decisive for speech intelligibility and, within this range, the 1000 Hz and 2000 Hz bands are critical.

The acoustic parameters measured in the spaces are presented in Tables 3–7. The acoustic parameters and their units are as follows: SNR [dB], T30 [s], *G* [dB], Ts [ms], D50 (unitless [0–1]), and STI (unitless [0–1]).

Speech intelligibility depends on the speaker's voice reaching the listener directly, as well as the effects of reverberation and background noise. Reverberation and background noise have a distorting effect on the sound that reaches the listener directly. In terms of objective measures, reverberation can be quantified by T30 and background noise by BNL. Since SNR is the ratio of speech to BNL, it is a key factor in determining intelligibility. The focus of the presented work is primarily on the impact of HVAC systems on speech intelligibility, which can be related to SNR. The average SNR values at 500 Hz and 1000 Hz SNR measured in the spaces, plotted against the blowing flow rate of the HVAC used are shown in Fig. 12. The results show that SNR values tend to decrease as the fan blowing speed of the HVAC systems increases, which, in turn, negatively affects speech intelligibility.

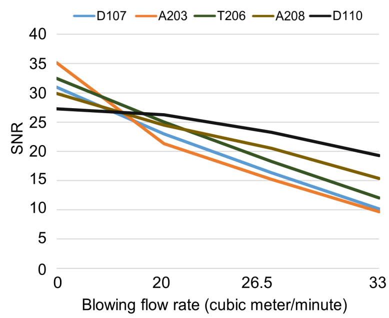

Fig. 12. Variation of SNR in the spaces depending on the impact of HVAC systems.

Table 3. Acoustic parameters measured at D107 for four different fan settings.

Fan	Parameter	Frequency							
			125	250	500	1000	2000	4000	8000
No fan	SNR		18.33	25.33	30.66	31.33	33.66	27.66	17.33
	T30		1.56	1.13	0.94	0.83	0.86	0.81	0.65
	G		23.28	21.16	20.27	19.96	20.26	19.78	18.68
	Ts		107.47	68.57	56.13	50.47	50.53	52.13	36.70
	D50		0.46	0.58	0.64	0.65	0.64	0.61	0.74
	STI	0.66							
Fan L	SNR		11.33	16.33	22.00	24.00	27.67	25.67	16.00
	T30		1.43	1.13	0.87	0.82	0.86	0.80	0.64
	G		23.12	21.17	20.14	20.15	20.24	19.78	18.70
	Ts		107.83	69.50	54.47	50.13	51.23	52.87	37.23
	D50		0.46	0.56	0.67	0.65	0.63	0.60	0.73
	STI	0.65							
Fan H	SNR		7.67	11.67	15.67	17.00	20.67	22.00	16.67
	T30		1.45	1.10	0.87	0.83	0.86	0.80	0.65
	G		22.36	20.01	19.09	19.18	19.12	18.26	17.85
	Ts		105.60	68.90	54.00	51.03	50.40	52.87	36.83
	D50		0.47	0.56	0.67	0.64	0.64	0.62	0.74
	STI	0.65							
Fan HH	SNR		2.67	7.00	10.67	9.67	13.00	14.33	14.00
	T30		1.35	0.98	0.82	0.78	0.83	0.80	0.64
	G		23.21	21.23	20.24	19.97	20.05	19.66	18.71
	Ts		109.33	67.67	54.43	50.53	51.53	52.53	37.17
	D50		0.46	0.57	0.66	0.65	0.63	0.62	0.73
	STI	0.63							

Table 4. Acoustic parameters measured at D110 for four different fan settings.

Fan	Parameter	Frequency							
			125	250	500	1000	2000	4000	8000
No fan	SNR		21.50	21.00	28.50	26.00	32.50	34.00	27.50
	T30		0.77	0.77	0.70	0.66	0.67	0.63	0.54
	G		24.81	22.98	22.76	21.54	22.12	21.53	20.76
	Ts		49.25	36.20	50.50	43.10	40.00	39.65	31.50
	D50		0.80	0.84	0.66	0.69	0.71	0.72	0.79
	STI	0.69							
Fan L	SNR		17.50	20.50	27.00	25.50	32.50	32.50	27.00
	T30		0.70	0.76	0.71	0.68	0.65	0.62	0.54
	G		24.30	23.60	22.83	21.88	22.28	21.72	20.71
	Ts		53.60	39.10	47.70	40.45	40.10	38.70	31.45
	D50		0.73	0.82	0.69	0.69	0.71	0.73	0.79
	STI	0.69							
Fan H	SNR		13.50	17.50	23.50	23.00	28.50	31.00	26.50
	T30		0.70	0.73	0.75	0.65	0.66	0.63	0.54
	G		24.21	23.57	22.91	21.93	22.33	21.60	20.68
	Ts		54.05	39.05	48.80	41.35	40.05	39.85	31.00
	D50		0.73	0.81	0.67	0.69	0.71	0.72	0.80
	STI	0.68							
Fan HH	SNR		6.50	14.00	19.50	19.00	21.50	24.00	22.50
	T30		0.83	0.78	0.69	0.66	0.67	0.62	0.52
	G		24.37	23.59	22.92	21.88	22.25	21.40	20.73
	Ts		57.30	39.60	48.10	41.70	38.50	40.15	31.20
	D50		0.71	0.81	0.68	0.69	0.73	0.72	0.79
	STI	0.63							

Table 5. Acoustic parameters measured at A203 for four different fan settings.

Fan	Parameter	Frequency							
			125	250	500	1000	2000	4000	8000
No fan	SNR		23.67	30.33	36.00	34.33	33.33	29.00	21.00
	T30		1.32	1.07	0.87	0.98	1.12	1.04	0.84
	G		20.24	20.01	18.93	19.47	19.93	19.67	18.22
	Ts		98.90	70.63	57.90	64.33	71.23	65.40	50.90
	D50		0.46	0.56	0.64	0.59	0.52	0.57	0.64
	STI	0.61							
Fan L	SNR		5.67	14.67	20.33	22.33	26.67	27.67	18.33
	T30		1.26	1.05	0.89	0.99	1.10	1.06	0.85
	G		20.35	19.94	18.75	19.45	19.84	19.52	18.15
	Ts		101.53	71.13	58.40	64.87	71.87	66.37	51.17
	D50		0.45	0.56	0.63	0.59	0.52	0.56	0.64
	STI	0.60							
Fan H	SNR		1.00	9.00	14.67	15.67	18.67	19.67	17.00
	T30		1.25	0.94	0.85	0.97	1.06	1.04	0.85
	G		20.54	19.93	18.75	19.35	20.12	19.72	18.39
	Ts		101.87	72.77	59.30	65.17	71.10	66.57	52.27
	D50		0.45	0.56	0.62	0.58	0.53	0.56	0.63
	STI	0.60							
Fan HH	SNR		−4.00	5.00	10.00	9.33	12.00	11.67	12.67
	T30		1.02	0.91	0.87	0.98	1.07	1.05	0.83
	G		20.60	20.14	18.73	19.28	19.98	19.55	18.32
	Ts		105.50	71.77	59.27	64.60	70.67	65.77	52.50
	D50		0.44	0.55	0.64	0.59	0.54	0.57	0.62
	STI	0.57							

Table 6. Acoustic parameters measured at T206 for four different fan settings.

Fan	Parameter	Frequency							
			125	250	500	1000	2000	4000	8000
No fan	SNR		19.67	24.17	32.5	33.30	37.83	34.83	24.00
	T30		2.23	1.48	1.12	1.15	1.23	1.17	0.91
	G		20.79	18.30	17.06	17.48	18.14	17.72	16.23
	Ts		116.58	77.08	77.88	71.15	74.70	69.35	50.87
	D50		0.50	0.56	0.50	0.56	0.54	0.55	0.65
	STI	0.60							
Fan L	SNR		13.17	18.00	23.83	26.17	30.33	31.67	22.83
	T30		2.28	1.46	1.12	1.15	1.23	1.17	0.90
	G		20.84	18.75	17.04	17.49	18.17	17.71	16.27
	Ts		117.03	77.70	77.32	70.70	74.83	69.13	50.90
	D50		0.50	0.56	0.50	0.56	0.54	0.56	0.65
	STI	0.60							
Fan H	SNR		7.83	12.17	17.50	19.00	21.17	20.50	18.17
	T30		2.04	1.43	1.10	1.15	1.22	1.15	0.90
	G		20.78	18.79	17.09	17.45	18.14	17.69	16.34
	Ts		119.07	78.45	78.12	72.25	74.42	69.72	51.02
	D50		0.50	0.55	0.50	0.55	0.54	0.54	0.65
	STI	0.59							
Fan HH	SNR		1.67	7.17	12.17	11.83	14.00	15.00	15.50
	T30		1.79	1.46	1.11	1.12	1.18	1.13	0.88
	G		20.84	18.82	16.99	17.46	18.03	17.65	16.28
	Ts		119.95	78.00	78.45	71.25	75.22	69.88	51.63
	D50		0.49	0.56	0.50	0.56	0.53	0.54	0.64
	STI	0.58							

Table 7. Acoustic parameters measured at A208 for four different fan settings.

Fan	Parameter	Frequency							
			125	250	500	1000	2000	4000	8000
No fan	SNR		19.50	25.00	29.25	30.50	33.00	30.75	24.50
	T30		1.31	0.79	0.79	0.82	0.86	0.84	0.71
	G		19.86	17.50	17.55	17.82	18.06	17.06	17.21
	Ts		90.58	64.33	63.83	58.28	59.63	58.30	44.33
	D50		0.52	0.57	0.52	0.59	0.58	0.58	0.69
	STI	0.64							
Fan L	SNR		14.25	19.00	24.25	24.75	28.25	29.25	23.25
	T30		1.17	0.79	0.79	0.79	0.85	0.85	0.71
	G		19.91	17.47	17.47	17.57	18.01	17.91	17.09
	Ts		90.63	64.70	64.35	59.30	59.95	58.43	45.68
	D50		0.52	0.57	0.52	0.58	0.57	0.58	0.67
	STI	0.63							
Fan H	SNR		8.00	13.50	20.25	20.75	23.50	25.75	23.25
	T30		1.23	0.80	0.78	0.80	0.86	0.83	0.71
	G		19.96	17.43	17.61	17.66	18.04	17.90	17.13
	Ts		90.18	65.45	64.55	59.03	59.88	58.30	44.70
	D50		0.52	0.56	0.52	0.59	0.58	0.59	0.68
	STI	0.63							
Fan HH	SNR		4.50	9.75	15.75	15.00	17.25	18.25	19.75
	T30		1.05	0.73	0.77	0.79	0.83	0.83	0.70
	G		20.10	17.52	17.56	17.63	18.11	17.92	17.21
	Ts		91.35	64.80	63.75	58.53	59.50	57.95	43.63
	D50		0.52	0.57	0.52	0.59	0.57	0.58	0.69
	STI	0.62							

The variation in T30 due to the fan blowing speed is also examined. The average T30 values at 500 Hz and 1000 Hz T30, measured in the spaces against the blowing flow rate of the HVAC used, are shown in Fig. 13. The results show that variations in T30 can be neglected if the just noticeable difference (JND) is taken as 5 % relative, according to (ISO, 2009).

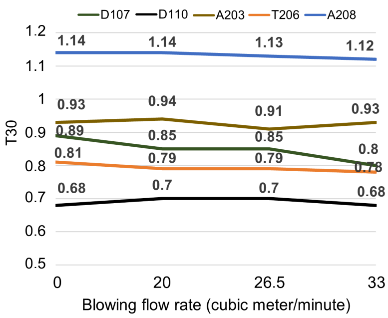

Fig. 13. Variation of T30 in the spaces depending on the impact of HVAC systems.

In line with the above discussion, objective measures for speech intelligibility include STI (Houtgast, Steeneken, 1985), ALC (articulation loss of consonants) (Peutz, 1972), and U50 (useful-to-detrimental ratio) (Lochner, Burger, 1964). Among these, STI is studied in this work to quantify speech intelligibility. The variation in STI in the spaces, depending on the impact of HVAC systems, is shown in Fig. 14. The ranking presented in the figure is based on the IEC (2020) standard. The results from the measurement survey indicate that the STI values for all five spaces can be categorized as 'good', even though the values tend to decrease with increasing fan speed. Note that the JND for STI is 0.03.

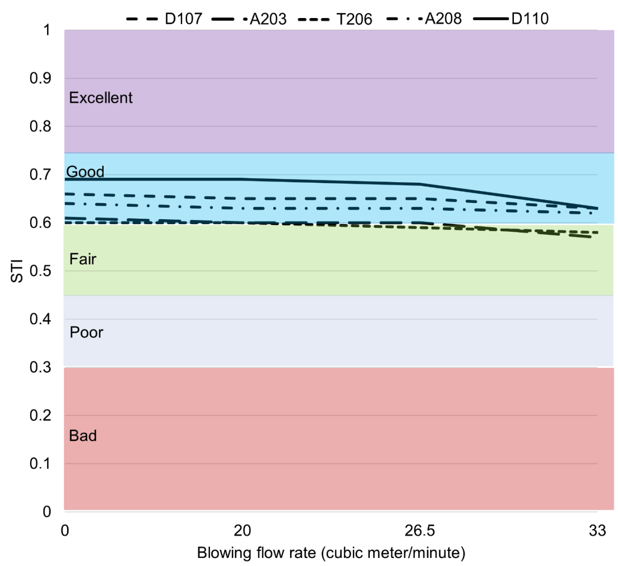

Fig. 14. Evaluation of STI in the spaces depending on the impact of HVAC systems.

On the other hand, it should be noted that some departments in the faculty offer courses in a second language. While the 0.6 threshold is considered 'good' for native English students, recent research suggests that this may not be the case for non-native speakers (ISO, 2003; Minelli *et al.*, 2022). For students whose first language is not English but who use English as a daily second language, an STI value of 0.68 and above can only be considered 'good'. For students with an intermediate level of proficiency and those with low level of their second language use, an STI value of 0.86 and above can be considered 'good'.

4. Conclusion

Background noise, RT, and the distance between the listener and speaker all affect STI values. Since SNR is the ratio of speech compared to BNL, it can be considered a key factor in speech intelligibility. The impact of HVAC systems on SNR is significant and negatively affects speech intelligibility, as reflected in the reported STI values.

As highlighted in previous studies (Longoni *et al.*, 2016; Razali *et al.*, 2024), the presence of HVAC systems increases BNL, decreases SNR and deteriorates speech intelligibility. Recommended values for speech intelligibility are T30 between 0.7 s and 1.2 s and D50 >0.5 in rooms (Masovic, 2021). For classrooms, optimum T30 values are <0.6 s for students under 12 years old and <0.8 s for students aged 12 and above (Building Bulletin, 2015; Minelli *et al.*, 2022). The studied spaces partially meet these optimal ranges.

The results show that SNR values tend to decrease as the fan blowing speed of HVAC systems increases, which negatively affects speech intelligibility.

Another concern is whether HVAC systems alter acoustic parameters that affect speech intelligibility, such as RT. The results of the study indicate that the impact of HVAC systems on the reverberation characteristics of space is negligible when the JND value is considered. On the other hand, it is clear that as the size of the space decreases, the RT also decreases, leading to a better STI value.

Previous research (Astolfi *et al.*, 2012; Murgia *et al.*, 2023) suggests that speech intelligibility for learners aged 12 and under requires an STI value of 0.65 and above, while for learners aged 12 and above, STI values of 0.6 and above are considered acceptable. For university students, it can be concluded that if STI values of 0.6 and above are achieved, there is no cause for concern in terms of speech intelligibility. The relevant standard (ISO, 2003) categorizes STI values between 0.6 and 0.75 as 'good'. However, it is worth noting that for non-native speakers of English, the STI value must fall between 0.68–0.86, depending on their level of English proficiency, to be considered 'good'.

Fundings

This study was supported by the Scientific and Technological Research Council of Türkiye (TUBITAK) under grant no. 123M884. The authors thank TUBITAK for their support.

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