ARCHIVES OF ACOUSTICS Online First September 11, 2025 https://doi.org/10.24425/aoa.2025.154824

Research Paper

Listening Effort in Reverberant Rooms: A Comparative Study of Subjective Perception and Objective Acoustic Metrics

Anna PASTUSIAK*, Łukasz BŁASIŃSKI, Jędrzej KOCIŃSKI

Department of Acoustics, Faculty of Physics and Astronomy, Adam Mickiewicz University
Poznań, Poland

*Corresponding Author e-mail: anna.pastusiak@amu.edu.pl

Received October 9, 2024; revised May 9, 2025; accepted August 4, 2025; published online September 11, 2025.

Modern room acoustics employs a variety of objective measures to characterize the acoustical properties of interiors. Despite these advancements, the relationship between these parameters and subjective assessments of room acoustics remains unclear. Subjective perception, particularly listening effort (LE), plays a critical role in how individuals experience acoustic environments, even when speech intelligibility (SI) is high. This study aims to bridge the gap between objective acoustic measures and subjective listening experiences. We conducted experiments in three rooms equipped with reverberation enhancement systems, resulting in nine different acoustic settings. Objective parameters, including reverberation time (RT), early decay time (EDT), clarity (C50), and the speech transmission index (STI), were measured. Additionally, subjective SI was assessed, and LE was rated on a 7-step Likert scale by 180 volunteers with normal hearing. The analysis revealed a non-linear relationship between LE and both RT20 and EDT (R^2 = 0.6), with an even weaker correlation for LE vs. C50 (R^2 = 0.46). The Pearson correlation coefficient for STI was 0.74, compared to 0.55 for SI. These findings indicate that the relationship between LE and objective parameters, as well as SI, is complex and not straightforward. Our results suggest the importance of incorporating LE into room acoustic design and evaluation. The disparity between objective measures and subjective experiences suggests that LE may be a crucial factor in accurately assessing acoustic environments. This approach sheds the light on a more holistic understanding of acoustic quality that prioritizes human perception.

Keywords: room acoustics; listening effort; speech intelligibility; reverberation time; early decay time; clarity (C50); speech transmission index.

1. Introduction

Processing spoken language, which begins with the extraction of key sensory information from a rapidly changing acoustic signal, requires a series of perceptual and cognitive analyses (STRAND *et al.*, 2018) that involve a certain amount of cognitive effort (PEELLE, 2018). The extent of this effort depends on several factors. Among the most significant are the presence and type of interfering signals, such as background noise or concurrent speech (FESTEN, PLOMP, 1990), the content and complexity of the speech being heard (JUST, CARPENTER, 1992), the degradation of the target signal (WILD *et al.*, 2012), the characteristics of a speaker (SCHMID, YENI-KOMSHIAN, 1999), and naturally, those of the listener (MATTYS *et al.*, 2012). In general, it can be stated that when the target signal is distorted, disrupted in some way, or its reception is somehow limited, listeners must engage significantly more cognitive resources to extract useful information compared to an undistorted signal presented in favorable conditions and received by an unrestricted auditory apparatus (PEELLE, 2018), even when speech intelligibility (SI) remains unchanged (HOUBEN *et al.*, 2013).

In clinical audiology, this increased cognitive load is particularly relevant for individuals with hearing loss or auditory processing difficulties, as they may exert disproportionately greater effort to achieve comparable levels of speech understanding. In this context, listening effort (LE) becomes an important metric for assessing not only the performance of hearing aid but also the broader effectiveness of auditory rehabilitation strategies (Ohlenforst *et al.*, 2017).

Undoubtedly, this is why, in recent years, there has been growing interest in research on the cognitive load associated with speech perception, which is referred to as LE (e.g., Pichora-Fuller *et al.*, 2016; Lemke, Basser, 2016). This phenomenon was first formally defined by the Cognition in Hearing Special Interest Group of the British Society of Audiology (McGarrigle *et al.*, 2014) as 'the mental effort required to listen to and understand an auditory message'. An extension of this formulation is a more generic description describing it as the intentional allocation of mental resources to overcome obstacles in goal pursuit during a (listening) task (Pichora-Fuller *et al.*, 2016). While this definition focuses on speech, it also accommodates other types of signals encountered in real-life conditions (Shinn-Cunningham, Best, 2008). LE thus serves as a bridge between audiological diagnostics and environmental design. It provides insight not only into what a listener hears, but also how much effort they must put to comprehend it – highlighting the importance of considering both technological and architectural solutions in parallel (Zekveld *et al.*, 2010; McGarrigle *et al.*, 2014).

Among the factors that can influence the amount of LE are the room acoustics parameters in which a speech signal is presented. One commonly used metric to describe such environments is reverberation time (RT). It is defined as the time it takes for the sound pressure level (SPL) of a specific sound source to decrease by 60 dB after being abruptly switched off (Sabine, 1922). Due to technical limitations (achieving a measurement range exceeding 60 dB is often not possible), RT20 and RT30 measures are typically used, beginning 5 dB below the steady-state energy level (PN-EN ISO, 2010). In such cases, RT20 is three times the time required for a 20 dB SPL decay, while RT30 is twice the time required for a 30 dB SPL drop.

It is commonly known that different event types require different RTs. For music with lyrical content, RTs of approximately 1 s are recommended (Sakai *et al.*, 2000; Ando, 2007), and for music without lyrics, longer RTs are generally preferred (Kuhl, 1954). In theatres, suggested RT may be up to 1.6 s (Meyer, 1978). In auditoriums, big classrooms, and other spaced where speech remains the main signal, lower RT, starting from 0.5 s–0.7 s to 1 s are recommended to maintain proper SI (Bradley, 1985; Everest, 2001). Values within this range prevent reflected sounds from overlapping with the direct signal, a common issue associated with excessively long RTs. From the standpoint of LE, prolonged reverberation may not significantly impact intelligibility scores, but it can impose greater strain on listeners, especially over longer periods or in cognitively demanding contexts. This is particularly relevant in educational or healthcare settings, where even small increases in LE may negatively affect comprehension, memory, and fatigue levels (Herrmann, Johnsrude, 2020).

Interestingly, the subjective perception of reverberation depends on the excitation and noise level, aligning more closely with the early decay time (EDT), which refers to the initial and most perceptually relevant portion of the decaying energy (Kuttruff, 2009), rather than with the RT itself (Ahnert, Tennhardt, 2008).

Due to questions and doubts regarding the potential relationship between objective and subjective parameters that determine a room's acoustics, numerous studies have been conducted at the intersection of room acoustics, audiology, and cognitive science. In numerous studies (e.g., Giménez *et al.*, 2014; Kociński, Ozimek, 2017; Blasinski, Kociński, 2023), objective room parameters are compared with SI as determined by listening tests. This line of research has been particularly prominent in recent years, although the importance of such analyses has long been recognized. The methods for evaluating room acoustics developed by Beranek and Ando are fundamental for this field. Beranek (2004) concentrated on technical parameters such as RT and SI. In contrast, Ando (1998) introduced a more subjective approach, focusing on auditory preferences that consider factors such as the timing of early reflections and the width of the sound source.

Recent approaches increasingly incorporate LE scales, eye-tracking, and pupillometry to assess the mental exertion required in specific acoustic environments. These tools help reveal subtle deficits in comfort or usability that may go undetected through traditional intelligibility measures alone (Wendt *et al.*, 2018). Although these suggested methods were not originally designed to assess LE, they have proven valuable in analyzing room acoustic perception and indicate that even with excellent SI, excessive LE can lead to negative evaluations of room acoustics (Visentin *et al.*, 2018). In this way, LE serves as a more sensitive indicator of acoustic quality than intelligibility alone. It captures the hidden cognitive cost of seemingly 'good' communication – an essential consideration for audiologists, designers, and engineers alike. Assessing LE is therefore crucial in the field of room acoustics, as the ultimate goal is to ensure that human listeners feel comfortable in various enclosures, regardless of whether correct objective parameters or high SI scores. Consequently, after over 100 years of advancements in modern room acoustics, there is a growing emphasis on subjective evaluations, which can now be quantified using objective measures (e.g., effort scale).

Similar to trends in audiology research (Ohlenforst *et al.*, 2017; Wang *et al.*, 2018), there is a growing interest in assessing LE, especially in situations where SI is high. An example that demonstrates the relevance of this distinction is a conversation taking place in a highly reverberant room, where multiple speakers are talking from different directions. An individual with normal hearing is likely to understand most, if not all, of the spoken words, achieving an SI score close to 100 %. However, the level of concentration and cognitive effort required in this scenario is significantly greater compared to a conversation with a single interlocutor in a quiet setting (Visentin *et al.*, 2018).

Ultimately, decisions regarding the placement of equipment that affects room acoustics should consider the comfort of the intended users, defined as achieving minimal or no LE wherever possible.

High SI and low LE are absolutely crucial for ensuring the quality and effectiveness of communication and public address systems in any context.

While SI is a critical requirement, often governed by stringent safety standards and type-approval regulations, such as those for building announcement systems or aircraft communications. Similarly, minimizing LE is essential in challenging environments such as vehicles, mobile phone or headset usage, and conference settings, where poor audio quality can significantly hinder communication.

Therefore, rigorous testing, optimization, and validation are not just recommended – they are essential to guarantee both optimal user experience and, where necessary, compliance with certification standards. Failure to address these factors may compromise both usability and safety.

2. Materials and methods

2.1. Aim

In this study, we focus on speech perception effort as a critical factor in room acoustics. We present an analysis of the subjective characteristic of auditory effort associated with logatome perception, juxtaposed with objective acoustic parameters such as RT20, EDT, clarity (C50), and speech transmission index (STI).

C50, introduced by Marshall (1994), represents the logarithmic ratio of early-to-late arriving sound energy, where 'early' pertains to the initial 50 (or 80) milliseconds, and 'late' denotes the period following this (Kociński, Ozimek, 2017). The 50-millisecond threshold plays a crucial role in distinguishing beneficial reflections from detrimental ones and is instrumental in evaluating a room's suitability for speech perception.

The STI is derived from measurements of the modulation transfer function (Houtgast, Steeneken, 1973) and quantifies signal quality on a scale from 0 (poor intelligibility) to 1 (excellent intelligibility). For the rooms presented in this research, the STI is classified as 'fair' (for enclosure 1 and one setting in enclosure 3) and 'good' for the remaining settings (STI above 0.6). The study was carried out with the greatest possible care, respecting the principles of anonymity of respondents and adhering to the guidelines outlined in the Declaration of Helsinki. Given the scope of the study, ethics committee approval was not required.

2.2. Measurement setup

To create a range of different reverberant conditions, recordings from three enclosures equipped with reverberation enhancement systems (RES) (Lokki, Hiipakka, 2001; Blasinski, Kociński, 2023) were used in the listening tests. RES are recognized for their capacity to augment early reflections and modulate RT while preserving the room's intrinsic acoustic properties (Bakker, Gillian, 2014) by employing digital signal processing technologies. Due to their greater controllability and precision, RES have become increasingly prevalent, and are gradually replacing traditional passive methods such as the use of absorbing panels (Lokki, Hiipakka, 2001).

The Polish logatome test (described in Subsec. 2.3) was convolved with specific room impulse responses (RIRs) recorded from the three enclosures. A detailed description of the room acoustic data collection, equipment used, and methods for estimating the objective parameters determining the characteristics of the enclosures at different RES settings is provided by Blasinski, Kociński (2023). Since these details are of secondary importance to the present research, they are omitted here. Sound samples were presented binaurally via Sennheiser HDA201 headphones connected to an SR46OH DOD preamplifier in a room compliant with American National Standard (1999). Prior to testing, the output sound-pressure levels of the headphones were calibrated using a Brüel & Kjaer 2203 level meter and a Brüel & Kjaer 4152 artificial ear. Throughout the 20-minute experiment, the speech level was maintained at 65 dB SPL at the eardrum. Each participant was presented with three phonetically balanced 50-element logatome lists convolved with RIRs from one of the three rooms under different RES settings. The logatomes were presented without any masking signal.

2.3. Listeners

Before the listening task, each of the 180 volunteers (60 per tested enclosure) underwent a hearing threshold examination conducted by a qualified specialist using a GSI 61 clinical audiometer and standard audiologic headphones (HDA200). The analysis of individual results, averaged across four frequencies (0.5 kHz, 1 kHz, 2 kHz, and 4 kHz), classified all participants as having normal hearing according to World Health Organization (2021) criteria. None of the subjects reported any accompanying symptoms such as tinnitus or auditory hypersensitivity.

2.4. Test material

Describing and evaluating an enclosure's acoustic characteristics involves measurable acoustic parameters. Another source of information, as demonstrated in this study, is the assessment of SI using language-based tests. The results of subjective evaluations of speech transmission quality should, as far as possible, depend on the physical parameters of the communication channel being tested. Therefore, elimination of the information at the semantic level using lists of logatomes (nonsense words) (Brachmański, Dobrucki, 2021) is one of the recommended solutions, employed in this study. Logatomes are indeed more difficult for listeners, but also more reliable and robust, due to their low redundancy compared to, e.g., words, digits or sentences. Similar test material has been utilized in Polish studies, for example, by Brachmański (2021), who evaluated logatome-based SI transmitted through communication channels using the STI method.

Using nonsense words has the advantage of eliminating higher-level language processing that listeners use to understand words of degraded quality (Danhauer *et al.*, 1985). Consequently, the influence of cognitive association is limited, making hearing acuity more important than lexical prediction based on speech context or the participant's vocabulary. This approach results in decreased SI, measured as the percentage of correctly repeated words or sentences, because the amount of provided useful (meaningful) information is reduced (Stickney, Assmann, 2001). To avoid unnecessary listener fatigue that could impact speech perception while ensuring sufficient accuracy, lists of 50 or 100 logatomes are typically used (Howard, Angus, 2017). In this experiment, each RES setup was tested using a 50-element logatome list.

To ensure consistent assessment and minimize bias, all responses were evaluated by a single individual with expertise in SI research. Only accurately written logatomes (excluding spelling errors) were deemed correctly understood, employing binary word scoring as proposed by Kociński and Ozimek (2017).

2.5. Listening effort determination

In addition to the intelligibility test described above, all participants were asked to evaluate their perceived LE after each logatome list presentation. A 7-point Likert scale was used, ranging from 1 (no effort) to 7 (extreme effort), following methods similar to those used by Johnson *et al.* (2015).

3. Results

As was mentioned above, the most important and commonly used objective parameters used in room acoustics assessment are RT (RT30/RT20, EDT), C50, STI, and subjective SI. To investigate their influence on LE, we decided to compare LE scores with these objective measures. The calculated objective parameters and logatome intelligibility results are described in (Blasinski, Kociński, 2023). The averaged LE values, along with their standard deviations (in parentheses), are presented in Table 1.

Table 1. LE ratings in all room setups and across different RT20.

Enclosure	Setup	RT20 [s]	LE [1–7]
1	Setup 1	0.8 (0.3)	2.57 (1.18)
	Setup 2	1.1 (0.1)	2.90 (1.24)
	Setup 3	1.4 (0.1)	3.32 (1.45)
2	Setup 1	0.9 (0.0)	2.59 (1.18)
	Setup 2	1.2 (0.1)	3.18 (1.39)
	Setup 3	1.6 (0.1)	3.50 (1.50)
3	Setup 1	2.5 (0.1)	3.45 (1.48)
	Setup 2	3.1 (0.2)	3.43 (1.48)
	Setup 3	4.2 (0.2)	3.58 (1.58)

Figure 1 illustrates the relationship between RT (all nine values – three from each enclosure) and repor-

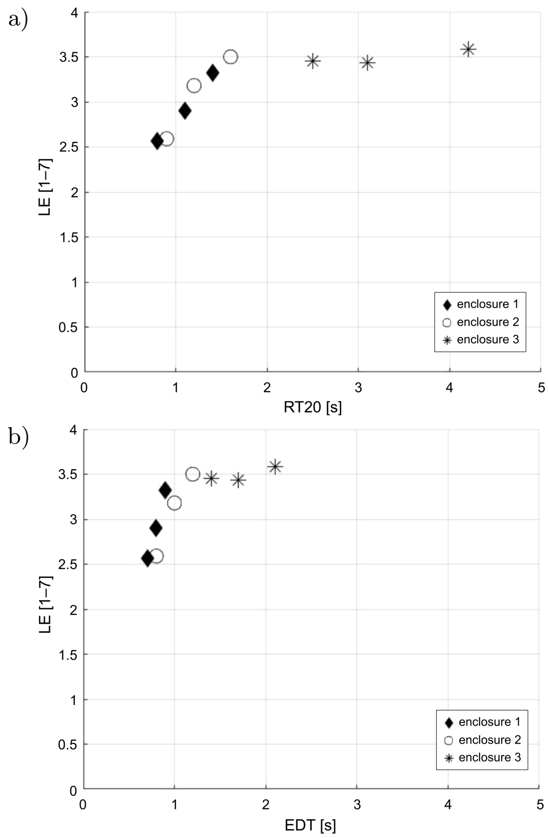

Fig. 1. LE as a function of (a) RT20 and (b) EDT.

ted LE. There is undoubtedly a trend where the reported LE increases with longer RT; however, a linear fit is not appropriate as $R^2 = 0.55$. A slightly stronger relationship is observed between LE and EDT, as indicated by an R^2 value of 0.56. Nevertheless, it still it is not sufficient to claim a linear relationship.

In this study, no significant correlation was found between LE and C50, as indicated by a Pearson correlation coefficient of 0.46 (Fig. 2). This suggests that variations in C50 do not reliably predict changes in LE.

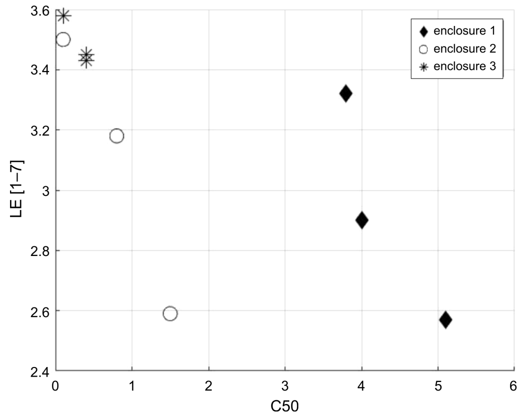

Fig. 2. LE as a function of C50.

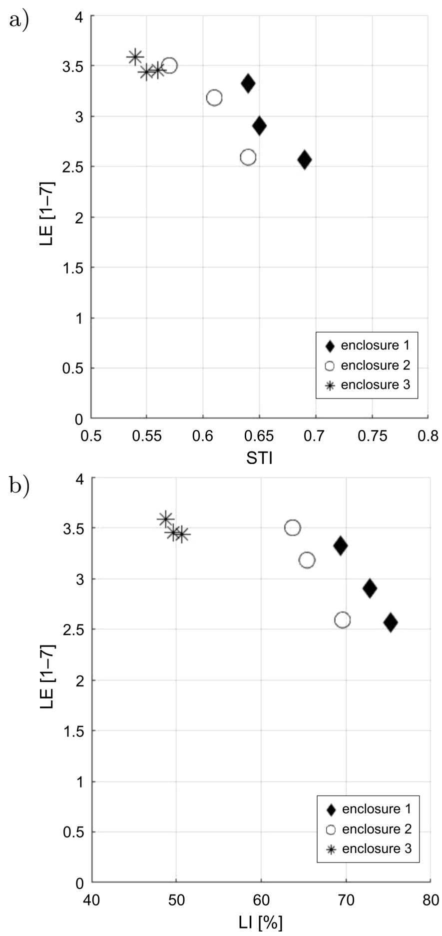

Fig. 3. LE as a function of (a) STI and (b) LI.

In the final analysis, LE was compared with both objective and subjective measures (determined in tests with listeners) of SI.

Here, SI was defined as the percentage of correctly repeated logatomes from a 50-element list (as described in Subsec. 2.3). In contrast, the objective indicator used was the STI, which considers not only the acoustic characteristics of the enclosure but also the entire transmission channel (Houtgast, Steeneken, 1984). Figure 3 depicts LE as a function of objective intelligibility (STI) and measured logatome intelligibility (LI). It can be observed that for STI Pearson correlation coefficient is 0.74, while for LI it is only 0.55.

4. Discussion

This study compared objective room characteristics with the LE associated with understanding speech presented under conditions defined by these parameters. Given that:

- the logatom test is unaffected by the individual's lexicon knowledge (Giovannone, Theodore, 2021);
- the test items eliminate reliance on the context of the utterance;
- the entire test lasted less than 20 min, consistent with Brachmański and Dobrucki (2021), minimizing the effects of fatigue;
- all participants were of similar age (mean 23.5) and had normal hearing.

It is assumed that the only factor affecting SI is the characteristics of the propagation path (i.e., the enclosure) with potential influence of other non-auditory factors.

A slight trend of increasing mean LE values with higher RTs, along with a a correlation between higher LE and decreased LI, was observed. However, no statistical significance ($p > 0.05$) was found with R^2 values 0.56 for RT20 and 0.61 for LI. It is plausible that listeners overestimate their performance despite lower actual intelligibility levels. This tendency is particularly pronounced when using nonsense words, as listeners find it more challenging to assess their responses compared to semantically meaningful linguistic material. Another potential explanation for this lack of significance, and a limitation of this study, is that the 7-point scale used to measure LE may not be sensitive enough to detect differences across the range of RT20 values.

It is noteworthy that, although STI values were below 0.6 in environments with the longest RT20 (which typically corresponds to a 'fair' quality rating according to International Electrotechnical Commission (2020) standard), the LE scores did not significantly differ from those observed in environments with higher STI values. This suggests that, despite less favorable acoustic conditions, cognitive effort required was not significantly influenced. While the limitations of using a 7-point scale to measure LE across a range of RT20 values are acknowledged, it is argued that eliminating subjective effort assessment from SI test batteries would be unjustified. Nonetheless, it is acknowledged that further research is needed to redefine the study protocol in this aspect.

These findings align with a broader body of research highlighting the complexity of LE and its multifactorial underpinnings (Pichora-Fuller *et al.*, 2016; Ohlenforst *et al.*, 2017). Rather than aiming to redefine established models, this study contributes additional empirical data to an evolving and nuanced discussion within audiology and room acoustics. Such incremental research remains vital as the field continues to seek integrative frameworks that combine objective acoustical parameters with subjective listener experiences (McGarrigle *et al.*, 2014; Visentin *et al.*, 2018).

For the three shortest RTs, reported effort falls slightly below a score of 3, whereas for all longer RTs, it edges slightly above 3 on a 7-point scale. This suggests that the effort required to comprehend logatomes remains relatively consistent across varying RTs.

Interestingly, LE correlates more strongly with the STI than with RT. However, due to the relatively small number of RES settings (nine in total), it would be premature to draw definitive conclusions. One possible reason behind this observation may be that STI is a more direct measure of intelligibility, encompassing a broader range of factors influencing speech signal comprehension. STI incorporates factors such as signal distortions and modulation, offering a more comprehensive assessment compared to the mere duration of sound persistence in a room after the source is switched off. It may be presumed that listeners subjectively assess their LE based on their overall SI, a metric better represented by STI than by RT.

Although statistical analysis reveals noticeable correlations between LE and various acoustic parameters, these relationships do not lend themselves easily to straightforward mathematical modeling. This is not entirely surprising, given the complex and inherently physical nature of LE. Still, the absence of a clearly defined functional relationship – such as that established between STI and LE or SI and LE – suggests that LE cannot yet be accurately predicted using objective parameters alone. This reinforces the idea that LE should be considered a separate and complementary descriptor when designing or adapting room acoustics. Its inclusion may help bridge the gap between objective acoustic indicators and the actual perceptual experiences of listeners.

While a linear fit can be applied to the relationship between declared LE and STI values, with Pearson's correlation coefficient reaching a significant R^2 value of 0.72, it cannot be assumed that cognitive effort in understanding speech in enclosures with varying acoustic characteristics, as defined by RES settings, can be estimated solely based on STI. Nevertheless, STI remains the measure most closely related to cognitive load, particularly LE. However, it is important to note that STI is not the only influencing factor. One should remember that until now it was assumed that one could rely on STI, with evaluations often limited to it (or other objective parameters). In some studies, additional measurements of SI with listeners were conducted (e.g., Hodgson, 2004). It turns out that the issue may be more complex, as indicated by results that are difficult to interpret clearly in terms of a specific functional relationship between predictors and LE. It should be noted that the relationship does not appear to be linear, but there is insufficient data to draw firm conclusions, necessitating further research. It is clear, however, that intelligibility alone is not sufficient, LE is also crucial. This effort can significantly influence the overall evaluation of a room. Consequently, a space might have good intelligibility and acoustic parameters indicating high quality, yet still be perceived poorly due to the high effort required from listeners.

Based on the obtained data, it is apparent that further research is essential. Although early attempts to consider the broad subjective experiences of listeners, beyond just physical measures and models, were made by Beranek (2004) and Ando (2007), it seems reasonable to address the issue of LE. This could involve developing specific tools and methods for its evaluation, incorporating a wider variety of system settings and possibly employing a different scale for rating LE (e.g., categorical or adaptive scales like ACALES (Krueger *et al.*, 2017)).

5. Conclusions

The presented findings reveal only a modest relationship between the objective acoustic parameters of the enclosures, as defined by the RES setting, and LE. Notably, there was lack of correlation with RT, commonly associated with SI but intricately linked to cognitive effort. Conversely, the strongest correlation coefficient was observed between LE and the STI, which may be attributed to the complexity inherent in this objective parameter. Over the past century, objective methods for room acoustics analysis have developed significantly. Numerous parameters have been established and are now considered standards widely used in measurements. However, it appears that the crucial role of the listener in the audience and the performer on stage in determining whether a room meets their acoustic expectations has been somewhat overlooked.

Given the ambiguous relationship between LE and standard acoustic parameters, it becomes evident that LE cannot be easily predicted or derived from existing objective metrics alone. This underscores its potential as an independent and valuable indicator in comprehensive room acoustic assessment. Incorporating subjective measures such as LE into the design and adaptation processes enables the capture of perceptual aspects that objective measurements may overlook (Pichora-Fuller *et al.*, 2016; McGarrigle *et al.*, 2014). Ultimately, it is the human listener – not the abstract parameter set – who validates acoustic quality. Thus, including cognitive effort metrics provides a more representative evaluation of real-world listening conditions (Visentin *et al.*, 2018; International Organization for Standardization, 2018). This aligns with the broader shift in acoustic and auditory sciences, toward emphasizing not only what is measurable, but also what is perceptually meaningful (Oxenham, 2017; Rudner, *et al.*, 2012).

In the case of spoken performances, which this study focused on, it seems that parameters such as RT, C50, and STI do not predict the LE required to understand speech. This effort, however, may be critical in the overall evaluation of a room's acoustics, similar to how subjective preferences influence hearing aid users, which often determine their use despite objectively measured and adjusted parameters indicating improved auditory performance. Although the current data is limited, it is clear that intelligibility alone is insufficient – LE plays also a crucial role. This cognitive effort can significantly influence the overall evaluation of a room. Consequently, an enclosure may exhibit good intelligibility and favorable acoustic parameters indicating high quality, but still be perceived poorly due to the high effort listening it requires. Given the substantial impact of cognitive effort on listener experience, it is essential to consider metrics describing cognitive effort in the characterization of room acoustics, particularly for the presentation of speech signals.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of 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.

Authors' contribution

Anna Pastusiak: conceptualization (equal), methodology (equal), data curation (equal), writing – original draft (lead). Łukasz Błasiński: conceptualization (equal), methodology (equal), data curation (equal), writing – review and editing (equal). Jędrzej Kociński: formal analysis (lead), writing – review and editing (equal), supervision (lead). All authors reviewed and approved the final manuscript.

Ethical approval

The study was conducted in accordance with the World Medical Association's Declaration of Helsinki. An informed consent was obtained from each participant. All data were anonymized prior to analysis.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors would like to thank all the participants and Maciej Buszkiewicz for assistance during listening tests.

References

1. Ahnert W., Tennhardt H.P. (2008), Acoustics for auditoriums and concert halls, [in:] *Handbook for Sound Engineers*, Ballou G.M. [Ed.], Focal Press, Waltham.
2. American National Standard (1999), *Maximum permissible ambient noise levels for audiometric test rooms* (Standard ANSI S3.1-1999 (R2003)).
3. Ando Y. (1998), *Architectural Acoustics: Blending Sound Sources, Sound Fields, and Listeners*, Springer New York, NY.
4. Ando Y. (2007), Concert hall acoustics based on subjective preference theory, [in:] *Springer Handbook of Acoustics*, Rossing T.D. [Ed.], pp. 351–386, Springer New York, NY.
5. Bakker R., Gillian S. (2014), The history of active acoustic enhancement systems, [in:] *Proceedings of the Institute of Acoustics*, **36**(Part 2).
6. Beranek L.L. (2004), *Concert Halls and Opera Houses: Music, Acoustics, and Architecture*, Springer.
7. Blasinski L., Kociński J. (2023), Perception of reverberation length in rooms with active acoustics enhancement systems, [in:] *Proceedings of the 10th Convention of the European Acoustics Association Forum Acusticum 2023*, pp. 1627–1634, https://www.doi.org/10.61782/fa.2023.0235.
8. Brachmański S. (2021), Test material used to assess speech quality in Poland, [in:] *Acoustics, Acoustoelectronics and Electrical Engineering*, Witos F. [Ed.], pp. 65–79, Wydawnictwo Politechniki Śląskiej, Gliwice.
9. Brachmański S., Dobrucki A. (2021), Impact of the level of noise and echo on the reaction time of listeners in the perception of logatoms, *Vibrations in Physical Systems*, **32**(2): 2021215-1–2021215-8, https://doi.org/10.21008/j.0860-6897.2021.2.15.

10. Bradley J.S. (1985), Uniform derivation of optimum conditions for speech in rooms, [in:] *Building Research Note* (no. BRN-239), https://doi.org/10.4224/40000478.

11. Danhauer J.L., Doyle P.C., Lucks L. (1985), Effects of noise on NST and NU 6 Stimuli, *Ear & Hearing*, **6**(5): 266–269, https://doi.org/10.1097/00003446-198509000-00008.

12. Everest F.A. (2001), *The Master Handbook of Acoustics*, 4th ed., p. 153, McGraw Hill, New York.

13. Festen J.M., Plomp R. (1990), Effects of fluctuating noise and interfering speech on the speech-reception threshold for impaired and normal hearing, *The Acoustical Society of America Journal*, **88**(4): 1725–1736, https://doi.org/10.1121/1.400247.

14. Giménez A., Cibrián R.M., Cerdá S., Girón S., Zamarreño T. (2014), Mismatches between objective parameters and measured perception assessment in room acoustics: A holistic approach, *Building and Environment*, **74**: 119–131, https://doi.org/10.1016/j.buildenv.2013.12.022.

15. Giovannone N., Theodore R.M. (2021), Individual differences in lexical contributions to speech perception, *Journal of Speech, Language, and Hearing Research*, **64**(3): 707–724, https://doi.org/10.1044/2020_JSLHR-20-00283.

16. Herrmann B., Johnsrude I.S. (2020), A model of listening engagement (MoLE), *Hearing Research*, **397**: 108016, https://doi.org/10.1016/j.heares.2020.108016.

17. Hodgson M. (2004), Prediction of speech intelligibility in rooms – A comparison of five methods, *The Journal of the Acoustical Society of America*, **116**(4 Supplement): 2638, https://doi.org/10.1121/1.4785523.

18. Houben R., van Doorn-Bierman M., Dreschler W.A. (2013), Using response time to speech as a measure for listening effort, *International Journal of Audiology*, **52**(11): 753–761, https://doi.org/10.3109/14992027.2013.832415.

19. Houtgast T., Steeneken H.J.M. (1973), The modulation transfer function in room acoustics as a predictor of speech intelligibility, *The Journal of the Acoustical Society of America*, **54**(2): 557, https://doi.org/10.1121/1.1913632.

20. Houtgast T., Steeneken H.J.M. (1984), A multi-language evaluation of the RASTI-method for estimating speech intelligibility, *Acustica*, **54**(4): 185–199.

21. Howard D.M., Angus J.A.S. (2017), *Acoustics and Psychoacoustics*, 5th ed., Routledge, Oxfordshire.

22. International Electrotechnical Commission (2020), *Sound system equipment – Part 16: Objective rating of speech intelligibility by speech transmission index* (Standard no. IEC 60268-16:2020).

23. International Organization for Standardization (2018), *Acoustics – Soundscape. Part 2: Data collection and reporting requirements* (ISO/TS Standard No. 12913-2:2018), https://www.iso.org/standard/75267.html.

24. Johnson J., Xu J., Cox R., Pandergraft P. (2015), A comparison of two methods for measuring listening effort as part of an audiologic test battery, *The Journal of the Acoustical Society of America*, **24**(3): 419–431, https://doi.org/10.1044/2015_AJA-14-0058.

25. Just M.A., Carpenter P.A. (1992), A capacity theory of comprehension: Individual differences in working memory, *Psychological Review,* **99**(1): 122–149, https://doi.org/10.1037/0033-295X.99.1.122.

26. Kociński J., Ozimek E. (2017), Logatome and sentence recognition related to acoustic parameters of enclosures, *Archives of Acoustics*, **42**(3): 385–394, https://doi.org/10.1515/aoa-2017-0040.

27. Krueger M., Schulte M., Brand T., Holube I. (2017), Development of an adaptive scaling method for subjective listening effort, *The Journal of the Acoustical Society of America*, **141**(6): 4680–4693, https://doi.org/10.1121/1.4986938.

28. Kuhl W. (1954), About trying to find the best reverberation time for big music studios [in German], *Acta Acustica United with Acustica*, **4**(5): 618–634.

29. Kuttruff M. (2009), *Room Acoustics*, 5th ed., Spon Press, London.

30. Lemke U., Besser J. (2016), Cognitive load and listening effort: Concepts and age-related considerations, *Ear & Hearing,* **37**(1): 77S–84S, https://doi.org/10.1097/AUD.0000000000000304.

31. Lokki T., Hiipakka J. (2001), A time variant reverberation algorithm for reverberation enhancement systems, [in:] *Proceedings of the COST G-6 Conference on Digital Audio Effects (DAFX-01)*, pp. 28–32.

32. Marshall L.G. (1994), An acoustic measurement program for evaluating auditoriums based on the early/late sound energy ratio, *The Journal of Acoustical Society of America*, **96**(4): 2251–2261, http://doi.org/10.1121/1.410097.

33. Mattys S.L., Davis M.H., Bradlow A.R., Scott S.K. (2012), Speech recognition in adverse conditions: A review, *Language and Cognitive Processes*, **27**(7–8): 953–978, https://doi.org/10.1080/01690965.2012.705006.

34. McGarrigle R. *et al.* (2014), Listening effort and fatigue: What exactly are we measuring? A British Society of Audiology Cognition in Hearing Special Interest Group 'white paper', *International Journal of Audiology*, **53**(7): 433–440, https://doi.org/10.3109/14992027.2014.890296.

35. Meyer J. (1978), *Acoustics and the Performance of Music*, Frankfurt/Main: Verlag das Musikinstrument, Frankfurt/Main.

36. Ohlenforst B. *et al.* (2017), Effects of hearing impairment and hearing aid amplification on listening effort: A systematic review, *Ear & Hearing*: **38**(3), 267–281, https://doi.org/10.1097/AUD.0000000000000396.

37. Oxenham A.J. (2017), How we hear: The perception and neural coding of sound, *Annual Review of Psychology*, **69**: 27–50, http://doi.org/10.1146/annurev-psych-122216-011635.

38. Peelle J.E. (2018), Listening effort: How the cognitive consequences of acoustic challenge are reflected in brain and behavior, *Ear & Hearing*, **39**(2): 204–214, https://doi.org/10.1097/AUD.0000000000000494.

39. Pichora-Fuller M.K. *et al.* (2016), Hearing impairment and cognitive energy: The framework for understanding effortful listening (FUEL), *Ear & Hearing*, **37**(1): 5S–27S, https://doi.org/10.1097/AUD.0000000000000312.

40. PN-EN ISO (2010), *Acoustics – Measurement of room acoustic parameters. Part 1: Reverberation time in ordinary rooms* [in Polish: *Akustyka – Pomiar parametrów akustycznych pomieszczeń. Część 1: Czas pogłosu w zwyczajnych pomieszczeniach*] (PN-EN ISO 3382-1:2010).

41. Rudner M., Lunner T., Behrens T., Thorén E.S., Rönnberg J. (2012), Working memory capacity may influence perceived effort during aided speech recognition in noise, *Journal of the American Academy of Audiology*, **23**(8): 577–589, http://doi.org/10.3766/jaaa.23.7.7.

42. Sabine W.C. (1922), *Collected Papers on Acoustics*, p. 279, Cambridge (MA), Harvard University Press.

43. Sakai H., Ando Y., Setoguchi H. (2000), Individual subjective preference of listeners for vocal music sources in relation to the subsequent reverberation time of sound fields, *Journal of Sound and Vibration*, **232**(1): 157–169, https://doi.org/10.1006/jsvi.1999.2691.

44. Shinn-Cunningham B.G., Best V. (2008), Selective attention in normal and impaired hearing, *rends in Amplification*, **12**(4): 283–299, https://doi.org/10.1177/1084713808325306.

45. Schmid P.M., Yeni-Komshian G.H. (1999), The effects of speaker accent and target predictability on perception of mispronunciations, *Journal of Speech, Language, and Hearing Research*, **42**(1): 56–64, https://doi.org/10.1044/jslhr.4201.56.

46. Stickney G.S, Assmann P.F. (2001), Acoustic and linguistic factors in the perception of bandpass-filtered speech, *The Journal of the Acoustical Society of America*, **109**(3): 1157–1165, https://doi.org/10.1121/1.1340643.

47. Strand J.F., Brown V.A., Merchant M.B., Brown H.E., Smith J. (2018), Measuring listening effort: Convergent validity, sensitivity, and links with cognitive and personality measures, *Journal of Speech, Language, and Hearing Research*, **61**(6): 1463–1486, https://doi.org/10.1044/2018_JSLHR-H-17-0257.

48. Visentin C., Prodi N., Cappelletti F., Torresin S., Gasparella A. (2018), Using listening effort assessment in the acoustical design of rooms for speech, *Building and Environment*, **136**: 38–53, https://doi.org/10.1016/j.buildenv.2018.03.020.

49. Wang Y. *et al.* (2018), Relations between self-reported daily-life fatigue, hearing status, and pupil dilation during a speech perception in noise task, *Ear & Hearing*, **39**(3): 573–582, https://doi.org/10.1097/aud.0000000000000512.

50. Wendt D., Koelewijn T., Książek P., Kramer S.E., Lunner T. (2018), Toward a more comprehensive understanding of the impact of masker type and signal-to-noise ratio on the pupillary response while performing a speech-in-noise test, *Hearing Research*, **369**: 67–78, https://doi.org/10.1016/j.heares.2018.05.006.

51. Wild C.J., Yusuf A., Wilson D.E., Peelle J.E., Davis M.H., Johnsrude I.S. (2012), Effortful listening: The processing of degraded speech depends critically on attention, *Journal of Neuroscience*, **32**(40): 14010–14021, https://doi.org/10.1523/JNEUROSCI.1528-12.2012.

52. World Health Organization (2021), World report on hearing, https://www.who.int/publications/i/item/9789240020481 (access: 08.05.2025).

53. Zekveld A.A., Kramer S.E., Festen J.M. (2010), Cognitive load during speech perception in noise: The influence of age, hearing loss, and cognition on the pupil response, *Ear & Hearing*, **32**(4): 498–510, https://doi.org/10.1097/AUD.0b013e31820512bb.