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The impact of sound field amplification systems on speech perception of pupils with and without language disorders in natural conditions

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ABSTRACT

The purpose of the study was to investigate in natural conditions the impact of sound field amplification systems (SFAS) on the perception of monosyllabic nonsense words in first to fourth-grade students with and without language disorders in classrooms with different acoustics.

One hundred forty-five monolingual primary school pupils were included in the study. Two study groups were formed: pupils with typical language development (TD) (n = 145) and pupils with developmental language disorders (LD) (n = 72). Acoustic measurements were made in twelve classrooms with different reverberation time. Monosyllabic nonsense words perception tests, presented by an examiner, were carried out in classrooms with and without SFAS.

The number of errors in the test carried out with SFAS in different acoustic conditions reduced in pupils of Grade 1 with TD (Z = –2.273, p = .023; Z = –1.965, p = .049) and with LD (Z = –2.410, p = .016; Z = –2.156, p = .031). The SFAS installed in large classrooms with long reverberation time significantly increased the number of errors in nonsense monosyllables perception ($r_S = 0.361$, $p < .01$, $r_S = 0.229$, $p < .01$). The mean number of errors in children with LD was higher than in children with TD in monosyllabic nonsense words tests carried out with and without SFAS (U = 3194, p < .001; U = 3518.5, p < .001).

First-grade students benefit from sound field amplification in perception of monosyllabic nonsense words regardless of classrooms acoustics, and irrespective of the level of language development. The positive effect of SFAS on nonsense word perception was not observed in pupils of Grade 2, 3, and 4 of primary school. Classroom acoustics affects the expected positive impact of SFAS for children older than first graders. Amplification increases speech perception and decreases the number of errors in the reproduction of monosyllabic nonsense words in classrooms with short reverberation time.

1. Introduction

The education process is realized through strong interaction between teacher, children, and classroom environment. One of the education goals is the acquisition of knowledge. Academic success can be significantly impacted by poor classroom acoustics conditions and insufficient transmission of teachers' instructions. A major premise of the educational system is undermined if a child cannot hear the teacher clearly and consistently [1].

Listening is an essential element of lessons, especially in primary school. Listening involves auditory discrimination, aural grammar, selecting necessary information, remembering it, and connecting it to the process of comprehension [2]. A good sound discriminability improves understanding of verbal instructions [3]. According to Ling (2002) comprehension is the highest level of speech perception process. To reach this listener have to detect, discriminate, recognize, and identify speech sounds [4]. Learning to listen and becoming a discriminating consumer of auditory signals in a classroom is an often-overlooked factor in reducing the magnitude of acoustical barriers [5]. On the other hand, a good listening environment, which provides an accurate transmission of acoustic information in a classroom, improves speech perception in normal-hearing children as well as in children with language and hearing disorders, especially in early primary grades [5–8].

The interaction between classroom acoustics and acoustic signal inside the classroom produced by the teacher may impact listeners' attention, behavior, listening skills, speech sound discrimination and perception [7,9,10]. The different factors such as room acoustics, i.e. excessive reverberation and low speech clarity [11], low signal-to-noise ratio (SNR), large talker-to-listener

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distance, young age and poor language development can affect all functions mentioned above. Classrooms' acoustical quality correlates to speech comprehension, which is correlated to the Speech Transmission Index [12]. The Speech Transmission Index (STI) is an objective method for prediction and measurement of speech intelligibility, which combines the speech-to-noise level difference and the room acoustics in a single quantity [13]. Speech intelligibility is quantified as the percentage of a message understood correctly. Younger students in primary school have more difficulties understand words in the lower STI range than pupils of higher grades [14]. Speech intelligibility is closely related to reverberation time which depends on room volume and mode of use [15]. In unoccupied classrooms with pediatric listeners, maximum reverberation time for sound pressure level in octave bands with mid-band of 500, 1000, and 2000 Hz should not exceed 0.6 s for maximum speech recognition [16,17]. Astolfi et al. (2012) found that decrease of reverberation time results in increase of speech intelligibility in primary school pupils over the A-weighted speech-to-noise level difference of −15 to +6 dB [14]. Furthermore, the shorter reverberation times are perceived as being acoustically more favorable for spoken communication for people with speech processing problems and bilinguals [15].

One of the crucial factors promoting speech perception and sound discrimination is an adequate speech-to-noise level difference [18]. According to World Health Organization recommendations, students with language disorders, first graders, and bilingual speakers need higher SNR than other children [17]. Picard and Bradley (2001) estimated the optimal values of the mid-frequency reverberation time and the minimum value of the SNR for 6–7 years old students, in occupied classrooms, to be 0.5 s and +25 dB, respectively [19]. In a recent review by Greenland and Shield (2019) on acceptable classroom acoustics criteria for children with special hearing and communication needs (SHCN), they concluded that a reasonably criterion for reverberation time in occupied classrooms is 0.45 s in combination with +15 dB SNR, which is practically achievable with an ambient noise level of up to 40 dB(A) [20].

The typical strategy that teachers use for providing appropriate SNR in the classroom is to produce a louder voice [21–23]. Moreover, with long reverberation time a tendency to increase the voicing periods as the reverberation time increases was observed for teachers, with consequent possible increase in vocal fatigue [24]. These approaches are widespread in schools but are not supported from a voice ergonomics standpoint [25]. An alternative strategy of how to decrease vocal intensity and increase SNR is using sound field amplification systems (SFAS). These systems are designed to amplify the teacher's voice so that it is delivered clearly and consistently to all pupils [26]. Another benefit of SFAS is uniform amplification of the signal through the classroom. There are several studies which investigated the effect of SFAS on speech perception and auditory analysis [7,10,27]. The aim of Vicker et al. (2013) study was to investigate speech perception in quiet and in noise with and without SFA systems. They used a closed-set speech perception test which targeted consonant discrimination, to examine the effect of sound field amplification devices in regular classrooms. Forty-four children, most of them with bilingual language background, decreased expressive vocabulary age, middle ear dysfunction and special education needs, representing second and third school year, were tested twice, once with amplification systems and once without. Results showed that group performance in perception tasks was significantly better with SFA than without it. Also, the results showed that developmental language level critically affects the ability to perceive speech in listening conditions with high background noise, and researchers have highlighted that use of SFAS are more beneficial for children with language disorders [10]. The similar positive effect of SFAS on listening and perception was found in the study performed by Wilson et al. (2011). Wilson et al. compared improvement of students' listening, spelling, reading comprehension, and auditory analysis skills over 16–18 weeks in classrooms equipped both with and without SFA devices. One hundred forty-seven eight-year-old students represented monolingual and bilingual children, as well as children with typical and delayed language development. The use of SFAS contributed to small but significant improvement in listening and auditory analysis skills, but only in classrooms where lower background noise level and lower reverberation time were found [27]. Another study indicating beneficial effects of SFAS in the classrooms was carried out by Eriks-Brophy & Ayukawa (2000). Two randomized lists of 42 Inuit syllables were used to investigate the perception of speech intelligibility of 10 students with bilateral hearing loss and ten age-matched students with normal hearing. Students heard one list of syllables with the amplification system on and the other list with the system off. The additional background noise of 60 dB was provided during the experiment. Both groups of students showed significant improvement in performance on a speech intelligibility task in amplified conditions. The mean number of errors significantly reduced in children with normal hearing when SFA systems were turned on (the mean number of errors 14.6 vs 4.9 out of 42). Furthermore, learning new words more quickly and more active participation in discussions were reported as potential benefits of sound field systems in the study of Eriks-Brophy & Ayukawa [7].

Although all studies mentioned above had different study design, they shared the common conclusion that the use of SFA systems improves speech perception and listening abilities in students. However, none of them includes all set of factors that could impact speech perception, such as students age and grade covering a more extensive range of primary education and level of language development. Also, classrooms volume and acoustic properties such a reverberation time, background noise level and Speech Transmission Index for Public Address Systems (STIPA) play a significant role in speech perception. This study aimed to investigate the impact of SFAS on the perception of monosyllabic nonsense words taking into account all these factors, i.e., students from the first to fourth grade, students with and without language disorders, and classrooms with different acoustical conditions. Here and hereafter the perception of monosyllabic nonsense words referred to students' ability to identify speech sounds, i.e., ability to choose target phonemes from infinitive set of alternatives [4]. The study was intended to answer the following research questions: (1) Does the impact of SFAS on perception of monosyllabic nonsense words differ in children with and without language disorders? (2) Does classrooms acoustics impact the effect of SFAS on perception of monosyllabic nonsense words?

2. Methods

2.1. Study environment

The impact of SFAS on speech perception was investigated in three different architectural-style urban school buildings built over various periods: 1938, 1991, 2008. The use of different construction materials and the different size of classrooms created different acoustic conditions, which were the rationale for choosing these schools for the experimental study. Twelve classrooms were included in the study (see Table 1), and the number of students in each classroom ranged from 22 to 30. There was no heating, ventilation, or air conditioning (HVAC) making noise.

Table 1
Description of the schools and classrooms.

School	Location of the school	Classrooms, location	Description of classrooms
1 Anno 1991	On the outskirts of a residential area, near the seaside and harbor leading by a high traffic road. There was a square between the street and the school building.	N 1, 2, 3: first floor; N 4, 5, 6: second floor; N 7, 8: third floor. Classrooms N 1, 3–8 had windows facing the street. N 2 had windows facing the courtyard.	Walls: plastered and painted; Floor: linoleum; Ceiling: concrete-panels, 3.0 m high.
2 Anno 1939	Near the city center.	N 9, 10: on the third floor, windows facing the quiet street.	Walls: covered with wooden panels (1.5 m from floor) and painted plaster; Floor: wooden desks; Ceiling: concrete, 3.8 m high.
3 Anno 2008	Near the city center, near a high traffic street.	N 11: third floor, windows facing the high traffic street; N 12: third floor, windows facing the courtyard.	Walls: painted plaster walls; Floor: linoleum; Ceiling: concrete, 3.5 m high.

2.2. Participants

Three hundred nineteen primary school students from 12 classes of three schools underwent a screening procedure which included assessment of oral and written language, assessment of phonological decoding function with the Latvian version of the Word Chain Test (WCT) [28], and peripheral hearing screening (Handheld audiometer PA 5, Interacoustics). One hundred two children were excluded from participation in the study due to hearing disorders ($n = 9$), attendance of integrated special education programs (children with intellectual disability, autism spectrum disorders, $n = 7$), bilingualism ($n = 33$), other reasons such as the absence of parental consent to participate in the study ($n = 53$). Information about the children such as age, native language, other language uses, as well as educational track, was obtained through questionnaires answered by parents.

Two hundred seventeen children from first to fourth grade were included in the study. Developmental language disorders were detected during the assessment of oral and written language, and two study groups – children with typical language development (TD, $n = 145$) and children with developmental language disorders (LD, $n = 72$) were set up (see Table 2). The experimental study design envisaged an encoding of perceived non-words into written symbols. Therefore, phonological decoding function was assessed to all children at the participants' selection stage by the WCT. The WCT is a test of silent words recognition which is used for detecting children with reading difficulties. Following Jacobson's original version, WCT was preceded by the Letter Chain Test (LCT) which purpose was to control visuospatial function, i.e., letter recognition. Children with disorders of decoding functions were included in the LD group. All of these children had normal scores in the LCT. All children included in the study were monolinguals; their native language was Latvian.

Two classes (respectively, two classrooms) represented each grade from first to fourth in the school N 1, e.g., first-year students from two classes were selected to participate in the study. First and third-year pupils represented one class each in the school N 2. The same in school N 3 – second and fourth-year students represented one class each (see Table 2). The number of children with developmental language disorders was much higher in school N 1 than in other schools because there were special education programmes which provided intensive pedagogical assistance to children with language disabilities. School N 2 & 3 did not have such a programme, but children who had language disorders received the same speech and language therapy service individually. The demographic characteristics of the study participants were demonstrated in Table 3.

2.3. Acoustic measurements

Acoustic measurements were made in all 12 classrooms. Equivalent A-weighted continuous sound pressure level (L_{Aeq}) of background noise and reverberation time (T_{30}) were measured in unoccupied classrooms. Speech Transmission Index for Public Address Systems (STIPA) and L_{Aeq} during class activity (activity noise) were measured in occupied classrooms. In order to check the reverberation time in occupied conditions (T_{oc}), corrected reverberation time values were calculated applying the Sabine formula, in which the absorption of the seated children was added [29].

Reverberation time was measured using a wooden clapper as a source of impulsive excitation and was based on an assessment of T_{30} from impulse decay according to the EN ISO 3382-1 standard [11]. The clapping was made at a distance of 1.5 m from the floor at three different locations according to the measurement protocol. The reverberation time was measured by the handheld acoustic analyzer XL2 (NTi AUDIO). The microphone M4261 (Class 2/Type 2, sensitivity 15.2 mV/Pa) was placed on the stand at a distance of 1.1 m from the floor, 1 m from walls, and 0.5 m from desks and chairs. Additionally, the microphone was located away from the investigator to eliminate the impact on the measurement output. The measurements were based on three different sound source positions at three different microphone positions (six measurements in all) in empty classrooms in the late afternoon or during the weekend (when the school was empty). The response was measured and analyzed in octave bands from 125 Hz to 8 kHz and then the mid-frequency reverberation time, which is the average value in the 500 Hz, 1 kHz and 2 kHz octave bands was obtained according to the Building bulletin 93 [30].

Table 4 shows the values of the mid-frequency reverberation time measured in the unoccupied classrooms, as well as the mid-frequency value estimated occupied [31] and the optimal occupied values across the frequency range from 125 Hz to 4 kHz according to the DIN 18,041 standard [15]. The reverberation time for classrooms 1 to 8 (school N 1) was 0.66 s (range 0.60–0.82 s), the mean volume 176 m^3. For classrooms 9 to 12 (schools N 2 & N 3) - mean $T_{es\_oc} = 1.1$ s (range 0.99–1.04 s), volume 208 m^3. Results for both the schools are far from the optimal ones, with worse conditions in school 2. A statistically significant difference $p < .001$ (Mann-Whitney U Test) was found between classrooms 1 – 8 and classrooms 9 – 12 in classrooms volume and acoustic parameters T_{unoc}, T_{est_oc}, L_{Aeq_unoc}, L_{Aeq_oc}, $STIPA_{oc}$. Shorter reverberation times are perceived as being acoustically more favorable for people with speech processing problems [15]. Moreover, reverberation time over 1 s produces a loss in speech discrimination and makes speech perception more difficult and strained [17]. Therefore, based on the mean T_{es_oc} in classrooms 1 to 8 and 9 to 12, two groups of classrooms were set up for further analysis. Classrooms, where mean T_{es_oc} was 0.7 s, were named as classrooms with lower reverberation time (RT) (school N 1) and classrooms where mean T_{es_oc} was 1.1 s – classrooms with higher reverberation time (RT) (schools N 2 & N 3). The former can be ascribed as classrooms with good acoustics, while the latter with bad acoustics, from a study by Astolfi et al. (2019) that considered the optimal occupied reverberation time in primary and secondary school classrooms in the

Table 2
Distribution of Children with Typical Language Development (TD) and Developmental Language Disorders (LD) between grades, schools, and classrooms.

School- classroom	Grade	Total N	TD	LD
1–4,6	1	26	14	12
1–3,5	2	27	18	9
1–1,8	3	36	16	20
1–2,7	4	32	23	9
2–9	1	23	11	12
2–10	3	23	20	3
3–12	2	25	21	4
3–11	4	25	22	3
Total n (%)		217 (100)	145 (66.8)	72 (33.2)

Table 3
Demographic characteristic of participants.

School	Classroom N	Grade	N	Age, year M (SD)	Male n (%)	Language disorders n (%)
1	4, 6	1.	26	7.27 (0.53)	13 (50.0)	12 (46.2)
1	3, 5	2.	27	8.33 (0.48)	13 (48.1)	9 (33.3)
1	1, 8	3.	36	9.56 (0.61)	17 (47.2)	20 (55.6)
1	2, 7	4.	32	10.16 (0.37)	16 (50,0)	9 (28.1)
2	9	1.	23	7.35 (0.57)	15 (65.2)	12 (52.2)
2	10	3.	23	9.22 (0.42)	10 (43.5)	3 (13.0)
3	11	4.	25	10.36 (0.49)	12 (48.0)	3 (12.0)
3	12	2	25	8.40 (0.50)	13 (52.0)	4 (16.0)

Table 4
The values of acoustic parameters measured in the occupied and unoccupied classrooms.

School	Classroom N	V (m^3)	T_{unoc} (s)	$T_{est–oc}$ (s)	$T_{opt–oc}$ (s)	$L_{Aeq–unoc}$ (dB)	$L_{Aeq–oc}$ (dB)	$STIPA_{oc}$	SPLmean@0.2 m (SD) without SFAS dB	SPLmean@0.2 m (SD) with SFAS dB
1	1	180	0.85	0.7	0.55	31.2	54.3	0.62	76.8 (0.6)	76.7 (0.5)
1	2	165	0.77	0.64	0.54	32.9	49.1	0.66	76.4 (0.7)	76.7 (0.6)
1	3	178	1.00	0.82	0.55	32.9	56.1	0.63	76.7 (0.4)	76.5 (0.4)
1	4	180	0.77	0.65	0.55	38.6	53.8	0.60	76.8 (0.6)	76.1 (0.5)
1	5	175	0.83	0.68	0.55	37.2	51.0	0.62	76.6 (0.6)	76.6 (0.4)
1	6	176	0.73	0.61	0.55	31.0	48.6	0.61	76.5 (0.7)	76.2 (0.3)
1	7	176	0.73	0.6	0.55	30.7	50.6	0.67	76.7 (0.6)	76.6 (0.6)
1	8	180	0.70	0.6	0.55	32.1	50.4	0.66	76.5 (0.7)	76.2 (0.6)
2	9	206	1.27	0.99	0.57	39.2	51.8	0.67	76.3 (0.7)	76.7 (0.5)
2	10	212	1.25	0.98	0.57	40.6	49.0	0.65	76.6 (0.9)	76.6 (0.7)
3	11	205	1.34	1.03	0.57	42.4	49.4	0.63	76.7 (0.5)	76.5 (0.3)
3	12	209	1.36	1.04	0.57	42.8	52.0	0.68	76.3 (0.4)	76.5 (0.4)

Note. V = volume; T_{unoc} = reveberation time in unoccupied classrooms; T_{est_oc} = estimated reveberation time in occupied classrooms; T_{op_oc} = optimal reveberation time in occupied classrooms; $L_{Aeq–unoc}$ = equivalent A-weighted sound pressure level in unoccupied classrooms; $L_{Aeq–oc}$ = equivalent A-weighted sound pressure level in occupied classrooms (activity noise); $STIPA_{oc}$ = Speech Transmission Index in occupied classrooms; Values of T_{unoc}, $L_{Aeq–unoc}$, $L_{Aeq–oc}$ and $STIPA_{oc}$ are average values across the classroom; SPLmean@0.2 m (SD) = mean examiner vocal intensity 0.2 m from the speaker's mouth and standard deviation in classrooms with and without SFAS.

range between 0.5 and 0.8 s, according to a number of studies which concerned both speech and listening performance [32].

Background noise L_{Aeq} was measured in an unoccupied classroom where only the investigator was present. The acoustic analyzer was placed at the distance of 1.1 m from the floor (at the level of pupils' ears sitting at their desks) and at the distance of 1 m from the walls and 0.5 m from the furniture. Three measurement points were set up: at the first row of desks near the doors, in the middle of the classroom, and at last row near the window. The measurements were taken in the late afternoon and during weekends when school buildings were empty. Windows and doors were closed, and all electrical devices were switched off during the tests.

The activity noise was measured in the classrooms when they were occupied by pupils (22–30 children per classroom). Windows and doors were closed, and ceiling lights were on. The examiner gave a short introduction lecture about noise and silence in daily life and the importance of silence in providing a good learning environment for children. After the presentation, students were requested to take a pencil and draw how they imagine noise and silence. Students were not allowed to talk during the task. The activity noise L_{Aeq} in the classrooms was measured during the task at three measurement points (the same that were used during measurements in the unoccupied classroom). A measurement period af activity noise was 1.5 min for each measurement point. The values of background and activity noise are shown in the Table 4.

STIPA was measured according to the IEC 60268-16 (2011), using the acoustic analyzer XL2, microphone M4261, and the acoustic signal generator TalkBox (NTi Audio) [13]. STIPA is a method obtained by using a simplified version of the STI method but still responsive to distortions found in room acoustics. It can be used alternatively to STI and consists of a modulated, speech shaped signal with a predefined set of two modulations per octave band that are generated simultaneously. The standard signal of 60 dBA SLP @ 1 m was generated from the TalkBox. The TalkBox was placed on the stand at a distance of 1.5 m from the floor in front of the classroom, where the teacher usually is. STIPA was measured with an acoustic analyzer placed at a distance of 1.1 m from the floor at three points in the classroom: first-row desk, middle of the classroom, last row desk. A mean distance from the signal generator to the measurement points in different school buildings was the following: school 1–1.6, 3.9, 6.18 m; school 2–0.9, 2.8, 5.4 m; school 3–1.0, 3.0. 5.5 m. Two to three subsequent measurements for each measurement position in occupied classrooms were carried out. The STIPA value in each measurement position and the average of the performed measurements was reported in the Table 4.

2.4. Monosyllable nonsense word (Logatome) perception test

The logatome is a short nonsense word consisting of a monosyllabic unit. Logatome tests are used in acoustic experiments to examine speech recognition and phoneme perception [33].

For the test procedure, two different phonetically balanced monosyllable nonsense words lists were used. Each of the lists consisted of 50 logatomes (test items) which represented almost all the 12 vowels (V) and 26 consonants (C) of the Latvian language in the same proportion as they exist in Latvian language. The Latvian language has phonetic spelling, i.e., a high degree of grapheme-phoneme correspondence and the syllables adhere to CVC and VC structure. Both lists were equivalent concerning syllable structures and consonant–vowel content, they were phonetically balanced and validated in the sample of monolingual children with typical language development.

The number of monosyllables was reduced to 20 items for the Grade 1 pupils because they had a shorter attention span than older students and slower writing speed. The short list of logatomes was identical to the 50-nonsense monosyllables list by the phoneme representation. The both 20-monosyllables lists (test 1 and test 2) were phonetically balanced and equals.

2.5. Procedure

A repeated measures design was used for this study in which the ability to perceive nonsense monosyllables was tested in 217 pupils of first to fourth grade in two conditions: in classrooms with and without SFAS.

The first 50 monosyllable nonsense words list (test 1) was presented to students of Grades 2 to 4 by the examiner in their classrooms where the SFAS was not installed. After a short introduction about the test procedure, children were requested to listen carefully and write the syllable they heard. During the task, the examiner slowly read the monosyllables with the interval of 10 s in front of the classroom at the place where usually a teacher is. The choice of presenting the list directly by the examiner and not by an artificial mouth was due to the need of reproducing the real environmental and teaching conditions that the children have during a lesson. It has been chosen to test teaching–learning outcomes in natural or ''ecological'' conditions. The notion of ecological condition was introduced by Gibson (1979) [34], in the visual domain, to express the need to take contextual and environmental cues into consideration to study perception, but now currently applied also in acoustics [35]. Particularly, according to Miller (2002), this is particularly true in the case of children, who extract information from the environment in order to learn and navigate in the world [36]. Moreover, as stated by Stacey et al. (2016), studies have observed that listeners can benefit from visual information by a talker's voice and that audio-visual benefit is derived from the optimal combination of auditory and visual sensory cues [37].

The syllables were presented in ''normal'' intensity voice by the examiner (49-year-old female without voice disorders) according to the standards ISO 9921 (2003) and ISO/TR 4870 (1991), i.e. about 60 dB(A) at 1 m from the speaker's mouth [38,39]. The vocal intensity measurements have been made to control that the speaker's speech level stay about the same along the measurement sessions. Vocal Holter Med device (PR.O.Voice Srl), which was calibrated at the distance of 0.2 m from the speaker's mouth, measured speech level [40,41]. This vocal intensity value was not directly measured during the test administration sessions, but it was measured by doing measurements of the examiner's vocal effort while she was speaking for 8 min in the classrooms under analysis, at the level typical for everyday talking conditions. The average vocal intensities for each classroom with and without SFAS and their standard deviations over an overall period of 8-minutes speech for each session, are listed in Table 4. An average value of the mean sound pressure level, SPL_{mean}, of 76.6 dB and 76.5 dB @0.2 m from the speaker's mouth without and with SFAS respectively (standard deviation equal to 0.6 and 0.5 dB) have been obtained, which correspond to 62.6 dB and 62.5 dB @1m from the speaker's mouth respectively, and both to about 60 dB(A) @1m after the correction of minus 2.5 dB to A-weighted according to Pearsons et al. (1977) [42]. Table 4 also shows as the speech level did not change between the two schools, which have classrooms with different reverberation time (see paragraph 3.1). This was also found by Bottalico and Astolfi (2012), in classrooms with comparable reverberation times of the two groups of classrooms in the present study [43].

The examiner's reading rate matched the writing speed of children, which was followed up during the test. Each test item was presented only one time; no repetitions were provided. The duration of the test procedure was approx.10–15 min depending on the pupils' age.

Test 1 gives baseline information about students' monosyllabic nonsense words perception ability in their classrooms. We tried to maintain the experimental procedure close to the natural conditions of the classroom environment. Therefore, the list of monosyllables was produced by the examiner and not as a recording. The same examiner carried out monosyllables' perception tests in all classrooms with and without SFAS.

The examiner repeated the same procedure after one week in the same classrooms equipped with the SFAS. The 360° omnidirectional sound field amplification system PentaClass Runa (Certes.lv SIA) with built-in Bluetooth and teacher's/presenter's HD wireless microphone Runa (2.4 GHz) was used in the study. The system provides a smooth distribution of sound in the room and amplifies the speaker's voice in the room up to 120 square meters. The SFAS was installed at the back of each classroom, middle aisle of the last row of desks, at a distance of 2.3 m from the floor. According to the manufacturer's recommendations, the SFAS was located as far away as possible from the person using the microphone for better performance. The second list of the test items (test 2) was used during the task (20 nonsense monosyllables for Grade 1, 50 nonsense monosyllables for Grades 2–4). The second list of the monosyllables was used to avoid any possibility of students completing the task from memory. During the second task, the examiner stood at the same place where she was the previous time. The thumb-sized microphone Runa with remote control was connected to the PentaClass SFAS, and it was hung on a lanyard, which was adjusted to reach a distance of 10 cm between the microphone and speaker's mouth. The examiner eliminated any distracting noise or echo by adapting the microphone settings. The mean voice intensity during test 2 along the classrooms under analysis was about 60 dB (A) @ 1 m, as shown in Table 4. SFAS did not alter the examiner's voice quality across the tests.

The first and second testing were conducted in the morning at the beginning of the lesson in all classes. All students were in the same classroom during test 1 and test 2.

Substitution and omission of consonant and vowel sounds (letters) were considered as errors, whereas changes in the consonant position in the syllable and incorrect spelling of the letter were not considered errors.

2.6. Data analysis

The statistical analysis was carried out with IBM SPSS Statistics v.23. The Kolmogorov-Smirnov test was first applied to determine the distribution of the obtained data. The acquired data were not normally distributed, and nonparametric statistical analysis methods were used. Related Samples Wilcoxon Signed Rank Test was used for analyzing the number of errors in non-words perception in selected groups of participants in classrooms with or without amplification. The Independent Sample Mann-Whitney U Test was used to determine the differences between classroom acoustic parameters in schools with different acoustic conditions. The associations between the number of errors in test 1 and test 2 and classrooms acoustic parameters (T_{est_oc}, L_{Aeq_oc}, $STIPA_{\_oc}$) and classrooms size were investigated using Spearman's Rank Correlation. All calculations have a confidence interval of 95%.

Ethics Approval

The Ethical Committee of Clinical Research of P.Stradins Clinical University Hospital (Riga, Latvia) approved the study.

3. Results

3.1. Effect of SFAS on speech perception in children with typical language development

One hundred forty-five monolingual children with typical language development were tested in two different classroom acoustic conditions: in classrooms with and without sound field amplification system Certes PentaClass. Wilcoxon Signed Rank test was performed to understand whether there was a statistically significant difference in the number of errors between test 1 (without SFAS) and test 2 (with SFAS) in all cohort of monolingual primary school pupils with typical language development. There was a statistically significant improvement in the perception of logatomes when amplification was used in classrooms with shorter RT ($Z = -2.581$, $p = .001$, $n = 71$). The statistically significant difference between the results of test 1 and test 2 was also observed in all primary school pupils with typical language development in classrooms with longer RT ($Z = -4.381$, $p < .001$, $n = 74$). However, in classrooms with longer RT, only 16 students had a lower number of errors in test 2, while 48 pupils demonstrated an increase in the number of errors in test 2; no differences were observed in 10 cases. Further data analysis grade by grade in all school types was provided.

Table 5 shows the mean number of errors obtained in test 1 and test 2 in each grade. A statistically significant decrease in numbers of errors in test 2 was observed in pupils of Grade 1 from school N 1 and school N 2, which were characterized as classrooms of shorter and longer RT, respectively. Students of Grade 2, 3, and 4 of classrooms with shorter RT made fewer errors in test 2, but the differences were not statistically significant. The opposite results were observed for pupils of Grades 2, 3, and 4 from classrooms with longer RT. They demonstrated a statistically significant increase in the mean number of errors in the second non-word perception test, which was provided in classrooms equipped with SFAS. An increase in the range of errors was also observed in this group of pupils.

The number of students of each grade was comparable in the classrooms with shorter and longer RT (Grade 1: 14 and 11; Grade 2: 18 and 21; Grade 3: 16 and 20; Grade 4: 23 and 22). No statistically significant difference in the mean number of errors between pupils of the same grade in classrooms with different reverberation time was shown without SFAS (test 1): Grade 1 $U = 71$, $p = .767$; Grade 2 $U = 170.5$, $p = .600$; Grade 3 $U = 141.5$, $p = .560$; Grade 4 $U = 198$, $p = .208$ (Mann-Whitney *U* test). These findings suggest that the original acoustics of the classrooms do not impact the perception of nonsense monosyllabic words when classrooms are not equipped with SFAS.

The mean number of errors in test 2 (classrooms with SFAS) did not differ in the Grade 1 students from classrooms with shorter and longer RT ($U = 60.5$, $p = .373$). For Grades from 2 to 4 the mean number of errors in test 2 in the classrooms with longer RT was significantly higher than the classrooms with shorter RT (Grade 2 $U = 68.5$, $p = .001$, Grade 3 $U = 97.5$, $p = .045$, Grade 4 $U = 165.5$, $p = .046$). These findings imply that the installation of SFAS in classrooms with longer RT may negatively impact the perception of nonsense monosyllabic words in 2nd to 4th Grade children with typical language development. This observation is not relevant to the first graders who benefited from SFAS in conditions of different reverberation times.

3.2. Effect of SFAS on speech perception in children with developmental language disorders

The LD group consisted of seventy-two children with developmental language disorders. All pupils had difficulties using correct grammar categories, and they had limited vocabulary, discourse problems, disorders of phonological awareness. The general language problems and phonological disorders affected reading and writing skills, and all of those students were worse readers and writers than their peers. The mean number of errors in children with language disorders was higher than in children with typical language development in both monosyllabic nonsense words perception tests ($U = 3194$, $p < .001$; $U = 3518.5$, $p < .001$).

The results of test 1 and test 2 for Grade 1 to 4 students with developmental language disorders are reported in Table 6. These data indicate that classroom amplification significantly decreased the mean number of errors only in the first graders in school 1 & school 2 ($p = .016$; $p = .031$). In the case of other grades, improvement of signal-to-noise ratio by sound amplification systems did not demonstrate the expected effect in classrooms with shorter and longer RT. However, we observed that the number of errors increased with SFAS in five out of six classes regardless of the classrooms' acoustic parameters.

Comparing the performance of first-graders between school 1 (shorter RT) & 2 (longer RT), we did not find a statistically significant difference in the mean number of errors in either test 1 or test 2 ($U = 51$, $p = .242$; $U = 52.5$, $p = .266$, Mann-Whitney Test) which allowed us to conclude that classrooms' acoustics in this case did not impact the perception of logatomes in first-graders with developmental language disorders.

3.3. Impact of classroom acoustics on speech perception in classrooms with or without SFAS

The results demonstrated that the effect of SFAS on monosyllabic nonsense word perception was associated with a classroom's acoustics in the group of children with typical language development. We did not find statistical correlations between classrooms acoustic parameters and scores of nonsense monosyllables perception in the group of students with LD Table 7 reports correlations between classroom volume (V), estimated reverberation time in an occupied room (T_{es_oc}), activity noise (L_{Aeq_oc}), $STIPA_{oc}$ and TD pupils performance in perception of nonsense monosyllables in two different acoustic conditions. Spearman's Rank-Order Correlations showed a negative and statistically significant relationship between the classroom size and number of errors in test 1. Children in larger classrooms had fewer errors than children in smaller classrooms. Volume and estimated reverberation time had a statistically significant impact on the number of errors in test 2, which

Table 5
Number of errors in the monosyllabic nonsense word perception tests in classrooms equipped with and without SFAS in children with typical language development (n = 145).

School	Grade	n	N of errors Test 1 (without SFAS)			N of errors Test 2 (SFAS)			Z	p
			M	SD	Range	M	SD	Range		
1	1	14	7.14	2.51	4–11	5.14	2.83	1–10	−2.273	0.023
1	2	18	7.11	4.35	1–17	5.06	4.40	1–16	−1.939	0.053
1	3	16	6.13	5.92	0–24	4.94	2.67	0–11	−0.788	0.431
1	4	23	6.48	3.82	1–17	6.43	3.82	2–15	−0.450	0.652
2	1	11	6.64	4.52	0–14	3.91	2.12	0–7	−1.965	0.049
2	3	20	4.60	3.24	1–15	7.35	3.76	3–21	−2.726	0.006
3	2	21	6.33	3.57	1–12	9.95	4.07	1–16	−2.860	0.004
3	4	22	5.09	2.65	0–12	9.41	5.23	3–24	−3.466	0.001

Note. p-value based on related samples Wilcoxon signed rank test.

Table 6
Number of errors in the monosyllabic nonsense word perception tests in classrooms equipped with and without SFAS in children with developmental language disorders (n = 72).

School	Grade	N	N of errors Test 1 (without SFAS)			N of errors Test 2 (SFAS)			Z	p*
			M	SD	Range	M	SD	Range		
1	1	12	11.17	4.39	5–17	8.67	3.39	4–16	−2.410	0.016
1	2	9	11.22	6.87	2–21	10.78	7.12	2–22	−0.210	0.833
1	3	20	7.25	4.05	1–14	8.25	3.57	3–16	−1.625	0.104
1	4	9	10.67	6.19	1–18	11.44	3.58	6–18	−0.655	0.512
2	1	12	8.92	2.28	4–12	6.92	3.06	2–12	−2.156	0.031
2	3	3	6.67	6.43	2–14	10.00	9.64	3–21	−1.604	0.109
3	2	4	7.75	2.97	4–11	12.75	3.40	3–21	−1.461	0.109
3	4	3	12.33	8.08	5–21	16.00	7.94	10–25	−1.604	0.109

Note. p-value based on related samples Wilcoxon signed rank test.

means that the number of errors increased in bigger classrooms with longer reverberation time when SFAS was installed.

4. Discussion

The purpose of the study was to investigate the impact of sound field amplification systems on the perception of monosyllabic nonsense words in primary school students in classrooms with different acoustic conditions. A particular focus was placed on results from pupils with developmental language disorders as well as the children's age (grade).

The intention to carry out test procedure as much as close to natural classroom environment probably was the weakness of the study from point of methodology. The examiner's voice intensity was not measured simultaneously to reading of the test syllables. This was done in order to make the situation of the test as ecological as possible, and in particular to not disturb children while performing the test with the teacher's image wearing the Holter Vocal Med device. Moreover, it was done as no statistical difference was found by Puglisi et al. (2017) between speech level measured across four days with the Vocal Holter Med device (former Voice Care) on primary school teachers, and by Gaskill et al. (2012), who monitored the voice use of two primary school teachers over two five-day workweeks using an Ambulatory Phonation Monitor (APM by KayPentax) [21,44]. Furthermore, Hunter and Titze (2010) found that occupational voice speech level of teachers remains constant throughout the working day [45] and Castellana et al. (2017) found that the intra-speaker variability in repeated readings is within 1 dB (a range of 0.3–0.9 dB was found as individual standard deviation in the case of mean sound pressure level) [46].

An additional argument for consideration to use natural examiner voice instead of recording was the providing of both auditory and visual cues to students during the test procedure. Children perceive teacher's speech not only based on audial signal but also taking into account visible articulation (coordinated movements of lips and face). This fact could not be neglected during the study. The visual speech influences all levels of perceptual processing in children [47] and improves speech perception [48].

Table 7
The associations between the classroom parameters and the average number of errors in Test 1 and Test 2 in pupils with typical language development (n = 145).

		Number of errors	
		Test 1 (without SFAS)	Test 2 (with SFAS)
Number of errors	Test 1	–	
	Test 2	0.300^{**}	
Volume		-0.175^{*}	0.229^{**}
$T_{es\text{–}oc}$		−0.092	0.361^{**}
$L_{Aeq\text{–}oc}$		−0.034	0.004
$STIPA_{oc}$		−0.036	$–^{a}$

[a] Correlation between STIPA_oc and an average number of errors during test 2 has not been shown as STIPA_oc was not measured with SFAS.
[*] p-value < 0.05.
[**] p-value < 0.01.

In the natural classroom environment, the assumed activity noise was the typical noise encountered in the classroom when the pupils are carrying out a silent task, that is expected while they listen to the teacher. In this particular case, the activity noise was measured in occupied classrooms when children performed silent drawing task. The idea was to catch the same activity noise level that would be expected during monosyllabic nonsense words perceiving test. The drawing and the writing are quite similar activities and therefore it has been assumed that the noise level taken in the preparation stage before the test represents the same activity noise level during the tests. The noise levels are comparable to those measured in silence in typical primary schools in Italy [21,43] and slightly lower than those measured in primary schools in London, but they are much lower than those measured while pupils perform an individual work or a group work with movement, which overcame 70 dB [49].

4.1. Impact of SFAS on improvement of monosyllabic nonsense words perception in 1 to 4 grade students with typical language development

The perception of monosyllabic nonsense words or logatomes read by the examiner in classrooms with and without SFAS was chosen as the main research tool. We did not find many studies where monosyllabic nonsense word lists were used for investigating the effectiveness of SFAS for speech perception. There was a study carried out by Eriks-Brophy and Ayukawa, which measured speech intelligibility through two randomized lists of 42 Inuit syllables in 7–11 year old children with and without hearing loss in amplified and unamplified conditions [7]. Vickers et al. and Dockrell and Shield (2012) used groups of monosyllabic minimally contrastive confusing words for an investigation of speech perception [10,50]. Our decision not to use words was based on the theory that perceived speech sound can activate word, and in this case, children can guess the word based on their hypothesis [51]. Listeners first map the incoming acoustic signal onto prelexical representations (i.e., phonemes), after which the prelexical representations are mapped onto lexical representations (i.e., words) [52]. In the case of monosyllabic nonsense words, the task involved segmenting phonemes, generating an appropriate sound-letter output representation and writing the letters in a specific order. In other words, we wanted to check the prelexical level of the speech recognition process, to find whether SFAS benefits the first stage of speech perception.

In the beginning, we compared the number of errors in test 1 and test 2 of all children with typical language development together without dividing them into grades. Statistical analysis demonstrated that primary school students in classrooms with good acoustics benefit from SFAS, i.e., the speech perception improves in amplificated classrooms (p = .001). A similar result was achieved by Eriks-Brophy and Ayukawa, who found that the mean error score of the speech intelligibility decreased in amplified classrooms for 7;4 to 11;3 year old Inuit children with normal hearing [7].

Further analysis of each grade's results showed that the first conclusion was misleading, and a positive effect of SFAS on speech perception was observed only in Grade 1. Based on this result, we would suggest analyzing acquired data according to children's age and avoid conclusions about a group of primary school pupils as a whole.

Based on the short review above, the key result was that only Grade 1 pupils (average age 7.34 years) benefited from SFAS in the perception of monosyllabic nonsense words. First graders demonstrated a statistically significant decrease in the mean number of errors in amplified classrooms.

These findings support results reported by Rosenberg et al. (1999), who found that first graders in amplified classrooms demonstrated more considerable improvement of listening and learning behavior than Grade 2 students [53]. The results also correlate with findings by Darai (2000). She observed that Grade 1 students in the classrooms with SFAS achieved more significant literacy gains than control students in classrooms without SFAS [54]. Our study measured the number of errors in speech perception in pupils from Grade 1 to Grade 4. The results obtained demonstrate that children of different ages have different reactions to sound amplification in the classroom. In particular, Grade 1 showed statistically significant improvement with SFAS compared to other grades. This is probably related to the development of auditory processes with age. Indeed, the study of Szkiełkowska, Włodarczyk, and Piłka (2018) showed that the processing of auditory information in seven years old children significantly differs from children aged 8 to 12; seven years old children showed lower scores in psychoacoustic tests than older children [55]. The study by Kwok et al. (2017) examined cortical auditory evoked potentials found that the processing of auditory stimuli differs in school-age children with typical development [56]. Maturing in auditory event-related potentials differs in 7-to 8-years children from 9-to 10 years old children. Also, they found that auditory evoked potential predicts significant variances in language ability. Children who had the strongest language skills showed the most mature auditory cortical responses [57]. Therefore, age is a significant predictor of auditory evoked potential and could make an impact on speech perception ability in younger pupils.

At the same time, studies have shown that the detrimental effect of noise and reverberation on speech intelligibility is proportionally greater for younger children [14,50,57]. Results of this study showed that improvements in logatomes perception with SFAS occurred both in classrooms with shorter and longer RT for Grade 1 pupils, which means that the increase in the signal to noise ratio with SFAS was effective in both reverberation conditions for first graders.

The statistically significant improvement in the perception of logatoms with SFAS was not observed in older pupils in classrooms with shorter RT because of their more advanced development in the processing of auditory information and skills of sound perception, discriminating and encoding. Overall, our findings are in accordance with those of Dockrell and Shield, who pointed out that significant benefits of the amplified classrooms for academic achievement, attention and the processing of spoken language in 8 to 11 old children were not found [50].

However, at the same time, our results demonstrated that Grade 2, 3, and 4 students from classrooms with longer RT had significantly lower results in test 2 than test 1. The number of errors increased when SFAS was installed, which is an important finding in understanding the effect of SFAS on speech perception scores. Wilson et al. described the relation between classroom acoustic parameters and the benefit of SFAS on listening and auditory analysis skills in 8 years old students, and the positive effect of SFA devices was found in classrooms with lower background noise and lower reverberation [27]. The SFAS improves intelligibility by increasing competing background noise, but this improvement is mitigated with an increase in reverberation. This reverberation creates masking in the signal, thus reducing intelligibility [58]. The SFAS devices should "not be routinely employed" and establishing classrooms' acoustic parameters is necessary before installing an amplification system [27,59].

4.2. Impact of SFAS on improvement of monosyllabic nonsense word perception in grade 1 to 4 students with developmental language disorders

Seventy-two children with developmental language disorders performed speech perception tests. Of these, 24 were first-graders. Our results demonstrated that a significant decrease in the number of errors in amplified classrooms conditions was observed only in Grade 1 pupils regardless of reverberation time in classrooms, as was the case with typical language development children. Vickers et al. found that SFAS gave more benefits to those children (6;11–8;10) who had poorer vocabulary age [10]. The effect of vocabulary age for accessing speech information in quiet classrooms and classrooms with 46 dB noise is reduced with the use of SFAS [10]. We did not provide any special testing of expressive vocabulary in children who were included in the LD group, because we assumed that reduced expressive vocabulary is one of the symptoms of developmental language disorders. The test of phonological decoding abilities was performed during the respondents' selection procedure, and all children who had difficulties with phonological decoding were included in the LD group. Phonological decoding skills reflect the development of phonological representations. According to Bishop, underspecified phonological representations can determine slow vocabulary acquisition in children with language disorders [60]. We can speculate that first-graders with language disorders had more vocabulary deficiencies than older children, and therefore our results are compatible with Vickers et al. findings. Another explanation of the positive effect of SFAS on monosyllabic nonsense word perception task in first-graders might be related to the development of the auditory process, which was discussed above.

The mean number of errors in the LD group was significantly higher than in children of the TD group. Nonsense word repetition (writing) tasks reflected weakly established representations of phonetic feature extractions and phonological analysis, and we believed that sound field amplification devices could improve signal-to-noise ratio which could facilitates the improved perception of the speech signal, but they did not have an impact on sound processing at the phonological level.

4.3. Impact of classroom acoustics on speech perception in classrooms with or without SFAS

We did not observe that the classrooms' estimated reverberation time, background noise level, and STIPA had statistically significant associations to children's (without language disorders) performance in monosyllabic nonsense word perception test 1. The analysis found evidence for a negative but statistically significant relationship between classroom size and the number of errors in test 1, without SFAS. The negative association between classroom size and the number of errors without SFAS was an unexpected result because speech intelligibility should decrease in larger classrooms with longer reverberation time [14]. In this study we observed that a lower equivalent A-weighted sound pressure level was found in the larger occupied classrooms. The mean voice intensity of the examiner remained the same in all types of classrooms, and so we tend to assume that the signal-to-noise ratio was higher in the classrooms of schools 2 & 3, which led to a decrease in the number of errors in test 1. According to Bradly & Sato (2008), speech intelligibility scores are significantly related to signal-to-noise ratio [61]. Moreover, the effect of varied reverberation time, which is directly associated with the classrooms' volume, on the intelligibility of speech for young children was much less than the effect of varied signal-to-noise ratio [62].

The opposite trend was observed in amplified classrooms. The number of errors in test 2 increased in larger classrooms with longer reverberation time. SFAS led to a significant increase in errors in rooms with longer RT due to echo and increased sound reflection, as shown in Table 5 for all the grades except the first. A similar effect was observed by Nelson & Soli (2000), who found that additional problems, without providing significant improvement in signal-to-noise ratio, arose by adding amplified sound into a noisy and reverberant room [63].

These findings emphasize the necessity to scrutinize classrooms acoustics, e.g., reverberation time and background noise, before installation of sound field amplification systems. It is important to underline that improvements of signal-to-noise ratio have not been documented in this study. Thus, the effect of SFAS could be only due to the room acoustics properties of the classrooms. Siebein & Gold (2000) suggest including an audiologist and an acoustic consultant on the design team for new and remodeled facilities to accomplish a satisfactory learning environment [64].

5. Conclusions

This study has been conducted in order to determine the impact of sound field amplification systems on monosyllabic nonsense word perception in primary school pupils with particular attention devoted to children with developmental language disorders. The associations between classroom acoustic parameters and speech perception were also investigated in the study.

Our study showed, that first-grade students benefit from sound field amplification regardless of classrooms acoustics, and irrespective of the level of language development. The effect of SFAS on nonsense word perception was not observed in pupils of Grade 2, 3, and 4.

Classroom acoustics impacts the effect of SFAS for children older than first graders. Sound field amplification increases speech perception and decreases the number of errors in the reproduction of monosyllabic nonsense words in classrooms with short reverberation time but decreases speech perception in classrooms with longer reverberation time. Acoustics should be fixed to recommended condition or at least excess reverberation should be attenuated when amplification systems are used.

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CRediT authorship contribution statement

Baiba Trinite: Conceptualization, Methodology, Investigation, Writing - original draft, Funding acquisition. **Arianna Astolfi:** Formal analysis, Writing - review & editing.

Declaration of Competing Interest

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

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