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Listen to the walls – how electroacoustic transducer type affects spatial sound perception in stereo systems

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ABSTRACT

An important aspect of sound perception are spatial impressions, which play an important role in the immersion experienced by the listeners. The most common way of research in this area is experimenting with multichannel systems of various kind. In this paper we present an alternative approach that utilizes an uncommon type of the electroacoustic transducer: distributed mode loudspeakers (DML). With diffuse radiation patterns and no typical acoustic axis, they create different impressions for the listener than traditional cone loudspeakers. We conducted a series of listening experiments, where the subjects assessed stereo systems based on the DMLs and three-way studio monitors in terms of perceived audio quality, especially spatial impressions, namely: general listening satisfaction, realism of reproduction, sound clarity, stage width, listener envelopment, and ease of localisation. Assessment was performed in three different listener localisations, for various music excerpts. Results of statistical tests imply that in most cases there is a significant difference between perceptions of stage width, localisation and envelopment depending on the type of the speaker.

1 Introduction

The Distributed Mode Loudspeaker (DML), also referred to as the flat panel loudspeaker, employs a different sound radiating element than the conventional cone-shaped diaphragm. In the DML the radiator is a flat and stiff panel of rectangular shape and considerable mass. An electrodynamic (or piezoelectric) exciter attached to the panel induces uniformly distributed bending wave vibration. One or more exciters can be used, and the higher quantity allows for inducing more complex modes. An introduction to the technology can be found in [1, 2] and a review of its evolution with an extensive list of references was written by Heilemann et al. [3].

The DMLs have very advantageous form factor – they are flat and can easily be flush mounted in walls so that they become invisible. But they also have unique properties as sound sources, different than those of cone loudspeakers: (a) their radiation pattern is wide throughout the entire audible frequency range, and (b) they are incoherent sound sources [1, 2, 4]. Thus there is a considerable perceptual difference between the sounds reproduced through DMLs when compared to the reproduction over conventional cone diaphragm loudspeakers.

Another property of DMLs, originating from their inherent resonant structure is that their frequency responses are clearly more uneven than those of conventional cone diaphragm loudspeakers. However there is an ongoing development in that area [3, 5].

There have been few works published on perceptual properties of DMLs, in particular when compared to conventional cone loudspeakers. Mapp and Colloms [6] compared samples of speech reproduced from three cone and one DML loudspeakers, in on-axis and off-axis positions, according to five attributes. In both listening positions the DML had the highest average score, more significantly for the off-axis condition. Harris et al. [7] found that the DMLs improved stereo localization of pink noise stimuli when compared with cone loudspeakers in an untreated room. Flanagan and Moore [8] compared spectral shape discrimination for a DML and a cone loudspeaker and showed that detection of a spectral ripple was easier for the DML than for the cone loudspeaker. Flanagan and Harris [9] observed that for the same measured SPL of pink noise, the DML sounded louder than a cone loudspeaker, and proposed a hypothesis that the loudness level attenuation with distance in a given acoustic is reduced by the use of DML.

Heilemann et al. [10] performed anechoic measurements in 70 points of three different types of DMLs (one- and multi-exciter) and a 2-way conventional coaxial passive bookshelf loudspeaker. They used a prediction model of loudspeaker preference by Olive and obtained objective evaluation strongly in favour of the conventional system. Roessner et. al. [11] performed a listening comparison between: two advanced multi-exciter DML prototypes, one one-exciter commercial DML and two conventional 2-way passive systems in monophonic reproduction, with five music tracks. Listeners were asked to rate each loudspeaker comprehensively with one number. The two highest average scores were obtained by two conventional loudspeakers, and two prototype DMLs scored about 10% lower.

The purpose of this work was to compare the perceptual attributes of DMLs with those of high-end loudspeakers, focusing on spatial and qualitative aspects of perception and minimizing the effect of the frequency response on the comparison. We simulated this condition by applying electronic correction to frequency responses of both types of loudspeakers at the listening area. In our listening experiment listeners subjectively evaluated the performance of loudspeaker systems of both types using six evaluation criteria.

2 Methods

2.1 Aim and scope of experiment

The aim of the experiment was to compare perceptual properties of two loudspeaker technologies: the widespread conventional technology of electromagnetic loudspeakers with cone-shaped diaphragms (further referred to as 'cone loudspeakers') with the DMLs. The main assumption was to design the experiment so that it was sensitive to perceptual differences brought about by omnidirectional radiation of low coherence of the DMLs, versus beaming with frequency and correlated radiation of cone loudspeakers. These properties are inherent in both technologies.

The planned context of the comparison was the most frequent use of both technologies, that is home entertainment. We chose to compare the technologies in the standard stereophonic sound reproduction scheme.

A further assumption was to use as examples commercial state-of-the-art of both technologies, and not those of intermediate quality, as these would not be representative of potentials of respective technologies. The result of this assumption was to use an active cone loudspeaker system.

We decided to use just one example of the cone technology: a three-way, all-analogue active monitor A25-M from PSI-AUDIO / Relec SA, which is their most advanced model, and two examples of DML technology: Amina Edge 5, a one-exciter DML from Amina Technologies Ltd., and a newer Amina Edge 5i, an improved and two-exciter model.

2.2 Do not compare apples and oranges – objectivism of comparison

Because of the fundamental difference in the technologies, their objective comparison brings several challenges. It is more difficult than any comparisons within the class of cone loudspeaker systems.

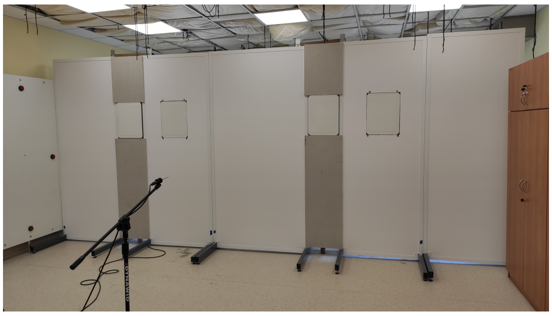

Fig. 1: . Artificial wall with the DMLs mounted.

Fig. 2: Arrangement of the loudspeakers used in the experiment.

2.2.1 Operating conditions of loudspeakers

DMLs are usually flush mounted in the walls. This way their natural advantage, small depth, is exploited to the advantage of the reproduced sound. We decided to construct a specific artificial wall where the DMLs would be installed. The wall had the following dimensions: 5.2 m x 2.4 m, was built of two layers of plasterboard with mineral wool in between and is presented in Figure 1.

The first challenging decision was about the method of installing the monitors. Objectivity of the comparison required flush mounting in the same artificial walls. On the other hand, the assumption of evaluating the technologies in their most frequent use, i.e. home entertainment, precluded flush mounting of the monitors since it is unusual in homes. Therefore we chose typical use of both types i.e. free standing monitors and flush mounted DMLs as a priority, at the cost of objectivity. The monitors were placed in front of the artificial wall, just below the DMLs.

Each of the pair of Amina Edge 5 DMLs was above and to the left of the acoustic axis of either of PSI monitors and each of the pair of Amina Edge 5i DMLs was above and to the right of it. The monitors were placed on stands so that the height of their acoustic centres was at 120 cm. The centres of the DMLs were at the height of 160 cm. Listeners were seated at a high chair so that on average their ears were at the height of 140 cm. The rrangement of the loudspeakers is shown in Figure 2.

This arrangement introduced the bias of vertical position. No effect of such a bias on perception of sound quality is known to us. Informal listening tests indicated very weak perception of the difference in vertical localisation of sound sources.

2.2.2 Equalization of frequency response

Frequency responses of DMLs are more uneven than those of cone loudspeakers and the difference is particularly noticeable when compared to frequency characteristics of high-grade active monitors. In order to minimize the effect of this factor on the experiment, individual equalization of amplitude frequency response was used in all six loudspeakers (three pairs) evaluated, with the same method. A loudspeaker and room correction at the point of listening was designed and implemented. Its presentation is beyond the scope of this paper.

2.2.3 Handling low frequencies

Another disadvantage of the DML technology is weak efficiency in low frequencies range, and power capacity of DML loudspeakers in that range precludes compensation by the correction system. Therefore for all pairs of loudspeakers, we used the same subwoofer – Dynaudio 9S, from Dynaudio A/S. The crossover frequency f_c was 107 Hz in all systems. The location of the subwoofer can be seen in Figure 2. It was chosen to avoid central localisation along the width of the room.

2.3 Other conditions of experiment

The experiment was held in a listening room of the Department of Mechanics and Vibroacoustics of the AGH University of Science and Technology with flexible acoustics. Details of the room can be found in [12]. The amount of absorption was subjectively adjusted to the optimal value. No absorbing materials were placed in the side walls in the area responsible for the first

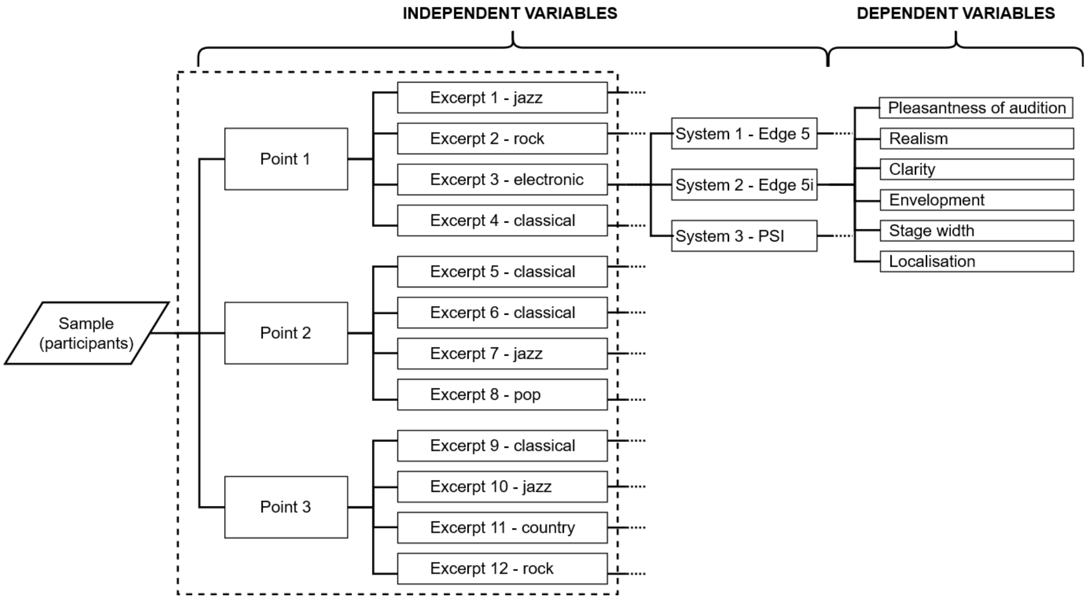

Fig. 3: Design of the experiment.

reflection. This was necessary so that wide radiation of the DMLs could have considerable effect on perceptual properties of their sound. The artificial wall seen in Figure 1 was located across the width of the room, 2.2 m from one of the shorter walls of the room. There were narrow spaces left between the side edges of the artificial wall and side walls of the room, about 15 cm on the left and 80 cm on the right. The space from the horizontal upper edge of the artificial wall to the suspended ceiling was 44 cm.

Most of the surface of the artificial wall including all loudspeakers was concealed from the listeners by an acoustically transparent curtain. The sound level was normalized between loudspeaker systems, so that the maximum difference between pairs did not exceed 0.5 dB(C).

2.4 Plan of experiment

There were two groups of participants who could take part in the experiment. Members of the first group could participate in only one session. They evaluated the loudspeakers in the stereophonic sweet spot, which was determined relative to studio monitors. Members of the second group could participate in three sessions. They evaluated the same loudspeakers in the same conditions and with the same procedure as the first group, in two more listening positions, one in each session. The supplementary positions were placed behind the sweet spot and symmetrically at the sides of it, each 70 cm from the sweet spot, along the line between the loudspeaker and the sweet spot.

The independent variables in the experiment were:

- A1 The listening spot. For each subject (second group), each session was held in a different listening spot on a separate day (three conditions).
- A2 A music excerpt. There were four evaluated excerpts per session and the sets of excerpts were different at each session. Together 12 excerpts representing classical music (4), jazz (3), rock (2), pop (1), country(1) and electronic music (1) were used (four conditions per variable A1), each up to 45 s long.
- B The loudspeaker system evaluated (three conditions, see Section 2.1).
- C* An evaluation attribute. Six attributes were used (see Section 2.4.1, six conditions). *They can be also treated as six dependent variables, and so are in analyses presented in this paper.

The design of the experiment presenting independent variables and their relations in graphical form is shown if Figure 3. The arrangement from left to right follows the sequence of variables in the above list.

Conditions A1 and A2 were mutually dependent. Each A1 condition was tied in with its individual set of four musical excerpts. Thus when the effect of one of A1 conditions is analysed, the four musical excerpts are independent variables. But when effects between levels of A1 are compared, then their individual sets of excerpts become confounding variables. The groups of four excerpts have been chosen so that the program was balanced, to minimize the confounding effect. In this case it was considered more efficient than randomization, as with small samples of four drawn from limited population of 12, the effect of randomization could increase the confounding effect.

2.4.1 Evaluation attributes

After careful analysis we selected six attributes. Their number was limited in order to limit the burden on the subjects. The main consideration was to include general quality attributes and spatial attributes, as on the ground of earlier experiments we expected a specific spatial performance of the DMLs.

The scoring scale was from 0 to 10 with one decimal point. We formulated the anchors of the assessment scale. The attributes with their anchors are presented in Table 1.

2.5 Course of experiment

Each session consisted of four trials, with training at the beginning of the first session. In each trial the participant listened to one excerpt of music presented over three systems identified by letters A, B and C. The test was fully randomized – the order of excerpts and assignment of letters in each trial was random for each listener. The training excerpt was the same for each subject, it was used to set the playback level comfortable to the listener and make them familiar with the test interface (in seccond and third session only for the former purpose). The first session lasted 30-40 min on average; the following ones were usually shorter (20 min), as the participants were already familiar with the procedure.

The playback system was set on the host computer with Foucsrite Clarett+ 8Pre audio interface. The interface sent the audio signal directly to the monitors and subwoofer, and to the DMLs via Anthem PVA-7 power amplifier. The host was connected wirelessly to a small notebook computer placed close to the listener. On this computer the evaluation application was running, where the listener could control playback and evaluate each criterion using sliders.

The listener could switch freely between the systems while listening almost instantaneously. Playback was started and stopped using buttons A, B and C, from the point where it had been paused. Evaluation consisted of two stages: firstly, the listener judged their general impression ('pleasantness of audition') for each system, then the remaining five criteria.

78 participants aged 19-69 (87% below the age of 28) took part in the experiment. None of them reported hearing problems; we did not carry out audiometric tests. Most of the participants were audio engineering students at the AGH University (78%), others included Krakow Academy of Music students and professors (13%) and other audio-related professionals (8%).

3 Results

3.1 Data and descriptive statistics

The number of evaluations was different, depending on the point (variable A1), since not all listeners could participate in all sessions. This reduces possibilities for repeated-measures analysis, yet still we have a full set of data from 40 participants.

The experiment results can be treated in two ways: either as described in section 2.4, the criteria being factors i.e. independent variables, and only the evaluation rating is treated as a dependent variable, or each criterion can be treated as a dependent variable on its own. Both approaches were used, with more focus on the second one.

We analysed the results firstly with a general, observational approach, which suggested differences in spatial criteria (envelopment, stage width, localisation). Apparently, the DMLs performed better in terms of envelopment and stage width, while the monitors were more precise in terms of localisation. Details on preliminary analysis of the first stage of experiment (results from the first point for half of participants) can be found in [13]. In Figure 4, an average rating of each criterion is presented for all listeners.

Table 1: Criteria of evaluation and their anchors, as given to the listeners in the experiment instruction.

Attribute	Lower anchor (0)	Upper anchor (10)
Pleasantness of audition	Low, not inviting	High, inviting
Realism	Artificial reproduction	Natural reproduction
Clarity (selectivity)	Low	High
Envelopment	Directional sound	Enveloping sound
Stage width	Narrow	Wide
Localisation	Hard to determine	Easy to determine

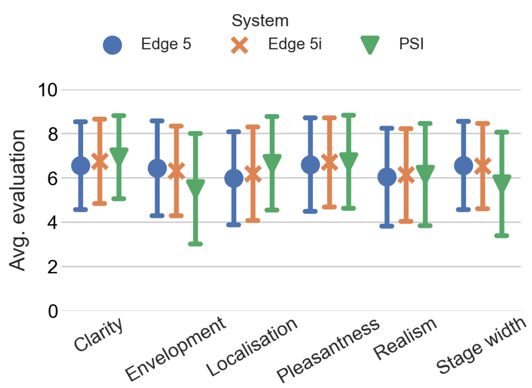

Fig. 4: Evaluation results averaged over all points and listeners for all participants, with standard deviation.

In general, all ratings are close to each other. Only the ratings for envelopment and stage width demonstrate the advantage of both DMLs over the monitor, while the ratings for localisation are in favour of the monitor. Total averages over all attributes and listeners were the following: Edge 5i – 6.44, Edge 5 – 6.37, PSI – 6.31.

In this work we present an analysis that aimed to verify statistical significance of the observed differences. We considered only the listeners who participated in all three sessions to avoid the imbalance, as we had the most results collected in the first point. The left side of Figure 5 shows histograms of the results for all-sessions participants (evaluation ratings are treated as a dependent variable). At this stage we consider only differences between the systems, therefore we averaged results for each criterion over all excerpts (right side of Figure 5). After averaging the distribution is closer to normal, which allows us to use classical analysis of

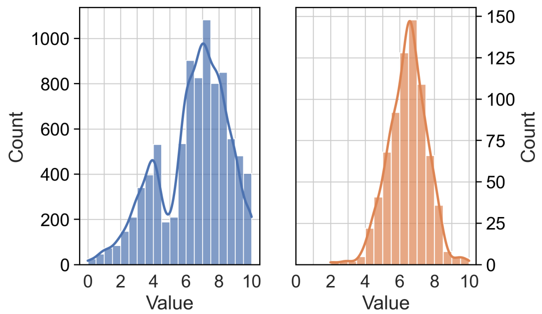

Fig. 5: Histograms and estimated kernel density functions for participants of all three sessions before (left) and after averaging over excerpts (right).

variance (ANOVA), described in section 3.2.

3.2 Inferential statistics

Since each listener was affected by all factors applied in the experiment, the repeated-measures analysis was the most appropriate approach, with the system being the 'treatment' or the within-subject factor. Each criterion was treated as a dependent variable with the rating for each system-listener being an average of 12 excerpts ratings; we decided to carry out the ANOVA, as almost all variables (except envelopment and stage width) follow normal distribution. Results of the Shapiro-Wilk normality test are presented along with the ANOVA results in Table 2.

We performed a one-way repeated-measures ANOVA for averaged evaluations from all-sessions participants (see section 3.1), using the `pingouin.anova_rm` function. The results are presented in Table 2. The value to be assessed when looking for significant differences is $p_{GG-corr}$, the p-value with correction for

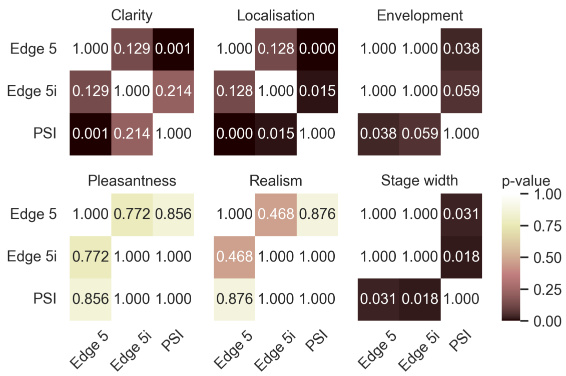

Fig. 6: Results of pairwise comparisons using T-test; p-value with Bonferroni correction is mapped.

sphericity (results of testing this assumption are shown in columns 7-9 – vairances were homogenous only for clarity and pleasantness).

Next, we performed pairwise comparisons using the `pingouin.pairwise_tests` implementation of the T-tests with Bonferroni correction for the p-value [14]. Corrected p-values for system comparisons are shown in Figure 6.

4 Discussion

Close assessments of three attributes (pleasantness, clarity, realism) may confirm the well-known loudspeaker property, that even frequency response is a very important determinant of sound quality. When its effect is removed from the comparison (or limited), the differences become more difficult to notice. This supposition is based on informal listening only, as we have not compared uncorrected DMLs with the monitors in a formal experiment.

ANOVA results (Table 2) show that for all attributes except pleasantness of audition and realism the corrected p-value is below $\alpha = 0.05$, meaning that the system might have had a significant effect. A look at the partial η^2 values, that describe how much of the variance is explained by the system used, shows that the effect size for clarity, localisation and stage width can be considered as large ($\eta_p^2 > 0.14$) and medium for envelopment.

When analysing pairwise comparisons results (Figure 6), we observe significant difference between DMLs and monitors for stage width and localisation, as well as for envelopment when comparing Edge 5 model with monitors. The test hypothesis did not assume the direction of the difference, yet after analysing the distribution of the evaluation for these criteria (Figure 4) for each system we can assume, that while DMLs scored higher in envelopment and stage width, the difference in localisation was in favour of the monitors. Based on the presented results, no significant differences between the two models of DMLs occur.

5 Conclusions

Average scores demonstrate very close assessment of both types of loudspeakers by the participants of the test. These findings are well-grounded in in a large group of 78 listeners, of which 40 participated in three sessions. The close ratings are unexpected, considering basic differences in the technologies and sophistication of the monitor used for the comparison.

They also confirm the well-known loudspeaker property, that even frequency response is a very important determinant of sound quality. When its effect is removed from the comparison (or limited), the differences become more difficult to notice.

Still, the results revealed meaningful perceptual differences between the technologies in spatial attributes: localisation, stage width and envelopment. In the first the monitor was rated higher, which could be expected, in view of a big contribution of the direct sound in the operation of the monitors. The other two spatial attributes were in favour of the DMLs. The latter finding is justified by wide radiation angle of the DMLs.

For most cases, the ANOVA precondition of normality was fulfilled; we used Greenhouse-Geisser correction for non-sphericity. The results, along with post-hoc pairwise comparisons, suggest that the technology used for reproduction matters in terms of spatial impressions at the significance level $\alpha = 0.05$.

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Table 2: Results of repeated measures ANOVA (40 subjects); within-subjects factor: system (80 degrees of freedom in numerator, 2 degrees of freedom in denominator). Evaluation rates averaged over all excerpts for each participant of all three sessions.

Criterion	F	p_{unc}	$p_{GG-corr}$	η_p^2	ε	sphericity	W_{sph}	p_{sph}	normality	W_{norm}	p_{norm}
Clarity	7.626	0.001	**0.001**	0.160	0.900	True	0.889	0.100	True	0.990	0.474
Localisation	12.832	0.000	**0.000**	0.243	0.857	False	0.833	0.028	True	0.985	0.209
Envelopment	5.646	0.005	**0.013**	0.124	0.695	False	0.561	0.000	False	0.960	0.001
Pleasantness	0.760	0.471	0.467	0.019	0.968	True	0.967	0.516	True	0.995	0.952
Realism	0.946	0.393	0.372	0.023	0.766	False	0.695	0.001	True	0.987	0.274
Stage width	6.557	0.002	**0.005**	0.141	0.771	False	0.704	0.001	False	0.976	0.027

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