User-Centred Evaluation of Printed Multi-Channel Loudspeaker Panels in the Context of Rail Vehicles

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Abstract: Innovative audio passenger information systems based on printed electronics can be a promising technological advancement in railways to increase user comfort. These kinds of speakers are extremely thin, light, flexible, printable and allow for a wide range of installation options. While laboratory experiments have examined speech intelligibility from a technical perspective, user-centered approaches to better understand the human perspective have not yet been undertaken. To close this gap, we conducted a usability study with *N* = 24 participants. The aim was to assess the perceived speech intelligibility and speech quality within a laboratory train setup while variations of background noise at different sound pressure levels were present. Results show improvements in subjective speech intelligibility and quality with higher signal-to-noise ratios.

Keywords: user-centred acoustic evaluation, speech intelligibility, speech quality, loudspeaker announcements, rail vehicles

1. Introduction

Trains are a daily mode of transportation for many, serving both personal and business travel needs. During their journey, passengers rely on necessary information such as current stops, delays, and connecting services. This information is typically provided by public displays and loudspeaker announcements. The acoustic information is an important factor for travel comfort, as more comprehensible announcements are better for passengers' comfort (Boltze et al. 2020). The innovative core of the paper is the first-time evaluation of loudspeakers based on technological advancements in printed electronics. Thin layers of plastic or paper filament are combined with printed electronics to create extremely thin speakers that not only offer advantages for the required installation space but are also inexpensive to manufacture (Schmidt et al. 2021). This is especially useful in trains or trams as it lowers the cost of installing multiple speakers in each carriage. Furthermore, the use of printed multi-channel loudspeaker panels in rail vehicles is expected to result in a more homogeneous distribution of sound compared to conventional speaker systems, which will positively impact the speech intelligibility of announcements. In addition, position-specific sound distribution allows the delivery of individual acoustic passenger information, such as addressing specific seating groups, to provide targeted information without unnecessarily distracting other passengers. While laboratory experiments have examined speech intelligibility from a technical perspective, user-centred approaches on trains for these kinds of speakers have not yet been undertaken. In this paper, we want to close this research gap with the following study.

2. Method

For the study, a laboratory setup based on the dimensions of a real tram railway carriage (Model TATRA T3D-M) was built (figure 1). The setup is a simplified replica of a wagon compartment in which two different sizes of printed loudspeaker panels (width: slim – 150 mm, wide – 300 mm) were mounted at a height of 2 meters using a wooden construction. The seats were aligned with the ceiling construction in such a way that they had the same dimensions as in a tram wagon in terms of seating height and distance from the loudspeaker panels. Commercially available stereo loudspeakers were used to simulate background noise such as engine sounds (figure 1 – speakers in the front). In order to assess perceived speech intelligibility, speech quality and listening experience, typical tram announcements were played over the printed loudspeaker panels. The announcements were reproduced at a sound pressure level of 68 dB(A) in the presence of background noises with signal-to-noise ratios (SNRs) of +7.5 dB(A), -5 dB(A) or no background noise at all. The sound pressure levels were measured and adjusted with a precision sound level meter (Type 2232 of Brüel & Kjaer). The reference for the measurement was a head height of 1.30 meters while sitting on the chair with a distance of one meter to the concerning loudspeaker panel. Background noise (BN) was reproduced in two different variants – either as pink noise (PN) or as a real record of environmental noise (EN) from a train cabin, using the set of additional stereo speakers. Altogether this resulted in 5 different variations of background noises. Therefore, the users experienced 5 randomized runs per loudspeaker panel where an announcement got interfered by different levels of background noises (within-design).

Figure 1: *Illustration of the laboratory setup.*

After each announcement speech quality was assessed by measuring subjective speech intelligibility and sound quality on a seven-point mean opinion score (1 = “extremely bad” to 7 = “ideal” [e.g. “I understood the announcement ...”]) (Streijl et al. 2016). Furthermore, additional questions were used to evaluate subjective speech quality in more detail by measuring the dimensions concentration and annoyance to also take the disturbing conditions into account under which the announcements had to be understood (Pennig et al. 2014; Sust et al. 2009; Volberg et al. 2006). Each dimension was measured via a seven-point rating scale with the endpoints labelled (1 = “strongly disagree” to 7 = “strongly agree” [e.g. “I experienced the conditions under which I had to understand the announcements as interfering.”]) (Sust et al. 2009). Moreover to assess listening experience and to survey a sound profile for this type of speakers a semantic differential scale with five-point bipolar scales (“quiet-loud”, “unpleasant-pleasant”, “unnatural-natural”, “brassy-not brassy”, “thin-full”, “muffled-not muffled”, “unintelligible-intelligible”, “hissing-not hissing”, “not spatial-spatial”, “unclear-clear”) had to be rated (Fastl 2005; Wältermann 2013).

3. Results

3.1 Sample

A total of *N* = 24 volunteers participated in the study. The sample consisted of 13 women and 11 men with a mean age of *M* = 29 years (*SD* = 8 years). All participants had very good skills in German language and reported normal hearing without any diagnosed hearing impairments.

3.2 Subjective speech assessment

The data analysis is based on the procedure of Pennig et al. (2014) who conducted a similar study in a simulated aircraft cabin. For the single subjective ratings concentration, annoyance, subjective speech intelligibility and sound quality there were high correlations between each other (Spearman correlations *r* = .59 - .86). Therefore, a principal component analysis was performed to reduce data from the questionnaire. Due to high factor loadings ranging between .824 (annoyance) and .949 (subjective speech intelligibility) the four single subjective ratings were summarized to a single factor – subjective speech quality. Furthermore, for reliability analysis, Cronbach’s alpha was calculated to assess the internal consistency of the new built subscale for subjective speech quality. The consistency of the subscale is satisfying with Cronbach’s alpha = .913. Over all variations of background noise conditions for the two differently sized loudspeaker panels (figure 2), the mean values of subjective speech quality significantly decreased when background noise was present.

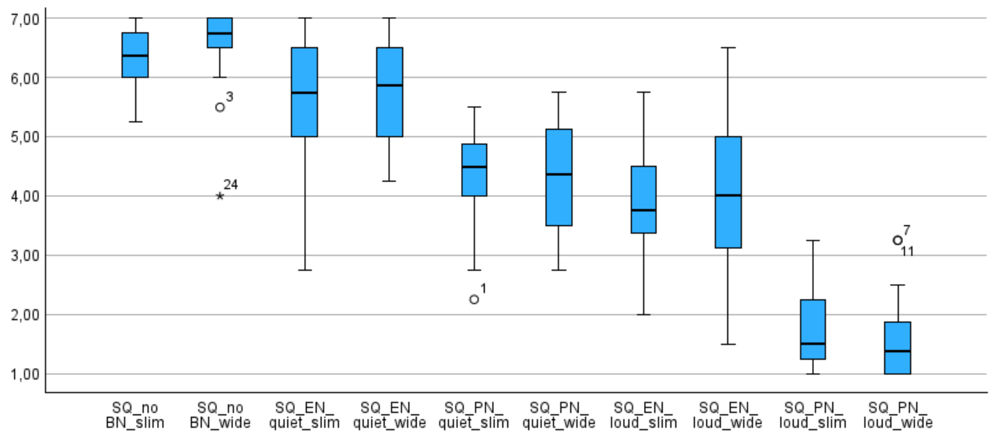

Figure 2: *Subjective speech quality (SQ) in each condition for the two loudspeaker panels (scale values: 1 = “extremely bad” to 7 = “ideal”). noBN = no background noise, EN = environmental noise, PN = pink noise, quiet = +7.5 db(A) SNR, loud = -5 db(A) SNR, slim = 150 mm loudspeaker panel, wide = 300 mm loudspeaker panel.*

Especially in the conditions where the background noise was louder than the announcement (-5 db(A) SNR) the ratings for the subjective speech quality ranged between “poor” to “fair” (SQ_EN_loud) and “extremely bad” to “bad” (SQ_PN_loud). The mean values and standard deviations for each condition are shown in table 1.

Table 1: *Mean values and standard deviations for the subjective speech quality in each condition for the two loudspeaker panels*

	M	***SD***
SQ_noBN_slim	6.35	0.52
SQ_noBN_wide	6.55	0.66
SQ_EN_quiet_slim	5.54	1.09
SQ_EN_quiet_wide	5.76	0.93
SQ_PN_quiet_slim	4.26	0.81
SQ_PN_quiet_wide	4.35	0.95
SQ_EN_loud_slim	3.93	0.92
SQ_EN_loud_wide	4.04	1.29
SQ_PN_loud_slim	1.72	0.69
SQ_PN_loud_wide	1.57	0.69

To assess the effects of background noises, signal-to-noise ratios (SNR) and size of the printed loudspeakers on subjective speech quality a repeated measures ANOVA (2x2x2) has been conducted. The conditions with no background noise have been handled separately in an ANOVA with only one factor (size). The ANOVA shows statistically significant differences for background noises, $F(1, 23) = 175.21$, $p < .001$, partial $\eta^2 = .88$, signal-to-noise ratios, $F(1, 23) = 722.77$, $p < .001$, partial $\eta^2 = .97$ and background noises paired with signal-to-noise ratios, $F(1, 23) = 27.99$, $p < .001$, partial $\eta^2 = .55$. The size of the printed loudspeaker panels had no statistically significant influence on the subjective speech quality in either the condition with or without background noise. However, the size had statistically significant impact on single items of the semantic differential scale when there was no background noise present. The semantic differential which represents the listening experience is shown in figure 3.

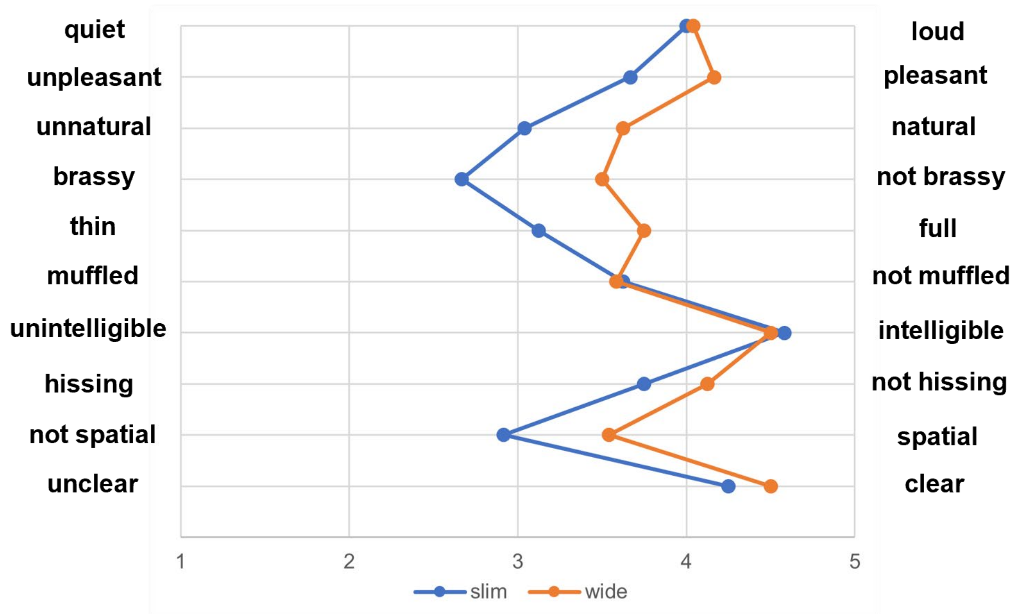

Figure 3: *Polarity profile for the listening experience without any background noise.*

A repeated measures ANOVA with the single factor loudspeaker size showed significant differences for the items “unnatural-natural”, $F(1, 23) = 7.88$, $p = .010$, partial $\eta^2 = .26$, “brassy-not brassy”, $F(1, 23) = 7.77$, $p = .010$, partial $\eta^2 = .25$, “thin-full”, $F(1, 23) = 6.82$, $p = .016$, partial $\eta^2 = .23$, “hissing-not hissing”, $F(1, 23) = 5.70$, $p = .026$, partial $\eta^2 = .20$ and “not spatial-spatial”, $F(1, 23) = 6.05$, $p = .022$, partial $\eta^2 = .21$.

4. Discussion

In this laboratory study the human perception of subjective speech quality of loudspeaker announcements from printed electronics in a simplified replica of a tram wagon compartment was tested. The announcements were interfered by variations of background noises with different sound pressure levels which led to different signal-to-noise ratios. To examine the effects on subjective speech intelligibility, speech quality and listening experience participants were examined using psychological test methods instead of measuring objective acoustic parameters.

As expected with decreasing signal-to-noise ratio (increasing sound pressure level of background noise) the subjective speech quality declined. In the +7.5 db(A) SNR environmental noise condition the subjective speech quality was rated as “good” to “excellent”, while in the pink noise condition it was rated as “fair” to “good”. This results are consistent with the ISO standard (ISO 9921, 2003) which determines signal-to-noise ratios higher than +7.5 db(A) as „very good“ or „excellent“. However, Mapp (2008) and Pennig et al. (2014) advocate for a definition of a higher SNR in the ISO standard and recommended aiming for values greater than 10 db(A) SNR for an “excellent” speech intelligibility and speech quality. For instance, Pennig et al. (2014) found only “good” to “very good” speech intelligibility for SNRs higher than 11 db(A) in their study. Regarding the significantly decreasing rating between environmental noise and pink noise in terms of subjective speech quality, Sust et al. (2009) reported similar results. This may be due to pink noise interfering the frequency range of human perception in a very consistent way, leading to an overestimation of its loudness (Schlittenlacher et al. 2011).

Although loudspeaker size did not affect subjective speech quality the results for single items of the semantic differential scale in relation to the listening experience underline the functionality of the printed loudspeaker panels. Wider printed loudspeakers lead to an improvement in the frequency response (Schmidt et al. 2021) and cover the frequency spectrum in greater detail.

5. Summary and Outlook

Acoustic passenger information plays an important role in public transportation as it provides passengers with essential information, warnings, and instructions. In this area, new technological advancements in printed electronics hold a considerable innovative potential. By combining thin layers of plastic or paper filament with printed electronics, it is possible to create extremely thin speakers that not only require less installation space but are also cost-effective to manufacture (Schmidt et al. 2021). The adoption of printed multi-channel loudspeakers in rail vehicles promises a more even sound spread than traditional speaker systems, enhancing speech intelligibility of announcements. Additionally, the technology enables the distribution of position-specific sound, allowing for the delivery of individual acoustic passenger information. This includes addressing specific seating groups to provide targeted information without distracting other passengers unnecessarily.

In this laboratory study the printed loudspeaker panels showed promising results regarding subjective speech quality. To evaluate the advantages of implementing printed electronics in rail vehicles, the next step will be a field study, where the printed loudspeaker panels will be installed in a rail vehicle and be compared with the conventional audio systems during a real-world tram journey.

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