Differences in speech intelligibility in noise between native and non-native listeners under Ambisonics-based sound reproduction system

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Abstract

The current paper examines how native and non-native listeners of New Zealand English differ in terms of speech intelligibility in noise in a number of room acoustics reproduced by a first-order Ambisonics-based sound reproduction system. Speech intelligibility test was conducted under three room acoustics environments (living room, lecture theatre and church) using the sound reproduction system, where a pink noise masker was played from one of five azimuthal angles (0, 45, 90, 135, 180 degrees) while the target speech was always played from 0 degrees. We found significant two-way interactions between language nativeness and speech-noise separation, language nativeness and room acoustics, as well as between room acoustics and speech-noise separation. This suggests that native and non-native listeners respond differently to the virtually reproduced acoustic environments and they benefit from spatial release from masking in a different manner. Post-hoc results showed the native listeners performing significantly better than their non-native counterparts for all the angles of speech-noise separation and the room acoustics.

Keywords: speech intelligibility, nativeness, pink noise, spatial release from masking, first-order Ambisonics

1. Introduction

It is of no surprise that non-native listeners struggle more to understand speech that is not in their native language when compared to native listeners. Previous studies have found non-native listeners to perform poorer than native listeners in a range of speech perception measures, such as the ability to discriminate and identify phonetic contrasts, spoken words recognition and listening to unfamiliar and synthetic speech [1, 2, 3, 4]. Even when a fluent non-native listener can understand speech similarly to a native listener in quiet and optimal conditions, studies have found that the non-native listener performs poorer in the acoustically adverse environments such as listening in noise [5, 6, 7, 8, 9] due to speech masking. Speech masking occurs by the presence of some interfering noise with speech, and thus causing the target speech to be masked by the noise.

Spatial acoustics of the environment can influence how well listeners can separate the target speech from the masking noises in the background [10, 11, 12, 13]. For example, it is well understood that reverberation affects speech intelligibility [14] more severely for non-native listeners compared to native listeners [15]. In contrast, when the locations of competing sound sources are spatially separated, it can benefit listeners to be “released” from the effect of speech masking, known as *spatial release from masking* [16, 17, 18]. A previous study suggests that non-native listeners could also benefit from spatial release from masking under a sound attenuated (semi-anechoic) laboratory environment [19], however, the effect under various spatial acoustics is yet unknown. Effect of reverberation on spatial release from masking is another interesting topic. A study which tested native listeners found the benefit of spatial release from masking decreases with increased reverberation [20], but the effect on non-native listeners is unknown.

Along with the rapid growth of virtual reality (VR) technologies, sound reproduction systems that virtually reproduce various acoustic environment have become widely available. Although the technique is often utilised for applications that involve speech communication, speech perception under virtually reproduced acoustic environment has not been studied well. Dagan

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et al. studied the spatial release from masking under binaural sound reproduction of different spherical harmonic orders [21]. The study found that a listener could benefit from spatial release from masking by as low as first order spherical harmonics when the environment is anechoic. A previous study by the authors [22] investigated how speech intelligibility is affected by various room acoustics reproduced by a first order Ambisonics-based sound reproduction system, which is one of the most commonly used audio VR technologies among audio engineers. The study focused on the speech perception of native listeners of New Zealand English. The present research is a follow-up study of [22] investigating the differences in speech intelligibility in noise between native and non-native listeners under virtually reproduced acoustic environment using first order Ambisonics-based sound reproduction system.

2. Methodology

The present study adopts the same methodology applied in the previous study [22] but tests non-native listeners and compare the results against that collected from native listeners presented in [22]. While this section briefly summarises the design of the study, readers are encouraged to refer to [22] for details of the experimental setup.

2.1. Participants

Forty participants (age range: 18 - 49 years old) were recruited for the experiment from the student and staff bodies at the University of Auckland, New Zealand. Twenty of the group were considered as native English listeners, most of whom speak New Zealand English. They were either born in an English speaking country, or moved to an English speaking country before the age of seven. Twenty were considered as non-native English listeners, who had moved to an English speaking country after the age of seven [23]. All participants were exposed to New Zealand English on a daily basis and self-reported to have no hearing impairment.

2.2. Sound reproduction system

The 16-channel Ambisonic-based sound reproduction system installed in the anechoic chamber at the University of Auckland reported in [22] was also used in this study to replicate spaces with different spatial acoustics. The room impulse responses of three room acoustics specified in Table 1 were measured using a first order Ambisonics microphone (RODE NT-SF1). The room impulse responses were measured by playing a swept sine signal over a loudspeaker (Genelec 8020D) via an audio interface (Roland Octa-Capture). These room impulse responses were convolved with the dry sound recordings of the target sentences and masker discussed in Section 2.3, and were then played back via the loudspeaker array using an Ambisonics decoder (Harpex [24]). Listener's seat was located at the centre of the spherical loudspeaker array, with the height of the seat adjusted so the height of the participant's ears were aligned with the centre of the loudspeaker array.

Table 1: Acoustical properties of measured rooms (RT60 and C50 values are averaged over the frequency range of 250 Hz to 4 kHz) (excerpt from [22])

Room	Approx. volume (m^3)	RT60 (s)	C50 (dB)
Living room	80	0.40	10.33
Lecture theatre	900	0.86	7.96
Church	2500	2.03	4.96

2.3. Stimuli

The participants listened to stimuli consisting of a target speech and masker played simultaneously. While the target speech was fixed at the front of listener (0 degrees), the azimuthal angle of the masker was varied clockwise from 0 to 180 degrees with 45 degrees interval. A target-to-masker ratio (TMR) of -3 dB was used to avoid flooring and ceiling effects; the target speech was played at 53 dBA (± 1 dBA) and so was the masker at 56 dBA, both calibrated at the centre of the loudspeaker array [22].

The sentences used for the target speech were nonsense sentences [25] to avoid top-down effect from the semantic and contextual cues. The speech stimuli, sampled at 22.05 kHz, were taken from SpeechBox [26] and follows the following structure: "The *(adjective)* *(noun)* *(verb)* the *(noun)*". Pink noise was used as the masker, which was generated by Adobe Audition at 22.05 kHz sampling rate.

In addition to the three room acoustics environments stated in Section 2.2, stimuli were also played directly in the anechoic environment without adding the virtual acoustical effect as the controlled condition.

2.4. Test Procedure

Participants were asked to type out the target speech sentences they hear per trial. The test involved the stimuli discussed in Section 2.3 where each combination of the room acoustics and speech-noise separation (the angular separation between the target speech and noise from 0° to 180°) were repeated four times, giving a total of 80 sentences per participant (4 room acoustics × 5 speech-noise separation × 4 repeats). The conditions were randomised to prevent any learning effect and the same order was kept consistent between all participants. A practice test of five sentences was carried out to allow the participants to familiarise with the test procedures and the sound reproduced by the system.

A monitor was installed below the 0 degree azimuth loudspeaker controlled by a wireless keyboard for participants to enter their answer through a graphical user interface (GUI).

The procedure was approved by the University of Auckland Human Participants Ethics Committee.

2.5. *Statistical analysis of speech intelligibility*

Speech intelligibility was measured as how well participants could recognise the words by their responses. Scoring of the sentences was performed manually according to the common errors discussed by Nye *et al.* [25]. Half a score was given for answers where the error included substitution, insertion and deletion of phonemes. Incorrect position of an identified word, homophones (e.g. ”son” and ”sun”), including words with vowels /iə/ and /eə/ (e.g. ”hear” and ”hair”), which have merged for New Zealand English speakers [27] were given one full score. A sentence can have a maximum of four scores and the scoring was carried out per sentence, giving a score out of four as the speech intelligibility results.

The speech intelligibility results in terms of the percentage correct were analysed using a linear mixed effect model (LME) with the R [28] package *lme4* [29] and model fitting was carried out using the step function from *lmerTest* [30]. Interactions between two and more factors were included when it improved the fitness of the model. Significance in fixed effects was determined using a likelihood ratio test by comparing between a model with the effect in question with a model without the effect. Post-hoc pairwise comparisons of the models were carried out using the *emmeans* package [31] with p-values adjusted using the Tukey method. The fixed effects were language nativeness of the participant, room acoustics and speech-noise separations. Participant ID was used in the model as a random effect.

3. Results

Figure 1 displays the mean and 95% confidence interval of the raw percentage correct results from the intelligibility test pooled across the room acoustics. The x-axis represents the speech-noise separation, and the y-axis shows the percentage correct from the speech intelligibility test. The line type (solid or dotted) denotes the listener’s language nativeness.

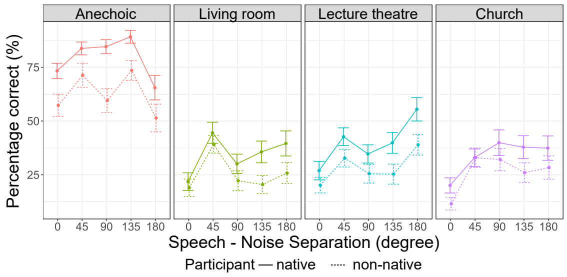

Figure 1: Raw percentage correct results from the intelligibility test.

Regardless of the acoustic environments, the non-native group performed worse in terms of speech intelligibility than the native group in general. For both the native and non-native groups, the listeners performed the highest intelligibility score for the anechoic case compared to the three reverberant rooms. For the reverberant rooms, we can observe some differences in terms of spatial release from masking (how speech intelligibility is affected by speech - noise separation) both between the two participant groups and the different room acoustics. Having said that, for both groups in all three room acoustics, the participant scored the lowest in speech intelligibility without spatial release from masking (i.e. at 0 degree speech-noise separation).

Using likelihood ratio tests to examine the main effects of the linear mixed effect models, we found a significant two-way interaction between language nativeness and speech-noise separation ($\chi^2(4) = 16.15$, p=0.0028), between language nativeness and room acoustics ($\chi^2(3) = 23.95$, p<0.0001) and between speech-noise separation and room acoustics ($\chi^2(12)$=224.58, p = <0.0001). Table 2, Table 3 and Table 4 display the post-hoc pairwise contrasts results of the three cases of significant two-way interactions from the linear mixed effect models, respectively.

Table 2 shows the pairwise comparisons between the native and non-native listeners in terms of the four room acoustics. The native listeners scored higher than their non-native counterparts in all room acoustics, with the largest difference of predicted probabilities (14.84%) in the anechoic case and lowest in the church (9.59%).

Table 3 shows the post-hoc pairwise comparisons between the native and non-native listeners in terms of the five speech-noise separation angles. Again, the native listeners scored significantly higher than the non-native

Table 2: Pairwise comparisons of contrasts between native and non-native listeners in terms of room acoustics

Room acoustics	Language nativeness (native - non-native)			
	Estimate(SE)	df	t.ratio	p.value
Anechoic	14.84(2.26)	78	6.57	**<0.0001**
Living room	12.8(2.26)	78	5.66	**<0.0001**
Lecture theatre	12.94(2.26)	78	5.73	**<0.0001**
Church	9.59(2.26)	78	4.24	**0.0001**

Table 3: Pairwise comparisons of contrasts between native and non-native listeners in terms of speech-noise separation

Speech-noise separation	Language nativeness (native - non-native)			
	Estimate(SE)	df	t.ratio	p.value
0	8.55(2.42)	93	3.523	**0.0007**
45	6.97(2.42)	93	2.88	**0.005**
90	12.49(2.42)	93	5.16	**<0.0001**
135	14.29(2.42)	93	5.90	**<0.0001**
180	13.39(2.42)	93	5.53	**<0.0001**

listeners for all speech-noise separations. Differences in predicted correct percent was the highest for 135° at 14.29%, and the lowest for 45° at 6.97%.

Figure 2 shows the interaction between room acoustics and speech-noise separation and Table 4 displays the pairwise comparisons between the different speech-noise separation. For the anechoic case, there were significant differences in terms of the percent correct scores for all speech-noise separation pairs other than 45° - 90° and 45° - 135°. For the living room, all speech-noise separation pairs other than 0° - 90°, 90° - 135° and 135° - 180° were significantly different. For the lecture thatre, all speech-noise separation pairs other than 45° - 135° and 90° - 135° were significantly different. In contrast, only comparisons between 0° and all other speech-noise separations were significantly different in church.

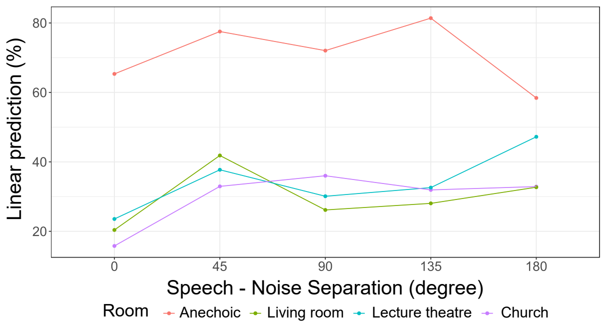

Figure 2: Predicted probabilities from linear mixed effect model of the room acoustics in terms of speech-noise separation.

4. Discussion

In line with previous studies, native listeners scored significantly higher than non-native listeners both in terms of room acoustics and different speech-noise separations. Previous studies have also shown reverberation to affect speech intelligibility detrimentally [14], especially for non-native listeners [15]. From our results, we found language nativeness to interact with room acoustics, suggesting that reverberation affects native and non-native listeners differently in terms of speech intelligibility. Native listeners scored 14.84% higher than non-native listeners in the anechoic condition, compared to 9.59% in church, which is the most reverberant room. This suggests that under the first order Ambisonics-based sound reproduction system, the higher the reverberation, the less advantage language abilities have in understanding speech.

We also predicted listeners to benefit from spatial release from masking as shown in [21], and expected speech intelligibility to be the lowest at the speech-noise separation being 0° and 180° [16]. We found that in contrary to the results from [19], spatial release from masking benefited the two groups differently, as shown from the significant interaction between the language nativeness and speech-noise separation. The groups differed by 8.55% in terms of speech intelligibility scores when the target speech and masker were co-located (i.e. at 0° speech-noise separation), compared to 12.49% at 90°, where previous studies have found that 90° speech-noise separation should yield robust benefit from spatial release from masking [32]. This suggests language nativeness makes a small difference when there is no spatial separation, but once the listeners can benefit from spatial release from masking, native listeners can take advantage of it more than non-native listeners.

Lastly, as shown in [20], we predicted reverberation to affect the benefit from spatial release from masking, where the longer the reverberation time of the room, the less benefit spatial release from masking would have on speech intelligibility. We also examined whether this effect would be different for native and non-native listeners. As there was only a 2-way interaction between room acoustics and speech-noise separation, we can conclude from the current study that reverberation affects the benefit from spatial release from masking similarly regardless of participants' language nativeness.

5. Conclusion

The present paper studied the differences in speech intelligibility in noise between native and non-native listeners of New Zealand English under a first order Ambisonic-based sound reproduction system. The experimental results suggest the amount of reverberation in the reproduced acoustic environment and the spatial release from masking (SRM) affect the listeners in their own ways, where the non-native listeners are at a disadvantage compared to their native counterparts when listening to speech in both anechoic and reverberant cases. However, both groups could benefit from spatial release from masking similarly in virtual acoustics regardless of the amount of reverberation. Future works involve examining whether this is a product of the lack of spatial resolution limited by first order Ambisonics through experimenting with a higher order Ambisonic sound reproduction system.

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Table 4: Pairwise comparisons of contrasts between speech-noise separation in terms of room acoustics

Contrast	Room acoustics	Estimate(SE)	df	t.ratio	p.value
0 - 45	Anechoic	-12.21(2.25)	3156.01	-5.43	**<0.0001**
0 - 90	Anechoic	-6.71(2.25)	3156.01	-2.99	**0.02**
0 - 135	Anechoic	-16.06(2.25)	3156.01	-7.14	**<0.0001**
0 - 180	Anechoic	6.92(2.25)	3156.41	3.08	**0.02**
45 - 90	Anechoic	5.49(2.25)	3156.01	2.44	0.10
45 - 135	Anechoic	-3.86(2.25)	3156.01	-1.72	0.42
45 - 180	Anechoic	19.12(2.25)	3156.41	8.50	**<0.0001**
90 - 135	Anechoic	-9.35(2.25)	3156.01	-4.16	**0.0003**
90 - 180	Anechoic	13.63(2.25)	3156.41	6.06	**<0.0001**
135 - 180	Anechoic	22.98(2.25)	3156.41	10.22	**<0.0001**
0 - 45	Living room	-21.45(2.26)	3156.07	-9.51	**<0.0001**
0 - 90	Living room	-5.76(2.26)	3156.07	-2.56	0.08
0 - 135	Living room	-7.66(2.26)	3156.07	-3.40	**0.0062**
0 - 180	Living room	-23.67(2.26)	3156.11	-5.45	**<0.0001**
45 - 90	Living room	15.69(2.26)	3156.01	6.98	**<0.0001**
45 - 135	Living room	13.79(2.25)	3156.01	6.13	**<0.0001**
45 - 180	Living room	9.14(2.25)	3156.04	4.06	**0.0005**
90 - 135	Living room	-1.90(2.25)	3156.01	-0.85	0.92
90 - 180	Living room	-6.54(2.25)	3156.04	-2.91	**0.03**
135 - 180	Living room	-4.64(2.25)	3156.04	-2.06	0.24
0 - 45	Lecture theatre	-14.17(2.25)	3156.01	-6.30	**<0.0001**
0 - 90	Lecture theatre	-6.55(2.25)	3156.01	-2.91	**0.03**
0 - 135	Lecture theatre	-9.04(2.25)	3156.01	-4.02	**0.0006**
0 - 180	Lecture theatre	-23.67(2.25)	3156.01	-10.53	**<0.0001**
45 - 90	Lecture theatre	7.62(2.25)	3156.01	3.39	**0.006**
45 - 135	Lecture theatre	5.13(2.25)	3156.01	2.28	0.15
45 - 180	Lecture theatre	-9.50(2.25)	3156.01	-4.23	**0.0002**
90 - 135	Lecture theatre	-2.49(2.25)	3156.01	-1.11	0.80
90 - 180	Lecture theatre	-17.12(2.25)	3156.01	-7.61	**<0.0001**
135 - 180	Lecture theatre	-14.63(2.25)	3156.01	-6.51	**<0.0001**
0 - 45	Church	-17.16(2.25)	3156.04	-7.62	**<0.0001**
0 - 90	Church	-20.22(2.25)	3156.04	-8.98	**<0.0001**
0 - 135	Church	-16.14(2.25)	3156.04	-7.17	**<0.0001**
0 - 180	Church	-17.10(2.25)	3156.04	-7.59	**<0.0001**
45 - 90	Church	-3.06(2.25)	3156.01	-1.36	0.65
45 - 135	Church	1.02(2.25)	3156.01	0.46	0.99
45 - 180	Church	0.06(2.25)	3156.01	0.03	1.00
90 - 135	Church	4.08(2.25)	3156.01	1.82	0.36
90 - 180	Church	3.12(2.25)	3156.01	1.39	0.64
135 - 180	Church	-0.96(2.25)	3156.01	-0.43	0.99