Extension of the generalized tangent law for multiple loudspeakers

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Introduction

Amplitude panning in the horizontal plane often relies on either simple mathematical models such as the tangent law [1, 2] or perceptual localization curves due to level differences ΔL_{dB} between loudspeaker pairs [3, 4]. Several works about lateral loudspeaker pairs show that the amplitude in the back needs to be slightly enlarged to perceive the auditory event in the middle of the loudspeaker pair [5, 6, 7, 8, 9, 10, 11]. Furthermore, the directional displacement of the auditory event from this position due to a small level difference is larger than it would be for a frontal loudspeaker pair. This behavior is reflected in the recent generalized tangent law [12] that describes the perceived angle φ using a shift w and slope γ adapted to the loudspeaker pair spacing α and midpoint angle $\bar{\phi}$

$$\frac{\tan\varphi}{\tan\alpha} = \tanh\left[\frac{\ln 10}{40}\,\gamma\,(\Delta L_{\mathrm{dB}} - w_{\mathrm{dB}})\right]. \tag{1}$$

The shift and slope parameters were experimentally determined for various loudspeaker pairs within the entire horizontal plane. In general, the parameters were similar for all tested spacings of 30°, 45°, and 60°. Thus, they could be summarized as analytic functions depending on the azimuth angle ϕ_l of each individual loudspeaker l and the midpoint angle of the loudspeaker pair $\bar{\phi}$, cf. Figure 1:

$$w_{\mathrm{dB}}(\phi) = -4.8 + 4.2\cos\phi + 0.3\cos 2\phi + 0.3\cos 3\phi, \tag{2}$$

$$\gamma(\bar{\phi}) = 2 - \tfrac{1}{\sqrt{2}}\cos(2\bar{\phi}). \tag{3}$$

Vector Model: The present paper extends the generalized tangent law to amplitude-panning methods that use more than two loudspeakers simultaneously, such as Ambisonics [13, 14] and Multiple-Direction Amplitude Panning (MDAP) [15]. For the tangent law, this is achieved by re-formulation in vector form [16], using the loudspeakers' gains g_l and directions $\boldsymbol{\theta}_l = [\cos(\phi_l), \sin(\phi_l)]^{\mathrm{T}}$

$$\boldsymbol{r}_{\mathrm{V}} = \frac{\sum_l \boldsymbol{\theta}_l\, g_l}{\sum_l g_l}. \tag{4}$$

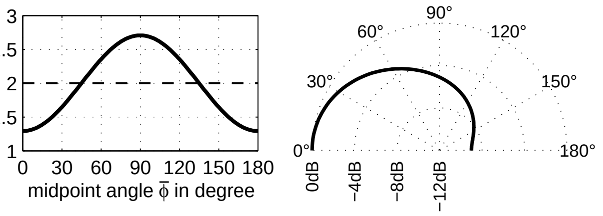

Figure 1: Slope γ and shift w_{dB} from [12].

The resulting vector is also known as the velocity vector and was proposed as a simple model to predict the localization of amplitude panning at low frequencies [17]. Similarly, for high frequencies, the energy vector was proposed that employs a slope $\gamma = 2$:

$$\boldsymbol{r}_{\mathrm{E}} = \frac{\sum_l \boldsymbol{\theta}_l\, g_l^2}{\sum_l g_l^2}. \tag{5}$$

It was found to nicely predict localization of amplitude panning in practice [18, 19, 20]. This is not surprising, as the direction-dependent slope in Figure 1 oscillates around 2.

A loudspeaker-direction-dependent exponent in the above equation is not producing any reasonable result, we propose the application of a single exponent within the summation. It represents the slope of the panning curve for the approximate localization by the energy vector using Eq. (3). Finally, the shift can be incorporated by a loudspeaker-direction-dependent weight $w(\boldsymbol{\theta}_l)$ according to Eq. (2), yielding $\boldsymbol{r}_\gamma^{\mathrm{w}}$ that includes both slope and shift for multiple loudspeakers

$$\boldsymbol{r}_\gamma^{\mathrm{w}} = \frac{\sum_l \boldsymbol{\theta}_l\,(g_l\, w(\boldsymbol{\theta}_l))^{\gamma(\boldsymbol{r}_{\mathrm{E}}/\|\boldsymbol{r}_{\mathrm{E}}\|)}}{\sum_l (g_l\, w(\boldsymbol{\theta}_l))^{\gamma(\boldsymbol{r}_{\mathrm{E}}/\|\boldsymbol{r}_{\mathrm{E}}\|)}}. \tag{6}$$

Experiment

An experiment should generate panning curves for Multiple-Direction Amplitude Panning (MDAP) and Ambisonics that are subsequently modeled. The two panning methods use either 2 or 3 loudspeakers and 2 or all loudspeakers for a single phantom source.

Setup

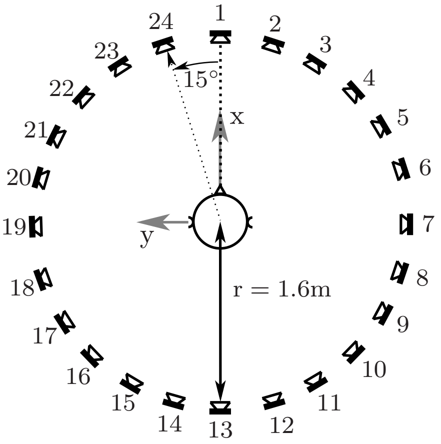

Figure 2: Loudspeaker setup in the anechoic room.

The experiment used a ring of 24 Genelec 8020 in 15° degree steps at a radius of 1.6 m at ear height (1.45 m), as shown in Figure 2. The loudspeakers were set up in an anechoic chamber and level- and delay-compensated to the central listening position.

In the experiment, listeners were asked to match the position of an amplitude-panned pink noise to the directional reference sound by moving either of two infinite MIDI pan pot controllers on their lap, a coarse one with 5° and a fine one with 1° increments. The directional reference was a pink complex tone with a fundamental frequency of 40 Hz, harmonic components between 120 Hz and 20.4 kHz, each of which using a random phase offset as in [12]. Both reference and adjustable sound had a sine-squared quarter-wave fade in and out of 200 samples length @44.1 kHz sampling rate (≈ 4.5 ms), with a 300 ms duration for each noise or complex tone burst. The periodically repeating sounds used a firing interval of 330 ms for the sequence ⟨stimulus⟩, ⟨stimulus⟩, ⟨pause⟩, ⟨reference⟩, ⟨pause⟩.

Listeners could confirm their adjustment and move to the next presentation by pushing a knob on the MIDI controller. The listeners were instructed to look forward during the entire experiment and to adjust the center of the pink noise location to match the direction of the reference sound by using the coarse and fine knobs.

During pre-tests, strong coloration and front/back-confusion artifacts appeared in some cases for the multiple-loudspeaker playback in the anechoic room. Listeners were advised to slightly wobble their translatory position in the range of centimeters if necessary to disambiguate their impression. However, their head orientation should stay strictly frontal during adjustment. The 6 listeners that took part in the experiment were experienced listeners in spatial audio in the age between 29 and 35.

Conditions

Amplitude-panned pink noise should be panned to match a single-channel reference playback from each of the 24 loudspeakers of the equi-angular ring. Panning employed 6 configurations (panning+loudspeaker subset), cf. Table 1.

	method	angles of loudspeakers in °
1	MDAP	[0 60 120 180 -120 -60]
2	MDAP	[30 90 150 -150 -90 -30]
3	MDAP	[0 45 90 135 180 -135 -90 -45]
4	2$^{\mathrm{nd}}$-ord. Ambi.	[0 60 120 180 -120 -60]
5	2$^{\mathrm{nd}}$-ord. Ambi.	[30 90 150 -150 -90 -30]
6	3$^{\mathrm{rd}}$-ord. Ambi.	[0 45 90 135 180 -135 -90 -45]

Table 1: Panning configurations in the experiment.

MDAP employs two separated pairwise amplitude-panned sources in order to avoid that single loudspeaker is playing when the panning direction coincides with a loudspeaker direction, such as in vector-base amplitude panning (VBAP) [16]. Typically, the separation of the two sources depends on the loudspeaker spacing and was set to equal the loudspeaker spacing. Thus, the two sources were panned ±30° around the desired panning direction for configurations 1 or 2 and ±22.5° for configuration 3. The Ambisonics configuration employed the highest possible order depending on the size of the loudspeaker subset, i.e. an order of 2 for configurations 4 or 5 and an order of 3 for configuration 6. Ambisonics was always played back using the appropriate max-r_{E} weighting [14] to achieve best results in terms of localization [21].

In order to facilitate balanced summarizing of left/right symmetric results, the reference directions 0° and 180° were twice as often compared to all other directions. This resulted in 156 adjustment tasks including 24+2 reference directions for each of the 6 panning configurations. Each task was repeated once after a short break, yielding an average duration of 90 min for the entire experiment.

Results

The adjusted panning angles were left/right-symmetrically summarized resulting in $24 = 2$ (symmetry) × 2 (repetitions) × 6 (subjects) panning angles for each reference direction between 0° and 180° for each configuration. Figures 3 and 4 show the resulting localization curves for all panning configurations along with their predictions by $\boldsymbol{r}_{\mathrm{E}}$ and $\boldsymbol{r}_{\gamma}^{\mathrm{w}}$. In general, the localization curves of Ambisonics are almost perfectly aligned with the panning direction, especially for the smaller loudspeaker spacing. Interestingly, the $\boldsymbol{r}_{\mathrm{E}}$ predictions seem to be superior in all cases, as also shown in Figure 6.

Post-Experiment

In order to investigate the cause for the inferior performance of the $\boldsymbol{r}_{\gamma}^{\mathrm{w}}$ predictor, a post-experiment evaluated some of the conditions of the previous study on whose results the model was based. In particular, we tested the same three loudspeaker configurations as used for MDAP and Ambisonics, however with VBAP and only for the most interesting lateral reference directions ±[60° 75° 90° 105° 120°]. The same listeners participated and they were allowed to perform the head movements described above. All 3 (configurations) × 10 (directions) conditions were repeated once. The new VBAP results are shown together with the previous results and their modeling in Figure 5. The results interestingly differ and while the previous results are well predicted by $\boldsymbol{r}_{\gamma}^{\mathrm{w}}$, the new results are better predicted by $\boldsymbol{r}_{\mathrm{E}}$.

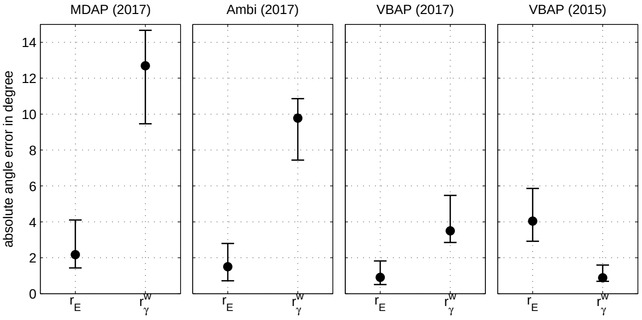

Figure 6: Median and 95% confidence interval of the absolute prediction errors for different experiments.

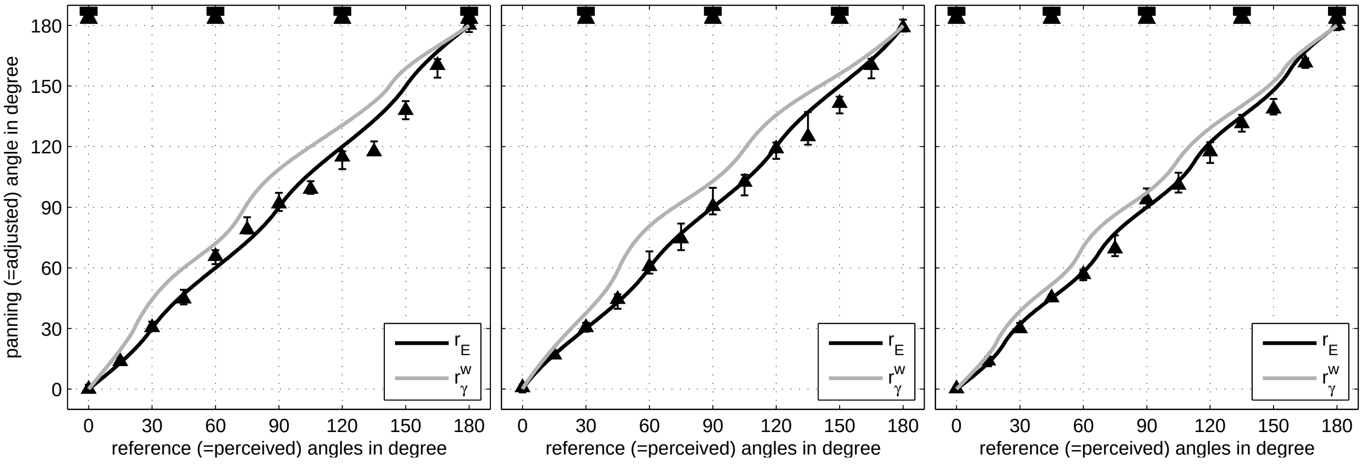

Figure 3: Symmetrized median and 95% confidence interval of the adjusted gains using MDAP and predicted angles. Loudspeaker symbols on top indicate the loudspeaker placements of the 3 configurations.

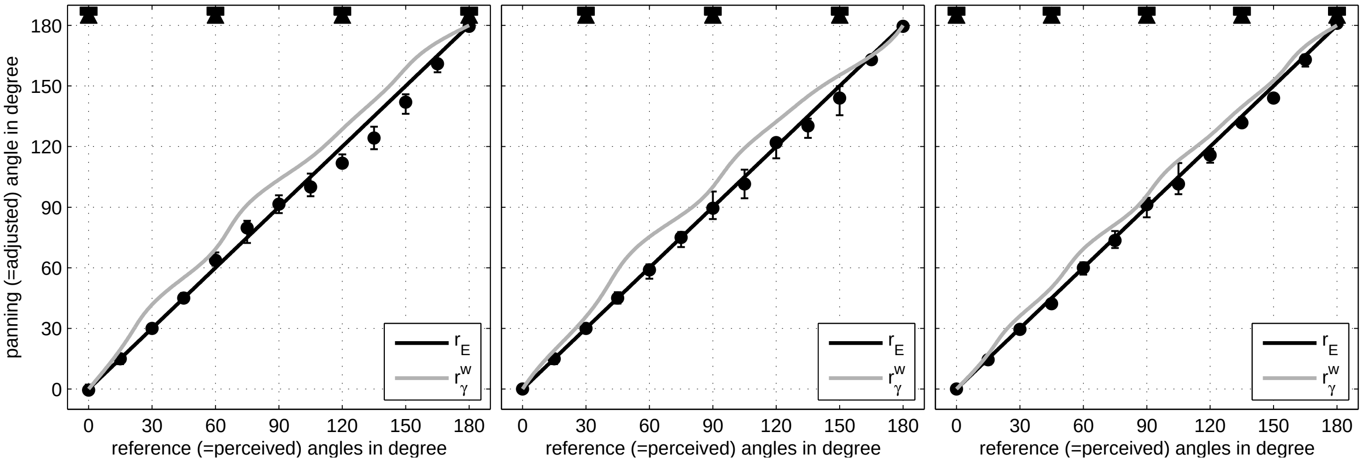

Figure 4: Symmetrized median and 95% confidence interval of the adjusted gains using Ambisonics and predicted angles. Loudspeaker symbols on top indicate the loudspeaker placements of the 3 configurations.

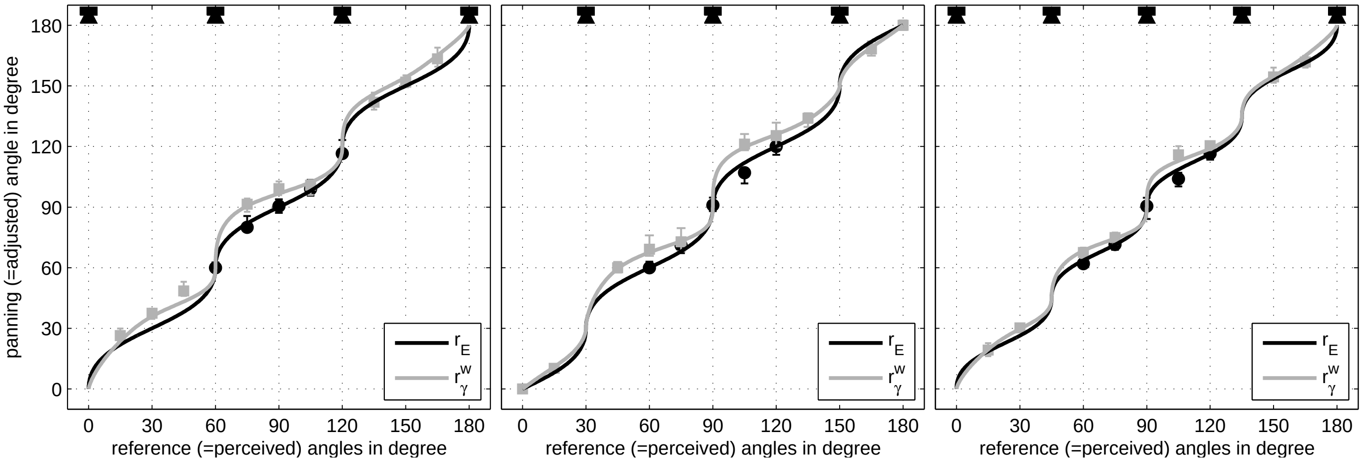

Figure 5: Symmetrized median and 95% confidence interval of the adjusted gains of the 2015 experiment (gray) and the present experiment (black) using VBAP and predicted angles. Loudspeaker symbols on top indicate the loudspeaker placements of the 3 configurations.

Conclusion

We presented an extension of the generalized tangent law [12] for multiple loudspeakers through re-formulation in vector form. The resulting model $\boldsymbol{r}_\gamma^\mathrm{w}$ incorporates direction-dependent weighting of the loudspeakers and a slope that depends on the estimated direction of the energy vector.

However, a listening experiment using Multiple-Direction Amplitude Panning and Ambisonics on different loudspeaker layouts revealed that the simple energy vector $\boldsymbol{r}_\mathrm{E}$ is a better predictor than the proposed $\boldsymbol{r}_\gamma^\mathrm{w}$.

Even a repetition of previous experiments used to establish $\boldsymbol{r}_\gamma^\mathrm{w}$ for pairwise amplitude now gave different results. While the previous results could be modeled precisely with $\boldsymbol{r}_\gamma^\mathrm{w}$, the present results fits the energy vector. As the experimental environments and procedures were the same, the difference in the results is due to the freedom of the listeners to slightly move their head in the present experiment. The rather natural freedom of motion seems to stabilize localization. This finding might question the practicability of experimental data without motion.

Comparing the three amplitude-panning methods, the linearity of the localization curve increases with the number of simultaneously actived loudspeakers: the most rippled curve is obtained for vector-base amplitude panning, the most linear one for Ambisonics.

Acknowledgments

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