Reproducibility of stereophonic amplitude-panning curves

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Introduction

Since the first larger studies about stereophonic amplitude-panning were published in the end of the 1950s [L59], there have been a lot of experiments to determining the relation between the level difference in a pair of loudspeakers and the perceived direction [W60, M60, W63, W65, R74, C75, R90, M99, P01, P03, S09, L13, Z15, F17].

Interestingly, the results for these amplitude-panning curves vary a lot between the various studies, more than the estimated confidence intervals of the various curves, and the question is why. This contributions compares some of the experimental environments, stimuli, reporting methods, and offers the data of digitized panning curves, in the hope to find explanations for the differences.

Generalized panning curve parameters

The extended tangent law suggested in [Z15] models any pairwise-panned auditory event by

$$R = \tanh \sigma, \qquad (1)$$

using the relative position $-1 \leq R \leq 1$ between the loudspeakers. Alternatively, experiments may specify a perceived angle φ that determines R from the loudspeaker angles $\pm\alpha$ as $R = \frac{\tan\phi}{\tan\alpha}$.

To compare several experimental curves in terms of center slope and offset, it helps to model them as a line depending on the level difference L in dB, and the constants W, γ describing the level offset for center panning and the center slope of the curve

$$\sigma = \mathrm{artanh}\{R\} = \gamma\,\tfrac{\ln 10}{40}(L - W). \qquad (2)$$

Least-square parameters. The resulting curve of any experiment assigns to each condition a vector of level differences $\boldsymbol{l} = [L_1, \ldots, L_C]$ a vector of auditory event locations $\boldsymbol{r} = [R_1, \ldots, R_C]$. If modeled, the error becomes

$$\boldsymbol{e} = \mathrm{artanh}\{\boldsymbol{r}\}\,\tfrac{40}{\ln 10} - \underbrace{[\boldsymbol{l},\, \boldsymbol{1}]}_{\boldsymbol{M}} \begin{bmatrix} \gamma, \\ -\gamma W \end{bmatrix}, \qquad (3)$$

and its squares weighted by $\boldsymbol{W} = \mathrm{diag}\{\boldsymbol{w}\}$ are minimized

$$\min \boldsymbol{e}^{\mathrm{T}} \boldsymbol{W} \boldsymbol{e} \qquad (4)$$

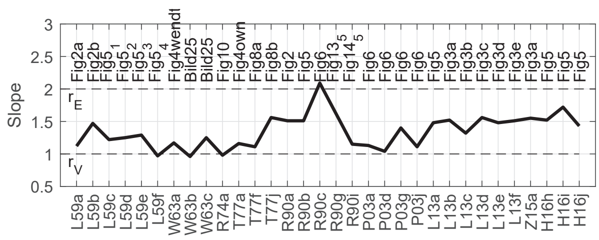
using the weights $\boldsymbol{w} = [w_i]$, $w_i = [1 + |\mathrm{artanh}\{R_i\}|]^{-1}$ to moderate any values of R_i close to unity. The solution is

$$\begin{bmatrix} \gamma, \\ -\gamma W \end{bmatrix} = \tfrac{40}{\ln 10} (\boldsymbol{M}^{\mathrm{T}} \boldsymbol{W} \boldsymbol{M})^{-1} \boldsymbol{M}^{\mathrm{T}} \boldsymbol{W}\, \mathrm{artanh}\{\boldsymbol{r}\}, \qquad (5)$$

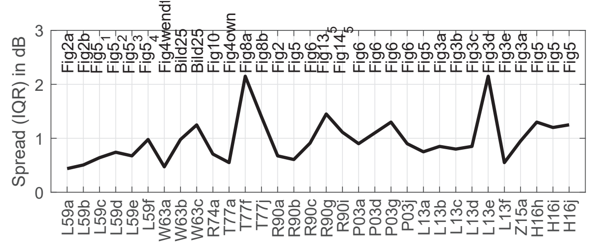
and in some experiments, only conditions with limited $|R_i|$ were considered for a visually reasonable fit. Where experimental IQR values were given or could be retrieved, a spread $\pm\Delta W$ was fit to experimental values around $L = 0$.

Broad-band frontal panning curves

In experiments using standard stereo loudspeaker setups with broadband sound material in the anechoic chamber or studio, experiments indicate a slope between 1 and 2, i.e. what the $\boldsymbol{r}_{\mathrm{V}}$ and $\boldsymbol{r}_{\mathrm{E}}$ measures would indicate, see Fig. 1. Moreover, an (equivalent) inter-quartile range (IQR) of ratings near the center image varies around 1 dB.



(a) slope



(b) spread (IQR)

Figure 1: Panning function slopes and spread for broadband.

Fig. 2 shows a 2D overview of the above material and indicates experimental parameters investigated below.

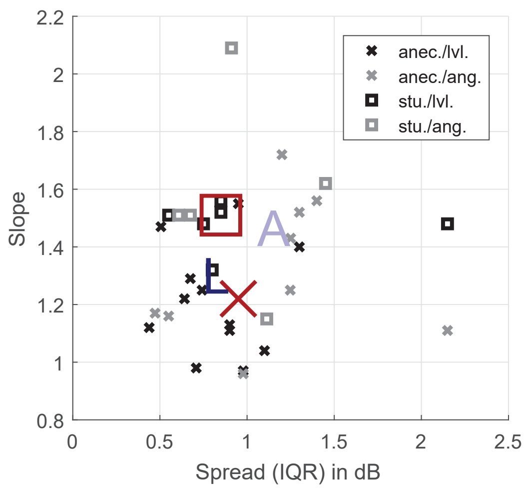


Figure 2: Frontal broadband-panning slopes and spreads for angle/level reporting tasks and studios/anechoic environments; large symbols are partial medians of slope and spread for studio (square), anechoic (x), level (L), and angle (A).

Reporting method. For all frontal-panning broadband curves, there are 18 with *level*-adjustment and 14 with *angle*-indicating tasks, which is a *weakly significant* factor on the 50%dB *spread* of the panning curve around the center image ($p = 0.09$, $\Delta W_{\mathrm{angle}} = \pm 1.16$dB, $\Delta W_{\mathrm{level}} = \pm 0.83$dB), but it is *not a significant* factor for the *slope* γ of the panning curve ($p = 0.25$).

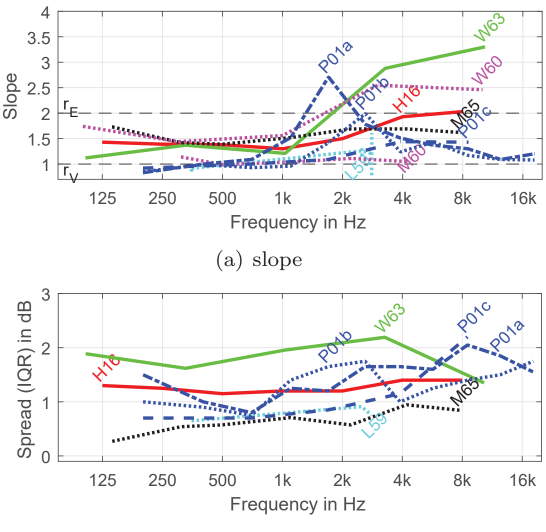
Acoustic environment. There were 21 experiments done in *anechoic* and 11 in *studio* rooms, which is *not a significant factor* for the dB *spread* ($p = 0.81$), but it implies a *significantly* different *slope* of the panning curve ($p = 0.01$), which is $\gamma_{\mathrm{studio}} = 1.5$ and $\gamma_{\mathrm{anechoic}} = 1.2$.

In *studio environments*, amplitude panning around the look direction requires a level change that is 20% smaller for displacing amplitude-panned auditory events than in anechoic environments.

Narrow-band frontal panning curves

For third-octave band noises or impulses (one in [P01] is double-octave), see Fig. 3, there is the tendency of their slope to increase at frequencies above 1kHz, as reported in most works [W60, W63, M60, W65, H16], but only partly so in [P01]. In their details, the studies rather appear to be diverging with no particular causes that could be understood from the experimental conditions described. The curve observed in [H16] appears to be a good compromise.

The available studies are all carried out in anechoic rooms. The statistical dB spread of the curves is similar to those of broad-band sounds, maybe slightly larger, and the slopes are covering a wide range from 1 upwards.



(a) slope

(b) spread (IQR)

Figure 3: Panning function slopes and spread over frequency.

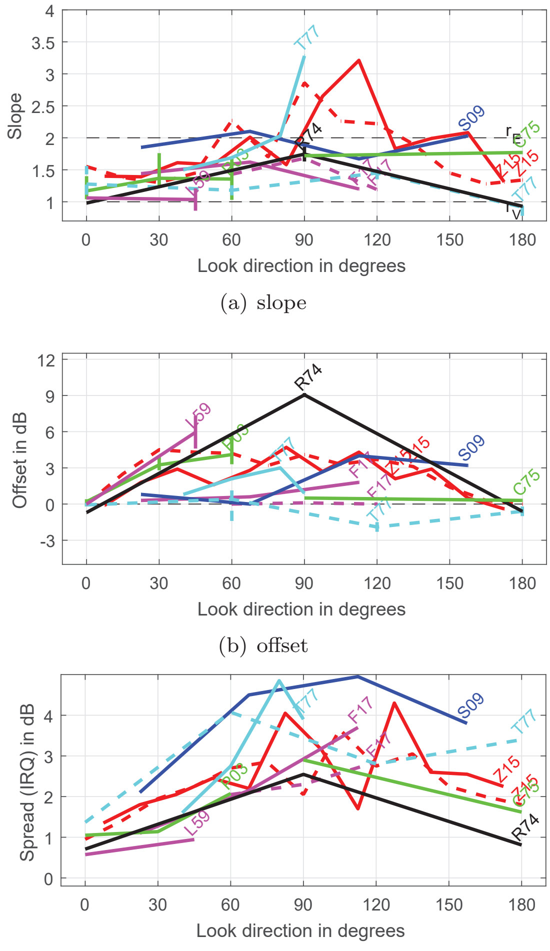
Broad-band lateral panning curves

For various look directions with regard to stereo pairs having 45°, 60°, and 90° spacings, Fig. 4 shows the slopes, center offsets, and equivalent dB spreads of the available experimental results. The different stereo pair apertures map qualitatively consistently into the dB / relative lateralization representation space chosen; while the magnitude of the auditory event shifts would clearly scale with aperture.

The large lateral spread of the results is what the studies clearly share, lifting the equivalent spread up to 3 dB on average.

While the direction of the center offset is frontal in most studies, the amount varies quite substantially, and reaches values larger than the equivalent spread converted to confidence intervals, which would typically be half or third as large for 30 to 80 responses per conditions. Only the experiments [C75, F17] avoid a center-image offset, maybe listeners used similar strategies to deal with uncertainty.

The slope of the panning functions diverges substantially for the lateral directions, and only experiments [L59, C75, P03, F17] indicate a largely constant slope, but of differing values $\gamma = \{1, 1.8, 1.3, 1.5\}$.



(a) slope

(b) offset

(c) spread (IQR)

Figure 4: Panning slopes, offsets, spreads over look direction.

None of the works used a rigid head fixation, however [T77, S09] either had self-monitoring methods or playback inhibition installed to help keeping the head still. Only in [F17] participants were explicitly advised to rather shift their head front-back or laterally by a couple of centimeters, avoiding rotation, in order to give better adjustments whenever there was uncertainty.

Conclusion

By this paper we could collect and offer digitized result data from listening experiments. This collection is done with the idea to consolidate and stabilize the results obtained in various places. Altogether, the collection consists of resulting panning curves of 172 individual stereophonic pairs with the variables look direction, stereo-pair aperture, reporting of level or angle, frequency bandwidth, signal type, loudspeaker type, IQR/CI/std, and where available, the responses are digitized with spread in terms of low, mid, and high whisker.

There is mainly one solid conclusion that we could draw from comparing the more neat frontal data: Stereophonic amplitude panning curves for studios deliver the more ecologically valid results, which turned out to be significant in one aspect: They are 20% steeper than for anechoic chambers. What is more, level-adjustment tasks appear to be slightly more accurate, but without clear effect on slope. The accuracy in experimental results from studios and anechoic chambers is comparable.

Differences in frequency-dependent results or such from lateral stereo pairs could not be as easily understood, yet. Maybe the data could be useful for interpretation or clarifying experiments within the scientific community. These stereophonic amplitude panning curves do not appear to be all reproducible in their greater detail. Some of these differences are admittedly insignificant in the practical use. And yet it is remarkable to observe systematic effects indicating that results from different laboratories are not fitting together like curves obtained from a larger, similar population under the same conditions.

It might be wise to always consider including own response data sets as accommodating material when writing a paper in order to promote comparison and comparability. The data from our own more recent experiments [Z15, H16, F17] are online `http://opendata.iem.at/projects/listening_experiment_data/`, and we gratefully received data that we could host by courtesy of Simon et al. [S09]. The online repository also includes the collected metadata of the 172 experiments investigated in this contribution.

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