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Phantom Source Widening by Filtered Sound Objects

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ABSTRACT

Audio effects increasing the perceived source extent (width/distance) often employ frequency-dependent panning of a single virtual sound object or real-time-controlled design of stochastic multi-channel filters. Both ways imply increased complexity required in the renderer or object representation. In this paper we present a frequency-dependent panning scheme to obtain constellations of 3, 4, 5, or 7 filtered sound objects, as a simplified object-based description of wide/distant sound for any renderer. We deal with the multi-channel filter-design questions: Are the filters rather temporally compact or frequency-selective, zero-phase FIR vs. IIR or causal-sided FIR, how strictly power-complementary? By results of a listening experiment for selected examples, we can provide some answers and an effective design of useful width-/distance-increasing filtered sound objects.

1 Introduction

Auditory images of increased extent (width or diffuseness) can be created based on filters and spatial audio playback on loudspeakers, as reviewed in Pihlajamäki's recent paper [1], together with the papers [2, 3, 4, 5, 6, 7, 8] that provide interesting views on new ways to do so. The main approaches are outlined in Kendall's paper [9] and there are a lot of other interesting works [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20] on the topic.

Many audio effects increasing the perceived extent/width/diffuseness can be interpreted as performing a kind of frequency-dependent phase/amplitude panning of a single virtual sound object, e.g. [2, 1, 9, 11, 12, 15, 17, 18]. For the resulting filters, as, e.g., in [18, 6] it provides an elegant simplification to use a filter structure of periodic frequency response, which

yields a system of sparse impulse responses that can be built out of uniform delay blocks. Typical values for this delay are in the range of 1.5...20 ms. Still, frequency-dependent panning requires to think of a panning technique and its control to obtain the filters, or to be restricted to STFT-based algorithms as done in [1, 9, 11, 12, 14], if real-time control is required.

With the papers such as [3, 2] the idea came up of how one could directly describe an analytic source phenomenon causing the impression of a diffuse or wide auditory image, instead of describing a frequency-dependent source placement, amplitudes, or phases. While the corresponding source phenomena or source arrangements such as derived from the paper [1] still deliver a rather complex description, we seek to find a simplified description of a virtual source constellation using just a few sources with simple filter functions driving them.

A simplified widened-source constellation permits implementation on any spatial audio rendering system that just needs to be capable of source positioning through an object-based audio format such as ADM [21]. This circumvents the understandable shortcoming that not all of the renderers, e.g. such implemented for own academic purposes, are able to express the source-extent-related ADM parameters such as width, height, depth, distance, diffuseness.

The focus here lies on constellations of 3, 4, 5, and 7 equiangularly spaced virtual sources and corresponding filters achieving modification of the spatial extent or distance. Sec. 2.1 presents the initial design that stems from an Ambisonic widening effect using loudspeakers, cf. [7]. Its finite and sparse impulse responses produces signals for ideally arranged loudspeakers. These signals are used to feed virtual sources in place of the loudspeakers. Moreover, the impulse responses are symmetric around one main time lag and decay in magnitude around the main direction, both in a way that easily permits angular and temporal truncation.

Alternatively, only using the causal side of the symmetric impulse responses is considered in Sec. 2.2 in order to reduce pre-ringing when using long time constants, at the expense of strictly power complementary filters. Sec. 2.3 presents a recursive (IIR) design, as another alternative. The IIR design is causal-sided and power complementary, and it only gives up on phase equalized responses. Magnitude responses of Sec. 2.1 serve as target, and the IIR design is implemented based on simple filters such as those in [18].

If an increased number of decorrelated channels is desired, the design schemes above yield responses that are more frequency-selective, therefore temporally longer. This response length is still to be studied, as a variation of the decorrelated output channels (Ambisonics order) was not considered in the initial study [7].

Finally, the listening experiment in Sec. 3 evaluate the filter designs (FIR/causal-sided FIR/IIR) and the impulse response length/number of virtual sources. Our study considers how strong wide/distant-source effects are produced and whether they are preferred in terms of audio quality, at two listening positions.

2 Filter designs and algorithms

All experiments and the proposed filter designs are based on the algorithm in [7], a zero-phase FIR design. The other designs under investigation, causal FIR and IIR, are derived from this and presented below.

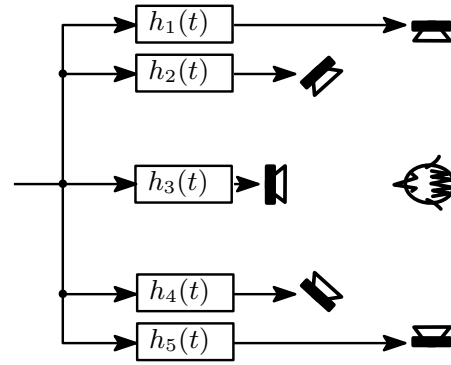


Fig. 1: Processing scheme for 5 filtered sound objects.

2.1 Symmetric FIR design

The Ambisonic widening filters that were tested in [7] supplies $L = 2N + 2$ equi-angularly arranged loudspeakers on a horizontal ring. It can be briefly derived from the max-rE Ambisonic panning function

$$h(\varphi) = \sum_{n=0}^N (2 - \delta_n) \cos \left[\frac{n\pi}{2(N+1)} \right] \cos [n(\varphi - \varphi_s)] \quad (1)$$

varying the source direction $\varphi_s = -\hat{\varphi} \cos(\omega T)$ for different frequencies, using φ as the loudspeaker angle, and inverse Fourier transform. The frequency-dependent term $\cos[n\varphi + n\hat{\varphi} \cos(\omega T)]$ is characterized by the identity $\mathcal{F}^{-1}\{\cos(\alpha + \beta \cos(\omega))\} = \sum_q \cos(\frac{|q|\pi}{2} + \alpha) J_{|q|}(\beta) \delta(t - q)$ so that its impulse response consisting of causal ($q \geq 0$) and anti-causal ($q < 0$) part is proportional to

$$h(\varphi, t) = \sum_{q=-\infty}^{\infty} h_q(\varphi) \delta(t - qT) \quad (2)$$

$$h_q(\varphi) = \sum_{n=0}^N (2 - \delta_n) \cos \left[\frac{n\pi}{2(N+1)} \right] \cos \left[\frac{|q|\pi}{2} + n\varphi \right] J_{|q|}(n\hat{\varphi}).$$

The implementation tested below used the modulation depth $\hat{\varphi} = 71^\circ$, a FIR limited to $-5 \leq q \leq 5$, a time shift by $5T$ enabling implementation, and the Ambisonic orders $N = \{1, 2, 3, 5\}$ requiring virtual loudspeaker arrays that were truncated to semi-circular: $\{\varphi\}_{N=1} = \{-90^\circ, 0^\circ, +90^\circ\}$, $\{\varphi\}_{N=2} = \{-90^\circ, -30^\circ, +30^\circ, +90^\circ\}$, $\{\varphi\}_{N=3} = \{-90^\circ, -45^\circ, 0^\circ, +45^\circ, +90^\circ\}$, and $\{\varphi\}_{N=5} = \{-90^\circ, -60^\circ, -30^\circ, 0^\circ, +30^\circ, +60^\circ, +90^\circ\}$.

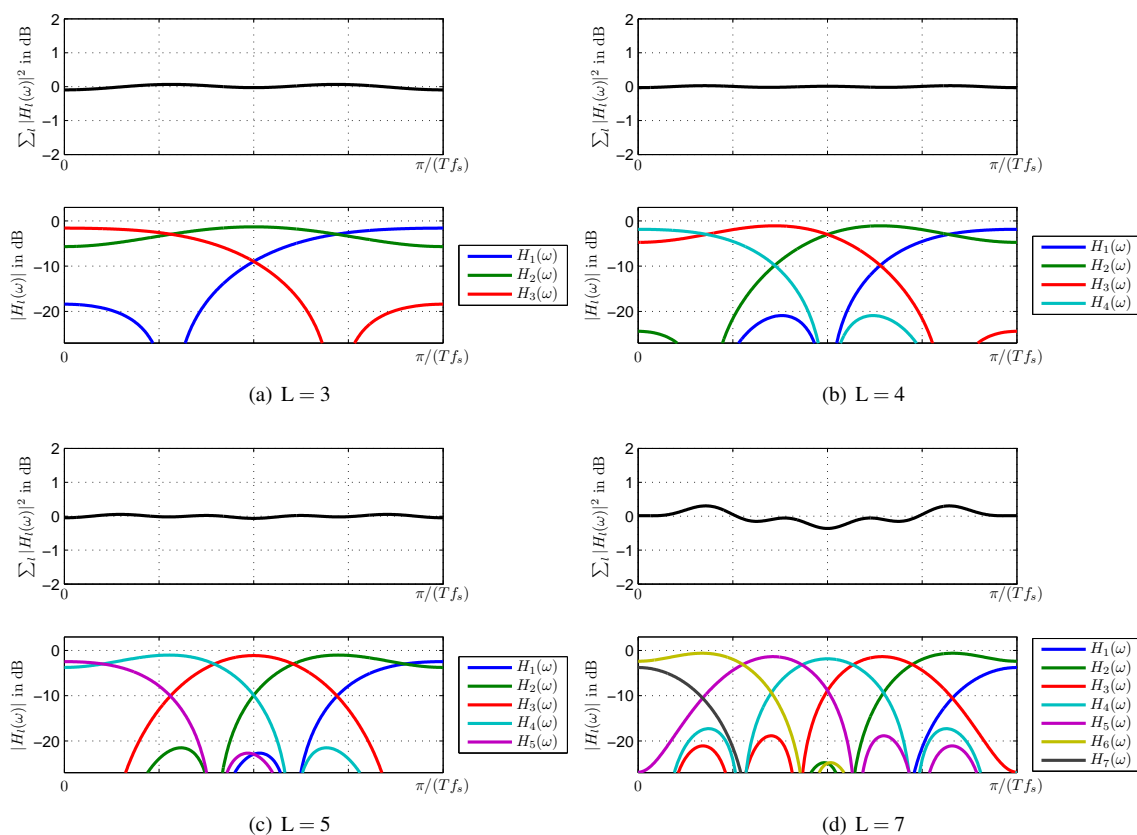


Fig. 2: Sum-square frequency responses and individual frequency responses of the *symmetric FIR* implementation of widening/diffuseness filters that drive 3, 4, 5, or 7 virtual sources arranged from -180° to 180° .

Fig. 2 shows the frequency responses of the *symmetric FIR* design. Fig. 1 sketches the processing scheme for the example $N = 5$, and Fig. 5 the loudspeaker setup for the experiment, which contains all positions as subsets. The time constant was set to $T = 1.5$ ms to widen the perceived sound image, and to $T = 15$ ms to make it appear distant.

2.2 Causal-sided FIR implementation

As the above-mentioned sparse impulse responses are symmetric in time, their slow onset can be disturbing, especially when used with long time constants T and large modulation depths $\hat{\phi}$. For this reason, e.g. the implementation in [22] uses the option *one-sided* that just truncates the impulse responses $h_q(\varphi, t)$ to the contributions for $q \geq 0$ in Eq. (3) or Tab. 1. This technically destroys both the power-complementary behavior and the phase equality of the original responses.

While this also makes responses in Fig. 3 lose some of their frequency selectivity, the sum-square response does not seem to incur disastrous variation and still looks acceptable.

2.3 IIR implementation

The *causal-sided implementation* presented before already used some relaxed design goals that had been considered ideal, initially. It immediately suggests itself to carry on and design much simpler power-complementary recursive filters that are sparse in time.

For decorrelation, Vickers presented recursive filters in [18] that used multiple unit delays z^{-M} to replace those in an original filter design. This operation is the same as zero-insertion between the time-domain samples yielding a spectrally repeated frequency response.

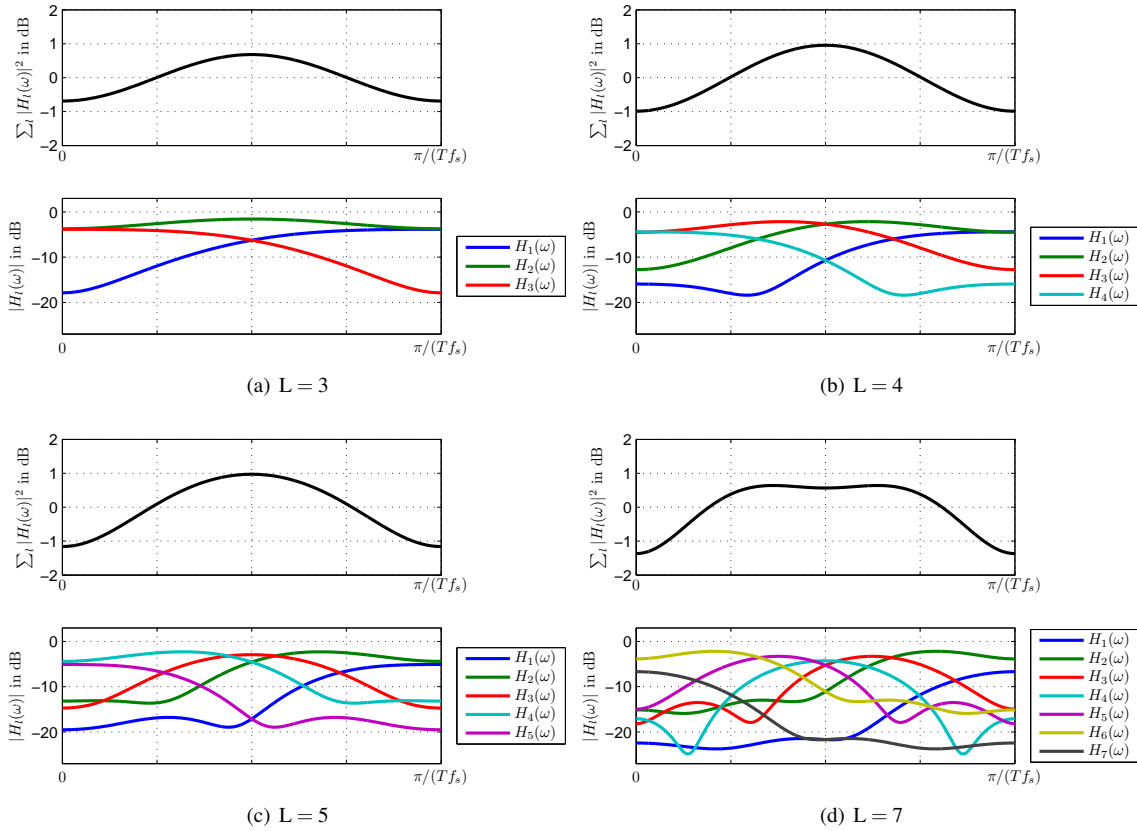


Fig. 3: Sum-square frequency responses and individual frequency responses of the *causal-sided FIR* implementation of widening/diffuseness filters that drive 3, 4, 5, or 7 virtual sources arranged from -180° to 180° .

We tuned simple 2nd-order *IIR* filters for each of the virtual sources by manual pole-zero placement to reconstruct the frequency responses in Fig. 2. Assuming that $M = Tf_s$, with the sample rate f_s , the implementation of each loudspeaker response obeys the z -transform

$$H(z) = \frac{b_0 + b_1 z^{-M} + b_2 z^{-2M}}{1 + a_1 z^{-M} + a_2 z^{-2M}}, \quad (3)$$

with coefficients tabulated in Tab. 2.

The result is shown in Fig. 4 and indicates a fair match to the design targets individually and in terms of the sum-square ripple, which seems superior to the one in Fig. 3. However, one new aspect here is that the phase differences may become 180° between different channels.

3 Listening Experiment

The different designs (*symmetric FIR*, *causal-sided FIR*, *IIR*) with different number of virtual sources $L = \{3, 4, 5, 7\}$ are examined at two listening positions in terms of the strength of their effect and sound quality. Each virtual source is directly played back by a loudspeaker at the corresponding location.

3.1 Setup and Conditions

Playback employed a semicircle of 9 Genelec 8020 with a radius of 2.5 m in the center of a $6.8 \text{ m} \times 7.6 \text{ m} \times 3 \text{ m}$ large lecture room with a mean reverberation time of 0.57 s. There were two listening positions: the center and 1.25 m ($= 1/2$ loudspeaker radius) off-center to the side, cf. Fig. 5. The first sentence of EBU's male speech reference recording [23] was used for evaluation.

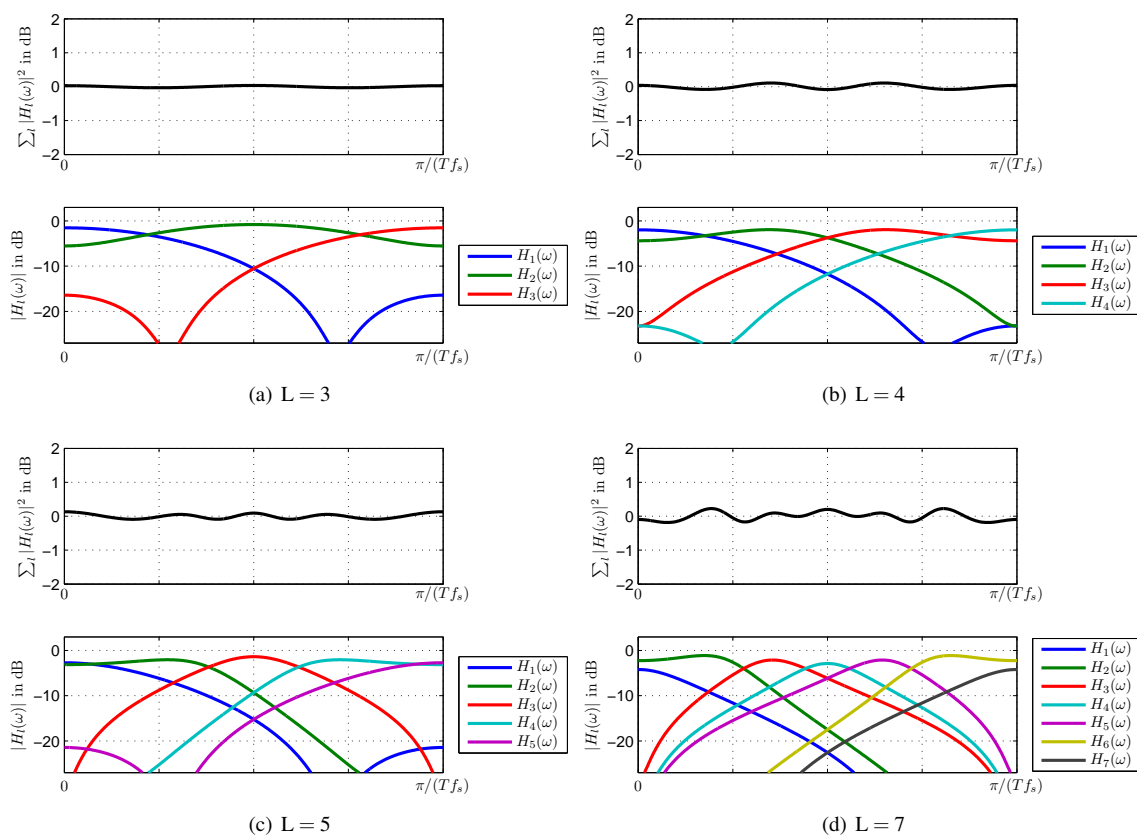


Fig. 4: Sum-square frequency responses and individual frequency responses of the *IIR* implementation of widening/diffuseness filters that drive 3, 4, 5, or 7 virtual sources arranged from -180° to 180° .

For both the widening and the distance-increasing effect, $T = \{1.5, 15\}$ ms, we compared 12 conditions corresponding to *symmetric FIR*, *causal-sided FIR*, *IIR* for $L = \{3, 4, 5, 7\}$ virtual loudspeakers. All filter designs were time-aligned so that the *causal-sided FIR* and *IIR* condition have their $t = 0$ impulse aligned with the symmetry point $t = 0$ of the *symmetric FIR* design and a reference playback from the central loudspeaker. Moreover, perceived loudness levels were equalized by three listeners to the reference before the experiment. To stabilize the sound image for the off-center listening position, the sound of each effect condition was blended with the -10 dB attenuated reference from the central loudspeaker for all conditions. Hereby, timbral differences between the filter designs diminished. Also note that in the preparation of the experiment blending with the central loudspeaker was found to yield a viable practical means to control the effect strength in all cases.

Using a graphical user interface (GUI), MUSHRA-like comparison of the 12 conditions were done with regard to a hidden reference, which is the single central loudspeaker. The reference is the lower anchor representing the narrowest perceived width and the upper anchor for the sound quality.

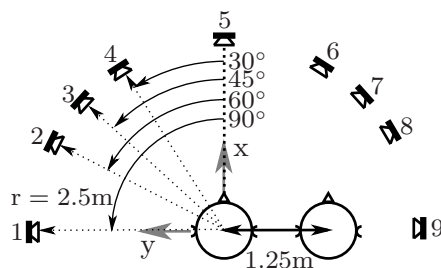


Fig. 5: Experimental setup in the lecture room.

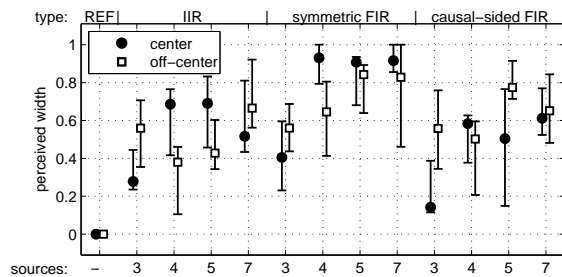


Fig. 6: Median values and corresponding 95% confidence intervals of the perceived width using the widening filters.

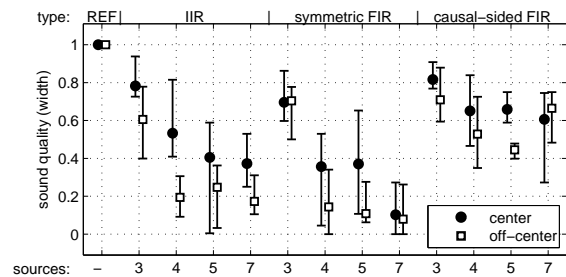


Fig. 7: Median values and corresponding 95% confidence intervals of the perceived sound quality using the widening filters.

At each listening position, listeners were asked to rate all conditions either with regard to the apparent source width (for $T = 1.5$ ms) or with regard to the perceived distance (for $T = 15$ ms), as measures of the strength of the effect. Moreover, the sound quality of all effects was rated at both listening positions for all 12+1 conditions. In total, questions result in 2 (listening positions) $\times 2$ (widening/distance effect) $\times 2$ (effect/sound quality) = 8 trials with 13 stimuli. Every trial showed 13 randomly arranged stimuli on the GUI, and either the effect strength or sound quality trial was presented first, randomly. The strength/quality trial pairs were in random order for the positions (center/offcenter) and effect types (1.5 ms / 15 ms) for every listener.

Ten male listeners (average age 33 years) participated in the experiment, IEM staff and students, who are all experienced in spatial audio. The average duration of the experiment was 34 minutes per listener.

3.2 Results

Despite listeners were advised to use the full scale to rate the different stimuli, the responses were scaled and shifted. For the sound quality, each listeners' rating was scaled/shifted so that the minimum and maximum rating were mapped to the values 0 and 1. For the effect strengths, scaling and shifting was used that maps the listener's response for the reference to 0 and the maximum to 1. For the distance effect, the mapping yields values < 0 whenever the stimulus was closer than the reference stimulus.

3.2.1 Widening ($T=1.5$ ms)

All conditions were significantly perceived wider than the reference ($p < 0.002$) for both listening positions.

In the center, the 3-source IIR filter yielded a significantly smaller effect ($p < 0.008$) than all other IIR filters which among themselves were not significantly different ($p > 0.34$). Similar behavior could be observed of the symmetric FIR filters ($p < 0.02$, $p > 0.19$) and the causal-sided FIR-filters ($p < 0.08$, $p > 0.32$). The symmetric FIR filters with 4 and 7 sources caused stronger widening than all other filters ($p < 0.013$).

At the off-center position, the differences were less significant. Within the IIR filters, the 7-source version is significantly wider than the 4-source version ($p < 0.04$). There were no significant differences between the symmetric FIR filters. The 5-source version of the causal-sided FIR filters was significantly wider than the 4-source version ($p < 0.016$). There is no overall-widest condition for the off-center position, however symmetric FIR with 5 and 7 sources, as well as causal-sided FIR with 5 sources are the widest conditions.

In terms of sound quality, all filtered conditions were significantly different from the reference ($p < 0.008$). Reversely to the strength of the widening effect, sound quality decreased with the number of sources for both listening positions. However, decreases were smaller for the causal-sided FIR conditions at both listening positions. At the center, the causal-sided FIR filter significantly outperformed its symmetric counterpart ($p < 0.021$) for 4 and 7 sources, as well as the IIR filters for 5 sources ($p < 0.011$). At the off-center position, all causal-sided FIR filters yielded significantly better sound quality than all other filters with more than 3 sources ($p < 0.034$), except for weakly better quality of the 4-sources causal-sided FIR compared to the 5-sources IIR ($p = 0.096$).

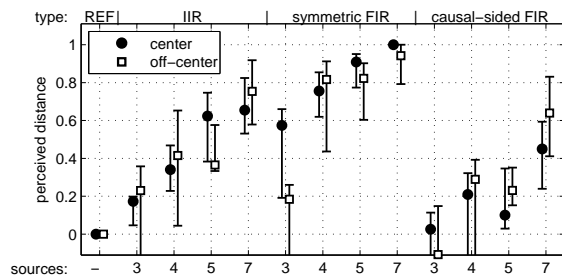


Fig. 8: Median values and corresponding 95% confidence intervals of the perceived distance using the distance filters.

3.2.2 Distance ($T=15$ ms)

Obviously, the perceived distance increased with the number of virtual sources for all filters. Surprisingly, various conditions appeared closer than the reference for some listeners: 3- and 4-sources causal-sided FIR filters at both listening positions, 3-sources IIR and symmetric FIR at the off-center position.

At the central listening position, the symmetric FIR filters yielded a significantly stronger distance effect for all numbers of sources ($p < 0.049$). The effect of the causal-sided FIR filters was significantly smaller than that of the IIR filters for 5 and 7 virtual sources ($p < 0.025$). Differences between the filter types reduce at the off-center listening position: The 7-source symmetric FIR design is no longer significantly more distant than its causal-sided FIR variant ($p = 0.061$).

Again, sound quality decreased with the number of virtual sources for all filters at all listening positions. At the center, the worst causal-sided FIR filter was significantly better than all symmetric FIR filters ($p < 0.001$), and significantly better than the IIR filters with 5 or 7 sources ($p = 0.002$). At the off-center position, the worst causal-sided FIR filter was still significantly better than all symmetric FIR filters and IIR filters with more than 3 sources ($p < 0.003$).

4 Discussion and Summary

We presented a simple virtual source or physical loudspeaker arrangement covering angles on a semicircle and fed by a set of decorrelation filters to render widening or distance-enlarging diffuseness effects.

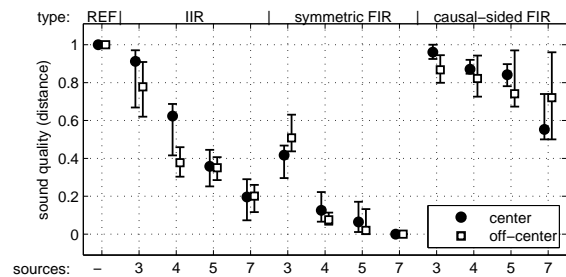


Fig. 9: Median values and corresponding 95% confidence intervals of the perceived sound quality using the distance filters.

The concept is efficient in terms of the short filters feeding the loudspeakers (IIR: 5 coeffs., causal-sided FIR: 6 coeffs., symmetric FIR: 11 coeffs.) and in terms of the rather neat number of virtual sources it employs (3, 4, 5, or 7).

Our evaluation shows that power complementarity and phase equality might not be the only relevant constraints to achieve effects with high sound quality.

Despite widening ($T = 1.5$ ms) already works for small numbers of virtual sources, we could show that it is more stable for off-center listening positions when using 5 or 7 virtual sources. In this range of output channels, the causal-sided FIR filter sounds best, despite its degraded power complementarity and somewhat smaller phase equality between the channels.

Moreover, a setting to longer time delays between the non-zero impulse response entries of the channel filters ($T = 15$ ms) achieves a distance-increasing effect by creating an impression of a short and diffuse room response, as already applied in [24]. For this distance-increasing effect, we could show that the impulse response length related to the number of output channels is relevant, however only yields high sound quality for the causal-sided FIR filter design, as e.g. used in the *one-sided* setting of the ambix_widening VST plugin [22].

Obviously, pre-ringing of the filters' impulse responses should be avoided for good sound quality and long time constants ($T = 15$ ms), and it leaves the symmetric FIR filters with the lowest sound quality ratings. The superior ranking of the causal-sided FIR design among the pre-ringing-free alternatives is despite the weaker

power complementarity of this design. It might be that the preference of the causal-sided FIR filters over the IIR design is due to its smaller inter-channel phase differences, shorter and less resonant impulse response.

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L = 3 (N = 1):

φ	$h_0(\varphi)$	$h_{\pm 1}(\varphi)$	$h_{\pm 2}(\varphi)$	$h_{\pm 3}(\varphi)$	$h_{\pm 4}(\varphi)$	$h_{\pm 5}(\varphi)$
-90°	0.5000	-0.3592	-0.0000	0.0254	0.0000	-0.0005
0°	0.9606	0.0000	-0.1192	0.0000	0.0040	-0.0000
90°	0.5000	0.3592	0.0000	-0.0254	0.0000	0.0005

L = 4 (N = 2):

φ	$h_0(\varphi)$	$h_{\pm 1}(\varphi)$	$h_{\pm 2}(\varphi)$	$h_{\pm 3}(\varphi)$	$h_{\pm 4}(\varphi)$	$h_{\pm 5}(\varphi)$
-90°	0.5188	-0.4400	0.2215	0.0312	-0.0358	-0.0006
-30°	0.9792	-0.4375	-0.2371	0.1076	0.0222	-0.0084
30°	0.9792	0.4375	-0.2371	-0.1076	0.0222	0.0084
90°	0.5188	0.4400	0.2215	-0.0312	-0.0358	0.0006

L = 5 (N = 3):

φ	$h_0(\varphi)$	$h_{\pm 1}(\varphi)$	$h_{\pm 2}(\varphi)$	$h_{\pm 3}(\varphi)$	$h_{\pm 4}(\varphi)$	$h_{\pm 5}(\varphi)$
-90°	0.5266	-0.4515	0.3132	-0.1240	-0.0507	0.0381
-45°	1.0338	-0.6997	0.0050	0.2850	-0.0607	-0.0411
0°	0.9221	0.0000	-0.6316	-0.0000	0.1470	0.0000
45°	1.0338	0.6997	0.0050	-0.2850	-0.0607	0.0411
90°	0.5266	0.4515	0.3132	0.1240	-0.0507	-0.0381

L = 7 (N = 5):

φ	$h_0(\varphi)$	$h_{\pm 1}(\varphi)$	$h_{\pm 2}(\varphi)$	$h_{\pm 3}(\varphi)$	$h_{\pm 4}(\varphi)$	$h_{\pm 5}(\varphi)$
-90°	0.4367	-0.3972	0.3528	-0.2414	0.1324	-0.0250
-60°	1.1877	-0.9938	0.4622	0.0160	-0.2511	0.1790
-30°	1.0316	-0.4852	-0.3793	0.6357	-0.1354	-0.2446
0°	0.7699	0.0000	-0.8063	-0.0000	0.5157	0.0000
30°	1.0316	0.4852	-0.3793	-0.6357	-0.1354	0.2446
60°	1.1877	0.9938	0.4622	-0.0160	-0.2511	-0.1790
90°	0.4367	0.3972	0.3528	0.2414	0.1324	0.0250

Table 1: Non-zero entries of sparse, *symmetric FIR* filters for the widening/diffuseness effect for modulation depth $\hat{\phi} = 71^\circ$, using the zero-phase design Eq. (3) with an arrangement of 3, 4, 5, or 7 virtual sources/loudspeakers. Note that the responses for each loudspeaker are (theoretically) symmetric around $q = 0$, and shifted by $5T$ in the argument of the Dirac Delta of Eq. (3) to enable causal implementation. For the implementation variant *causal-sided FIR*, the symmetry wrt. time is omitted by zeroing the coefficients for $q \leq 0$ in the above coefficients table.

L = 3:

φ	a_0	a_1	a_2	b_0	b_1	b_2
-90°	1.000000	-0.100000	0.000000	0.158489	0.183375	0.128376
0°	1.000000	0.000000	0.016900	0.446684	0.000000	-0.111671
90°	1.000000	0.100000	0.000000	0.158489	-0.183375	0.128376

L = 4:

φ	a_0	a_1	a_2	b_0	b_1	b_2
-90°	1.000000	-0.250000	0.000000	0.199526	0.244554	0.127697
-30°	1.000000	-0.352130	0.220900	0.398107	0.199054	-0.095546
30°	1.000000	0.352130	0.220900	0.398107	-0.199054	-0.095546
90°	1.000000	0.250000	0.000000	0.199526	-0.244554	0.127697

L = 5:

φ	a_0	a_1	a_2	b_0	b_1	b_2
-90°	1.000000	-0.350000	0.000000	0.202302	0.224189	0.163865
-45°	1.000000	-0.526045	0.360000	0.267301	0.324085	0.130977
0°	1.000000	0.000000	0.360000	0.363496	0.000000	-0.314388
45°	1.000000	0.526045	0.360000	0.267301	-0.324085	0.130977
90°	1.000000	0.350000	0.000000	0.202302	-0.224189	0.163865

L = 7:

φ	a_0	a_1	a_2	b_0	b_1	b_2
-90°	1.000000	-0.630000	0.000000	0.154882	0.171638	0.125454
-60°	1.000000	-1.057141	0.476100	0.237137	0.287514	0.116197
-30°	1.000000	-0.647871	0.476100	0.436516	0.000000	-0.377543
0°	1.000000	0.000000	0.490000	0.389045	0.000000	-0.336485
30°	1.000000	0.647871	0.476100	0.436516	-0.000000	-0.377543
60°	1.000000	1.057141	0.476100	0.237137	-0.287514	0.116197
90°	1.000000	0.630000	0.000000	0.154882	-0.171638	0.125454

Table 2: IIR filter designs for the widening/diffuseness effect, using an arrangement of 3, 4, 5, or 7 virtual sources/loudspeakers.