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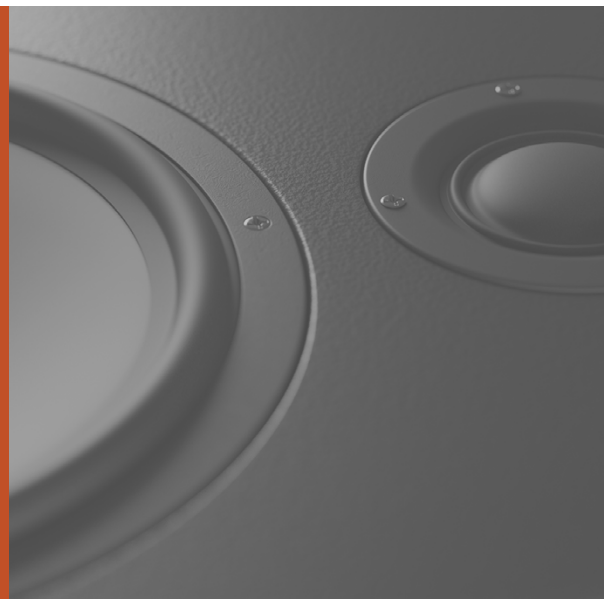
IMMERSIVE AUDIO DESIGN RECOMMENDED PRACTICE

VERSION 1.2

CEDIA™

Consumer Technology Association™

September 2023

FOREWORD

This recommended practice provides guidance for the design and specification of audio reproduction within private entertainment spaces. Industry professionals follow these practices to deliver the optimal performance for the equipment and the space. For the purposes of this document, the definition of *multichannel* is at least five discrete speaker feeds/channels and associated speakers, plus subwoofers.

Exclusions:

- This recommended practice does not discuss methods or best practice for the measurement or verification of as-built system performance. That will be the subject of another upcoming CEDIA/CTA recommended practice.
- Recommendations in this document apply only to consumer release formats, not theatrical.
- This recommended practice does not discuss methods for positioning speakers around large emissive (video wall) displays. Future updates to this document are anticipated as these technologies mature and proposals for such applications are more broadly adopted.

CEDIA recommendations are assembled from years of experience and the cumulative wisdom of its contributors. Industry standards, practices, and recommendations published by other relevant bodies, along with commonly accepted commercial practices now regarded as "de facto standards" in the audio reproduction industry, are also referenced in this document.

Standards include those from, but are not limited to:

- American National Standards Institute (ANSI)
- American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE)
- Audio Engineering Society (AES)
- European Broadcasting Union (EBU)
- International Electrotechnical Commission (IEC)
- International Organization for Standardization (ISO)
- International Telecommunications Union, Radiocommunications sector (ITU-R)
- Society of Motion Picture and Television Engineers (SMPTE)

Accepted commercial practices include those from:

- Dolby Laboratories, Inc. — also refer to the Dolby Atmos & Dolby Audio Logo Guidelines
- NewAuro BV (Auro-3D)
- Xperi Inc. (DTS) — also refer to the DTS Logo Brand Guidelines

INTELLECTUAL PROPERTY

Standards and recommended practices are adopted by CEDIA/CTA in accordance with the American National Standards Institute (ANSI) patent policy. By such action, CEDIA/CTA does not assume any liability to any patent owner, nor does it assume any obligation whatever to parties adopting the standard or recommended practice.

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CONTENTS

1   GLOSSARY

2   IMMERSIVE AUDIO OVERVIEW

3   AUDIO PERFORMANCE OBJECTIVES AND LEVELS

4   SEATING LAYOUT

5   SPEAKER LAYOUT

6   SPEAKER SELECTION

7   SUBWOOFERS AND LOW-FREQUENCY ROOM OPTIMIZATION

📖 BIBLIOGRAPHY

Procedure for achieving performance objectives

Performance Level selection

- Level 1
- Level 2
- Level 3
- Level 4

Seating layout

- Reference Seating Position (RSP)
- Listening area
- Proximity to walls

Speaker layout

- Number of discrete feeds
- Number of speakers
- Format support

Speaker selection

- Speaker directivity
- Speaker coverage
- Maximum SPL

Low frequency optimization

- Room proportions
- Subwoofer number and placement

Sound Isolation

- Construction Guidelines
- Sound Transmission
- Background Noise

Acoustical treatment

- Reverberation decay
- Materials selection and placement
- Projection screen acoustics

Equipment selection

- Processors
- Amplification

Performance optimization

- Commissioning
- Calibration and EQ

i.   INTRODUCTION

For the purposes of this document, **entertainment spaces** are considered to be any space in a building where people can enjoy the consumption of audiovisual content. Examples of content includes, but is not limited to, movies, TV Shows, games, and music, via a range of distribution methods. While some Entertainment Spaces may be dedicated to the consumption of audiovisual media, in many situations these spaces must also be designed to accommodate a variety of activities desired by the user.

As is evident from the length of this document, when designing such spaces, many factors come into play. Several are interdependent and interactive, and the design process will invariably be interactive. This means that every step will need to be revisited and potentially altered, continuing around the circle of decision points multiple times until the work is finished. Some compromises are inevitable. For example, the video screen and front speakers will compete for space as they need to be in the same location. Of the several ways to deal with that issue, some yield better overall results than others. Ultimately, the best performing systems are the ones with the most intelligent set of compromises.

The concept of "immersive" can be described by many experiential descriptions. Within the scope of this document it is the design of an installed audio system to faithfully deliver the creative intent of the artists responsible for the content, within the technical limitations of the physical environment.

ii.   SCOPE

This recommended practice outlines various audio design and engineering parameters relevant to the proper performance of audio within a private entertainment space that meets or exceeds relevant industry guidelines and delivers a user experience that renders content as close as possible to the intent of the content creator.

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iv. REFERENCES

The following documents contain provisions that, through reference in this text, constitute normative and informative provisions of this recommended practice. At the time of publication, the editions indicated were valid. All documents are subject to revision, and parties to agreements based on this recommended practice are encouraged to investigate the possibility of applying the most recent editions of the documents listed here.

Normative References

- **ANSI/CTA-2034-A R-2020** — *Standard Method of Measurement for In-Home Loudspeakers*
- **2019 ASHRAE Handbook** — *HVAC Applications*
- **CEDIA/CTA-RP28** — *HDMI System Design and Verification Recommended Practice*
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- **ISO 14163:1998** *Acoustics — Guidelines for noise control by silencers*
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- **ASTM E413-22** — *Classification for Rating Sound Insulation*
- **ISO 10140-2:2021** *Acoustics — Laboratory measurement of sound insulation of building elements — Part 2: Measurement of airborne sound insulation*
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Internet: https://www.ashrae.org/technical-resources

ASTM International Documents:
American Society for Testing and Materials
Internet: https://www.astm.org

CEDIA Documents:
CEDIA standards and recommended practices
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Internet: https://cedia.net/standards

CTA Documents:
Consumer Technology Association standards
Internet: https://shop.cta.tech/collections/standards

EIA/ECA Documents:
Electronic Components Industry Association (ECIA)
Internet: https://www.ecianow.org/eia-technical-standards

ISO Documents:
International Standards Organization
Internet: https://www.iso.org/standards.html

ITU Documents:
International Telecommunications Union, Radiocommunication sector (ITU-R)
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Phone: +41 22 730 6141; Fax: +41 22 730 5194
Internet: https://www.itu.int/pub/R-REC; Email: sales@itu.int

SMPTE Documents:
Society of Motion Picture and Television Engineers Standards
Internet: https://www.smpte.org/standards/document-index/ST

v.   COMPLIANCE NOTATION

This section defines compliance terms for use by this document:

should   This word indicates that a certain course of action is preferred but not necessarily required.

should not   This phrase means a certain possibility or course of action is undesirable but not prohibited.

vi.   UNIT CONVERSIONS

Lengths are referenced throughout this document in the international system of units (SI): metric. Imperial conversions are provided in most instances, but are approximate for ease of readability. The conversion formulas below can be used for greater accuracy, if required.

meters (m) to feet (ft)	m x 3.281 = ft
millimeters (mm) to inches (in.)	mm x 0.03937 = in.
square meters (m^2) to square feet (ft^2)	m^2 x 10.764 = ft^2
cubic meters (m^3) to cubic feet (ft^3)	m^3 x 35.315 = ft^3

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SECTION

1

GLOSSARY

1.1 DEFINITIONS

Anechoic
Space completely free from echo and reverberation.

Array
Two or more speakers connected to reproduce the same audio content (channel and objects), enabling a wider coverage of sound; for example, along the side and back walls in a commercial cinema room. Physical arrays are connected to a single processor output feed, either jointly or separately amplified, while software managed arrays utilize dedicated processor output feeds for each speaker to allow individual adjustments.

Astragal
A hardware molding used to close a clearance gap between two building elements, such as to the seal the "meeting stiles" where two swinging doors meet upon closing.

Axial mode
The pattern of sound waves between two parallel surfaces in a room. For instance, two side walls, front and back walls, or floor and ceiling.

Azimuth angle
In audio, the horizontal angle of a speaker in relation to the listener.

Baffle (speaker)
The front face of a speaker. Serves several functional and aesthetic purposes, key of which is to prevent the sound waves from the rear of the mounted speaker drivers interfering with the sound waves from the front. Aids in off-axis frequency response.

Baffle wall
A dedicated wall for the flush mounting of the front (screen) speakers, typically built out from the structural end wall of an entertainment space.

Bass contour
Active filter to taper the bottom end of the frequency response to limit the bass extension of a speaker, most commonly subwoofers.

Bass management
A processor function directing low-bass frequencies (typically below 80-120 Hz) from the full-range feeds (front, surround, and upper) to combine with the low frequency effects (LFE) channel for reproduction by the subwoofer(s).

Channel (audio)
Audio content intended for reproduction from a prescribed speaker location. For instance, a soundtrack with 6 channels of audio intended to be reproduced in a 5.1 speaker layout. Channelized content contributes to the output speaker feeds from an audio processor.

Channel (structural)

Structural batten typically made of metal and used as a fixing base for gypsum board over framework without direct contact. *Resilient channel* is used as a structural component in sound isolation, whereas *hat* or *furring channel* is used for spacing and leveling purposes, for walls and/or ceilings.

Crossover (speaker)

Function in a speaker or accompanying electronics in the audio chain, either physical components or digital signal processing (DSP), that rolls off the frequency response above or below a specified frequency to enable each speaker driver to reproduce only its optimal range; low frequencies (low pass) for the woofer and high frequencies (high pass) for the tweeter, and in the case of a 3-way speaker's midrange driver, a middle band of frequencies (bandpass). The term *crossover* comes from the frequency response plots of each band crossing over as each tapers away in opposing directions.
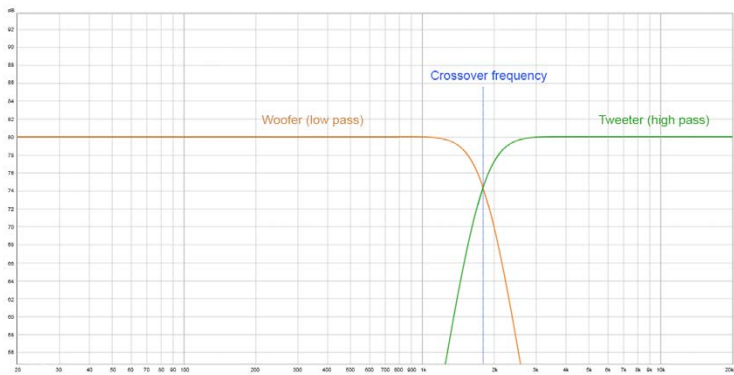
Decibel (dB)

Standard relative unit of measurement of sound level. Weighted measurements account for the relative loudness of sounds as perceived by the human ear — A-weighting, dB(A), gives more value to middle frequencies at lower relative volume levels whereas C-weighting, dB(C), gives more value to low and high frequencies at higher volume levels.

Diffusion

Spreading out sound energy by reflecting sound in non-specular (angle of incidence) directions using a diffusor (acoustical treatment device). Produces even distribution of sound energy, as distinct from scattering that produces uneven energy distribution. Depending on its design, a diffusor can function primarily in one plane (horizontal or vertical) or two planes (horizontal and vertical).

Directivity (speaker)

The degree to which a speaker focuses and projects the sound in a particular direction. The directivity index is an indication of the amount of forward-directed energy compared to omnidirectional energy.

Dispersion (speaker)

The degree to which a speaker spreads the sound horizontally and/or vertically across a broad range of frequencies. Wide dispersion enables better off-axis performance, and vice versa.

Double Bass Array (DBA)

A symmetrical arrangement of subwoofers on opposing walls (typically front and back) in a rectangular room, electronically optimized to mitigate room modes.

Dynamic range (audio)

The ratio of the very softest to the very loudest sounds produced by an audio system. Distinct from *video dynamic range,* being the brightest white to the darkest black in an image.

Dynamics

The variation in volume level over a period of time. A higher dynamic range enables greater dynamics.

Elevation angle

In audio, the vertical angle of a speaker in relation to the listener. Can be a plus (above the listener's ear level) or minus (below the listener's ear level) value.

Feed (speaker)

A discrete output signal from an audio processor for reproduction from a designated speaker location. Derives from channel-based content combined with audio objects assigned by the object audio renderer (OAR). Where content channel count and system speaker count do not match, discrete speaker feeds may also derive from the upmixing (to a higher number of speakers) or downmixing (to a lesser number of speakers) process. Subwoofer feeds are composed of the LFE channel combined with bass signals assigned through bass management.

Flanking path

Any noise paths around or through a main building partition, including gaps, cracks, structural members, and ductwork.

Flutter echo

A series of multiple distinct echoes that occur in rapid succession.

Free field

A space in which no sound reflections occur.

Helmholtz resonator

Named after its inventor, German physicist Herman von Helmholtz, it is a container with an opening/port via a short neck that causes the air inside the cavity to resonate at a certain frequency, effectively dampening the incident sound waves.

Horizontal angle

The left-to-right angle between two points relative to a reference position.

Horizontal plane

A horizontal slice of a space, parallel to a level floor. Several speakers on the same horizontal plane will all be the same distance from the floor.

Line array speaker

Most common configuration of line source speaker composed of multiple matching drivers arranged in a vertical line to reproduce a given frequency range with a cylindrical waveform. The resulting phase relationships in the vertical plane typically yield very narrow vertical dispersion (minimizing floor and ceiling reflections) while maintaining a relatively wide horizontal pattern. Used mostly in pro audio settings.

Line source speaker

A vertical column speaker that radiates sound in one dimension, resulting in a cylindrical waveform instead of the spherical radiation pattern from a [point source](). A true floor-to-ceiling line source propagates sound on a vertically aligned cylindrical curve, resulting in a halving of sound pressure level (-3 dB) for every doubling of distance in free field. This increases vertical directivity to virtually eliminate reflections from the floor and ceiling.

Listener level

The listeners' seated ear level plus a margin above or below.

Listening angle

The angle between two speaker locations, relative to a listener. Commonly used to describe the angle between front left and right (stereo) speakers, or the angle from the center speaker (0°) to any given immersive audio speaker location. For instance, 90° (from the center speaker) describes a surround speaker location directly beside the listener.

Loudspeaker

Device for converting electrical energy into acoustical energy (sound). Referred to simply as "speaker" throughout this document.

Metadata

A collection of data (information) packets combined into the AV delivery signal to provide instructions for how particular actions or features of the AV stream should be implemented by a receiving device. For example, data accompanying an audio stream about the audio format or audio object positions in a three-dimensional space.

Objects (audio)

Individual sound elements in an immersive audio soundtrack with locations in a three-dimensional space defined by metadata.

On-axis

Listener positioned in direct line with the front of a speaker. The speaker is pointed at the listener.

Off-axis

Listener positioned away from the direct sound path of a speaker. The speaker is not pointed at the listener.

Phantom image

Reproduced sound that is perceived by a listener as coming from between two or more physical speaker locations, enabling smooth movement of sounds throughout the sound field. It's function relies on appropriate spacing between any two speakers, relative to the listener — a listening angle too wide between two adjacent speakers (too far apart) will collapse the image to become two distinct sound sources.

Phase (audio)

The position of a sound wave in time. Sound waves that are *in phase* are aligned in time, whereas those *out of phase* will be misaligned which can lead to different parts of the sound waves conflicting, causing loss of amplitude at certain frequencies or even some audible cancellation of frequencies.

Point source (speaker)
A speaker that radiates sound from a single point, being a driver (woofer, midrange, tweeter) mounted in an enclosure or baffle. Its radiation pattern propagates sound in a spherical pattern, resulting in a quartering (-6 dB) of sound pressure level for every doubling of distance. The basis for typical residential and studio speakers. As distinct from line source.

Propagation loss
A measure of the loss of sound power as it propagates (spreads) through the air away from a speaker.

Reference Seating Position (RSP)
The nominated reference position in a space, at the occupant's seated eye and ear level, around which the optimal delivery of audiovisual performance objectives are primarily designed. RSP unifies the terms *main listening position* (MLP), primary seating position, reference viewing position, and other common terms (including the colloquial "money seat") to describe this reference position.

Renderer
A function of an audio processor to assign audio elements to discrete output feeds for reproduction at prescribed speaker locations.

Reverberation
The prolongation of a sound with gradual decay after the original sound source has ceased. Differs from *echo,* which is distinctly hearing a sound twice.

Sabin
Unit of total sound absorption for the interior of a room, equal to one square foot (929 cm^2) of a perfect absorber.

Scattering
Acoustical reflection of sounds in non-specular (angle of incidence) directions. Produces uneven distribution of sound energy, as distinct from diffusion that produces even distribution.

Schroeder frequency
See transition frequency.

Screen speakers
Or *screen wall speakers*. The front listener-level speakers in a surround/immersive audio system that are arranged across the span of a wall behind or around a video screen. Includes main front left/right, center, and optionally center-left and center-right "inter" speakers.

Spatial resolution
The ability of an immersive audio system to accurately resolve a sound field or localize a sound at the correct point in space.

Speaker feed
See feed (speaker).

Spectral
Of or relating to a frequency spectrum.

Timbre
The ability of an audio system to reproduce accurate harmonic structures that define the tonal quality of a sound.

Transition frequency
A room's transition frequency is defined by the point below which phase interference (room modes) changes the response of the speaker at the seating positions. Above the transition frequency, speaker response is largely reliant on the speaker's true response (a combination of its on and off-axis responses). The larger the room, the lower the transition frequency; occurring between around 150 and 500 Hz in small rooms. For acoustic purposes, a small room can be defined as having a volume of less than approximately 1,000 m³ (35,000 ft³). Transition frequency is sometimes called *Schroeder Frequency*.

Transmission loss
In acoustics, it is the accumulated decrease in the level of sound (noise) as it propagates through a building element or partition.

Upper speakers
The height (high on the walls) and top (on/in ceiling) speakers in an immersive audio system, generally with an elevation angle of at least 25° from the listeners' seated ear-level position.

Vertical angle
The up-and-down angle between two points relative to a reference position.

Vertical plane
A vertical slice of a space. Several speakers on the same vertical plane will form along the same line up a wall.

1.2 SYMBOLS AND ABBREVIATIONS

AVR	Audio/video receiver
dB	Decibels
dB(C)	Decibels, C-weighted
$D_{nT,w}$	Weighted standardized level difference (noise reduction coefficient)
D/R	Direct-to-Reflected (or Reverberant) sound ratio, sometimes referred to as DRR
DSP	Digital Signal Processing
kHz	kilohertz (1,000 Hz)
LFE	Low frequency effects
HVAC	Heating, ventilating, and air conditioning
Hz	Hertz
OAR	Object audio renderer
RdT	Reflection decay time
R_w	(Noise) Reduction, weighted (coefficient)
RSP	Reference seating position
RT60	Reverberation time (decay by) 60 (dB)
SPL	Sound pressure level
STC	Sound transmission class
SRI	Sound reduction index

SECTION

2

IMMERSIVE AUDIO OVERVIEW

2.1 DESCRIBING IMMERSIVE AUDIO SYSTEMS

Immersive audio broadly describes content and systems that together envelop an audience with sound to enhance the feeling of being physically present in an artificial environment — in this context, a private entertainment space. The goal is to deliver the artistic intent of content creators by making the audio experience more realistic and engaging. When delivered well, even monaural audio can provide an immersive experience. However, immersive audio most commonly refers to the use of multichannel reproduction, especially with the addition of an upper layer of speakers to augment the traditional surround sound layer for greater spatial awareness and improved localization of sounds.

Surround systems comprise five or more speakers configured in a horizontal plane on the same level as the listeners, with all front and surround speakers ideally at or just above seated ear level. This layer is referred to throughout this document as the **listener-level layer**.

Immersive audio formats add the crucial third dimension of height, being why it is sometimes referred to as 3D Audio. This comprises height speakers on the same vertical plane as the main listener-level layer speakers, typically high on the walls, and/or top (often called "overhead") speakers that are distributed at points on the ceiling and pointed towards the listeners. The height and top speaker groupings are described separately hereon, or jointly as the **upper layer**.
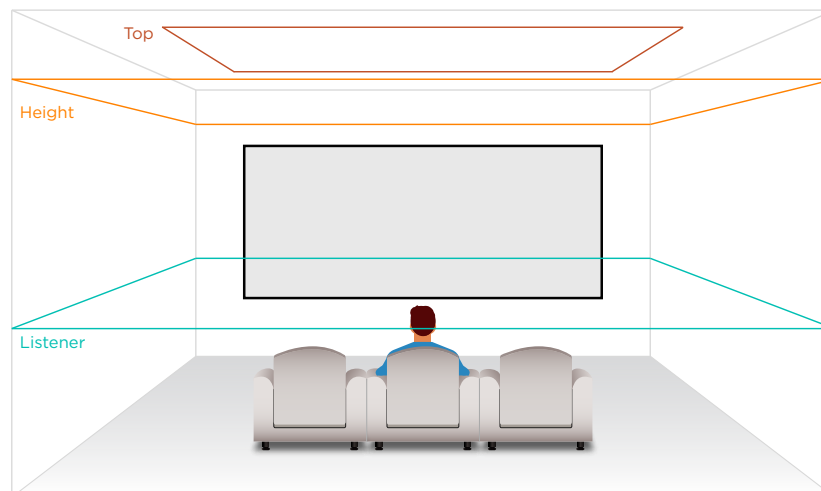
Figure 2-1: Immersive audio speaker layers. Height and top combine as the Upper layer

Immersive audio speaker configurations generally follow upon the standard *"x.y"* (for example, 5.1 or 7.1) nomenclature employed for surround sound systems. However, the addition of a third integer — denoted by *z* — specifies the number of discretely rendered upper layer speakers supported in the system, expanding the syntax to *x.y.z*.

Using 7.1.4 as an example:

- The first digit (7) represents the number of discretely rendered listener-level speaker outputs supported. These will typically be front left, front center, front right, surround left, surround right, surround back left, and surround back right.

- The second digit (1) represents the discrete subwoofer feed, including low frequency effects (LFE) and bass signals directed through bass management (see Section 7.2.3.2). It does not necessarily indicate the number of subwoofers.

- The last digit (4) represents the number of discretely rendered upper layer speakers supported.

This syntax should be used with two important caveats:

1. If the format is an object-based immersive audio format, each number represents how many **discretely rendered outputs** are available from the AV receiver or processor. It does not represent the number of possible speakers that may be employed in a system. If arrays are used (see Section 5.6.4), then all speakers connected in a single array are considered a single channel for the purpose of describing the capability of the system.

2. There is only one discretely rendered LFE output used in object-based immersive audio receivers or processors. Devices that claim support for more than one LFE output in an immersive audio system are simply splitting the single LFE signal into multiple outputs and possibly applying additional processing to each output. However, it should still be considered a single channel and therefore described as ".1".

2.2 CHANNEL-BASED VS OBJECT-BASED AUDIO

Multimedia content with **channel-based audio** has all the various sounds allocated to predefined channels that are then reproduced through speakers that are assumed to be in prescribed locations. **Object-based audio** instead describes the locations of the many separate audio elements by coordinates in a three-dimensional space. As such, one of the biggest benefits of object-based audio is that it is not limited to the main predefined speaker layouts as is the case in a channel-based delivery format. An object-based system is scalable in a way that channel-based systems are not.

In practice, an object-based mix can be reproduced from as few as 6 speakers (3.1.2) to as many as 34 speakers. However, in systems without these large numbers of speakers, everything in the soundtrack can still be heard from whatever speakers are available; the sounds simply get redistributed to the nearest available speakers based on the metadata information and the processor's notion of where the speakers are located in the room. **Rendering** is the process of allocating sounds to the available speakers.

When working on the audio in a program, the sound mixer may use a combination of the channel-based approach and the object-based approach, depending on their own preferences and workflows.

2.2.1   BEDS AND ACTIVE OBJECTS

Object-based audio consists of two types of audio objects:

Bed Objects

The "bed" is a prepared layer of audio in which the elements typically do not move around. It can be thought of as the foundation of the soundtrack. Examples include background music, or music that swells to accompany an emotional scene, or environmental sounds that create a sense of spatiality.

The bed in a channel-based mix is assigned to prescribed speaker locations, typically in either the basic 5.1 or 7.1 configuration. With object-based audio, the metadata typically describes the bed elements as fixed to expected speaker locations, effectively emulating the channel-based bed. Because the bed does not move around, its elements are sometimes referred to as "static" objects.

In some cases, the bed may expand to include either the wide channels (9.1) or a single pair of channels for speakers above the listener, such as in a 7.1.2 configuration. These choices are at the discretion of the people creating the soundtrack.

Active Objects

"Active" objects are audio elements that move around. Filmmakers isolate predetermined sound object(s) in a scene and decide exactly where they want to locate them and how they want them to move within a three-dimensional space. The sound mixers then employ content creation tools that represent sound as independent active objects, each of which is described by metadata that includes a number of parameters about the sound object, including its location, movement, relative volume level, and size.

In working with the bed and active objects, sound mixers are able to start by mixing most of the soundtrack as they are accustomed to doing for a channel-based mix, while preserving the ability to add the newer, dynamic audio objects in whatever ways they determine can benefit the soundtrack.

2.2.2   MIXING ROOM AUDIO STEERING

A benefit of object-based immersive audio formats is to provide one mix but with many possible applications. As mentioned above, a consumer object-based immersive audio mix can be reproduced with as little as 5 discrete feeds plus LFE (3.1.2) to as many as 34 discrete speaker feeds, depending on the capability of the object rendering and output capability of the AV receiver or processor.

The majority of content mixing rooms employ a 7.1.4 configuration to monitor the final "near-field" mix intended for consumer home playback. Some mixing facilities have installed a 9.1.6 configuration, adding front wide speakers and three pairs of overhead speakers. This is generally the highest speaker count employed for monitoring an object-based immersive audio mix intended for the home. However, this does not limit deployed systems to match the discrete channel count of the mixing room.

Object-based audio defines all aspect of sounds in a three-dimensional space, small or large. An AVR or processor that employs discrete rendering to a high number of output speaker feeds will accurately reproduce the object audio mix that may have been monitored in a lesser 7.1.4 or 9.1.6 configured studio.

2.2.3 CHANNEL-BASED CONTENT IN AN IMMERSIVE AUDIO DELIVERY FORMAT

Many object-based immersive audio delivery formats can support both object-based and channel-based mixes. This can create some confusion, especially for a client for whom an integrator may have designed a system that employs a high count of discretely rendered speakers, only for the user to discover that some speakers in their system do not appear to be "working" during playback of certain content.

For instance, music reproduction may be too complex for the effective use of active objects, so only channel-based reproduction is used. However, it may be delivered in an immersive audio format with content locked to expected speaker positions. Supposing a system is designed to be capable of discretely rendering to a 9.1.6 or 11.1.8 configuration, or larger still, but playback of the 7.1.4 content would limit reproduction to just twelve speakers in the system: those predetermined in the processor as the 7.1.4 positions.

Similarly, due to limitations that often accompany remote, on-location mixing and production such as live sports delivered in object-based immersive audio formats are likely to be delivered in a 5.1.2 channel-based configuration. In this case, only seven speakers (plus subwoofer/s) would be active during the broadcast. While this may not always be the case (some processors allow listener level and height beds to be distributed via upmixing or a channel spread solution), it is important for both the system designer and client to be aware of these possibilities.

2.2.4 RENDERING OBJECTS

Setting up a system to support object-based immersive audio formats requires the use of an appropriate AVR or processor, and to inform it about the number and location of speakers employed in the system.

Equipped with this information, the **Object Audio Renderer** (OAR) in the AVR or processor analyzes the positional metadata to describe each audio object, then scales them for optimized playback using the available discrete speaker feeds to their respective connected locations in the system. This process determines in real time exactly which speakers are employed to reproduce each sound.

Key to the reproduction of this three-dimensional sound field is the creation of a layer of sound above the listener. This is achieved with the upper layer or specific up-firing speakers in the system.

In a system with multiple seating positions, a greater number of discretely rendered speakers enveloping the audience can yield more precise object positioning, as described throughout Section 5.

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SECTION

3

AUDIO PERFORMANCE OBJECTIVES AND LEVELS

3.1 PERFORMANCE OBJECTIVES FOR AUDIO

The performance goals of high-quality audio systems can be considered in a set of nine core criteria as outlined below, each of which is discussed through the rest of this document.

1. Dialog clarity
2. Localization accuracy
3. Sound movement
4. Sound field immersion and envelopment
5. Tonal balance (timbre)
6. Dynamic range
7. Bass impact
8. Audience coverage
9. Sound isolation

The goal of this document is to provide recommended practices that will maximize performance in all these criteria. They should be discussed with customers as part of a conversation in seeking agreement about budgetary priorities.

3.1.1 DIALOG CLARITY

As the majority of the story in any movie or show is conveyed by dialog, it is essential that it be clearly intelligible. Competition from other sounds in the mix, along with specific regional accents and poorly recorded lines can all lead to the unpleasant feeling of not getting the whole story.

Factors that affect dialog clarity include:

- Speaker frequency response
- Speaker directivity index
- Speaker sound power
- Speaker audience coverage
- Speaker mounting and placement
- Room acoustics including direct to reflected sound ratio (D/R), reflection decay time, flutter echoes, and standing wave resonances
- Background noise levels and spectrum

3.1.2 LOCALIZATION ACCURACY

Multimedia (including movies, TV, and games) soundtracks are replete with sound effects placed throughout the sound field to increase immersion, realism, and dimensionality of the narrative. These pin-point sounds can include cars, airplanes, punches, gunshots, etc. Some of the sounds are targeted to positions where speakers are expected to be, and others are in-between speakers, formed by "phantom images." They should all be clearly positioned and audible.

Factors that affect localization accuracy include:

- Number of discrete speaker feeds and corresponding speaker positioning
- Audio format decoding and rendering capability
- Interchannel level calibration
- Interchannel time synchronization calibration
- Interchannel phase and accuracy of frequency range
- Speaker directivity index
- Speaker audience coverage
- Room acoustics, including reflection decay time and flutter echoes

3.1.3 SOUND MOVEMENT

The sound designer or mixer of media content can decide to move pin-point effects around the sound field to extend the action on screen, further enhancing the sense of realism for the audience. This can include things like cars traversing the screen or headed back behind the audience, airplanes flying over, or any other sounds that put the audience in the middle of the action. The sounds will move between speaker locations and phantom images, so timbre-matching is important. These movements should be smooth and match what the mixer intended to create realism in the movie.

Factors that affect sound movement include:

- Number of discrete speaker feeds and corresponding speaker positioning
- Audio format decoding and rendering capability
- Interchannel level calibration
- Interchannel time synchronization calibration
- Interchannel timbre, frequency and phase accuracy
- Speaker audience coverage
- Room acoustics, including reflection decay time and flutter echoes

3.1.4 SOUND FIELD IMMERSION AND ENVELOPMENT

Many scenes in programs call for an even, enveloping, and immersive sound field. Sounds to set an ambience, such as wind and rustling leaves, or music and reverberation can be employed by the sound mixer and should be distributed evenly throughout the space without specific localization. Immersive sounds may involve any combination of speakers, with timbre matching also being important.

Factors that affect immersion and envelopment include:

- Number of discrete speaker feeds and corresponding speaker positioning
- Interchannel level calibration
- Interchannel time synchronization calibration
- Interchannel timbre, frequency, and phase accuracy
- Speaker audience coverage
- Room acoustics, including reflection decay time and flutter echoes

3.1.5   TONAL BALANCE (TIMBRE)

Also known as spectral balance or **timbre**, this basic frequency domain notion is sometimes one of the hardest to describe, measure, and tune. Ideally, all tones in the audible spectrum are reproduced in the entertainment space, appropriately balanced in a way that matches the original production environment. The broader the frequency range of a sound, the more it may be affected by its reproduction accuracy. Deviations in tonal balance by as little as 1 or 2 dB can profoundly affect the audibility of sound effects, the character of music, spatial balance, and frequency balance of the soundtrack.

Factors that affect tonal balance include:

- Speaker on-axis and off-axis frequency response
- Speaker sound power response
- Speaker audience coverage
- Speaker placement
- Reflection decay spectral balance
- Standing wave resonances
- Digital signal processing (DSP) settings during calibration
- Quality and settings of spectrum analysis equipment

3.1.6   DYNAMIC RANGE

Multimedia soundtracks can contain upwards of 100 dB of dynamic range — the difference between silence and the loudest burst of sound. On the quieter side may be music passages, ambience sounds, subtle cues, reverberation tails, and many other types of subtle sounds that need to be reproduced faithfully. All sound peaks such as gun shots and explosions should be reproduced without distortion or limiting in the amplifiers or speakers.

Factors that affect dynamic range include:

- Speaker and subwoofer output sound pressure level
- Background noise in the room, due to ventilation, street noise, machinery, projector and equipment fans, etc., which can mask low level details and erode dynamic range
- Electronic noise or hiss in the equipment
- Poor sound isolation from adjacent noisy rooms
- Excessive reflection decay time that smears dynamics and raises the perceived background noise level
- Amplifier output power

3.1.7   BASS IMPACT

Multimedia soundtracks use a lot of bass effects to convey action, realism, mood, and dynamics. They can extend to 20 Hz and lower with peak levels of up to 115 dB SPL. Add the complexity of standing wave resonances in the middle of the bass range and it becomes evident that is an inherently challenging range of signals to reproduce. It is very common to have wide bass variations from seat to

seat, with differences of up to 25 dB in frequency response. However, dynamic, punchy, loud bass is a big favorite of audiences, so it is crucial to get it right.

Factors that affect bass impact include:

- Subwoofer amplifier output power
- Subwoofer(s) output sound pressure level (SPL)
- Bass headroom of all speakers
- Subwoofer and speaker placement
- Standing waves / room modes (see Section 7.2)
- Acoustical control of bass energy (wall damping, bass traps, etc.)
- Bass optimization, including calibration of frequency response, and time synchronization through the crossover region

3.1.8   AUDIENCE COVERAGE

Seat-to-seat variations in sound quality should be reduced to a minimum so that everyone in the entertainment space has a similar experience. Bass variations are the toughest to control, followed by localization and immersion. There are many ways to ensure consistency throughout the space, using proper equipment selection, placement, acoustical control, and calibration practices.

Factors that affect audience coverage include:

- Speaker sound power response
- Speaker dispersion
- Speaker count and placement
- Subwoofer number and placement
- Standing wave resonances / room modes
- Calibration of frequency response, time synchronization, and levels,
- Room acoustics, including reflection decay time and flutter echoes

3.1.9   SOUND ISOLATION

Under normal circumstances, noise originating outside the space should not be audible from within. Similarly, the loud sounds originating inside the space should ideally not be audible in sensitive adjacent spaces, or certainly not loud enough to disrupt normal activities. Appropriate sound isolation allows privacy and use of the space any time of the day or night.

Factors that affect sound isolation include:

- Wall, floor, ceiling, and door construction
- Ventilation systems with common paths to other rooms
- Plumbing and other mechanical equipment that can conduct sounds and vibration
- Small flanking paths that leak sound, such as electrical boxes and conduit pass-throughs.

See Section 8 for more information.

3.2   IMMERSIVE AUDIO PERFORMANCE LEVELS

This document uses objective targets to define four levels of performance for use during the design and engineering phases of a project. The targets may later be referenced for measurement and verification of a completed system using methodology to be published in an upcoming CEDIA/CTA Recommended Practice document.

The levels are described below, the parameters for each of which are introduced in Section 3.4.

Level 1 – The minimum level of performance necessary to convey basic artistic intent.

Level 2 – A higher level of performance that more accurately conveys artistic intent.

Level 3 – Meets or exceeds reference commercial cinema exhibition standards.

Level 4 – The maximum level of achievable performance across every parameter.

Performance levels apply to both **individual seating positions** as well as **the room**, with parameters therein attributed to one or the other.

3.2.1   INDIVIDUAL SEATING POSITIONS

Achieving any given Performance Level requires the reference seating position (see Section 4.1.1) to meet every criteria. It is recommended that at the engineering design stage, a calculated estimate of the Performance Level be recorded for every designated seating position in the room.

3.2.2   PERFORMANCE LEVEL FOR THE ROOM

The Performance Level of the room is defined as the maximum level applied to both the reference seating position and at least one adjacent seating position.

The Performance Levels exist to guide the complete project life cycle process from sales to handover. They are not mandatory. Use of Performance Levels provides the following benefits.

- Provide companies with objective metrics for the design, supply, installation, and commissioning of high performance entertainment spaces. This allows supplying companies to better value-engineer their proposed systems based on objective predicted performance rather than simply on price alone.

- Allow customers to better evaluate competing quotes on the basis of performance and value.

- The predecessor to this document, CTA/CEDIA-CEB22, included parameters for reference-grade rooms only, but these represent a very small proportion of rooms built. By introducing two levels below the reference level (and one above), this recommended practice enables application to a far wider scope of rooms and budgets.

- For the purposes of defining performance, definitions such as dedicated/home/private cinema/ theater, or media room are removed. It remains the discretion of the supplying company to decide how to brand, sell, and describe the use modes and naming of the entertainment spaces they build. This recommended practice addresses defining performance that is applicable to a specific space, and independent of the use modes of that space. There is no reason why a multi-use space cannot also attain the higher levels of defined performance.

- By having objective engineering-based system performance specifications, this recommended practice provides guidance on how to use manufacturer supplied engineering specifications to predict the performance of a system.

3.3 BALANCING PERFORMANCE OBJECTIVES WITH LEVELS

Holistic system design is the art and science of balancing the performance objectives described in Section 3.1 to achieve a desired Performance Level. This is an engineering exercise to ensure that the compromises made are in the best interests of overall customer experience while respecting artistic intent. These performance objectives can be summarized within three broad characteristics:

1. **Spatial Resolution** — the ability of the system to accurately resolve a sound field or localize a sound at the correct point in space. Factors affecting spatial resolution include:

   - Discrete rendering capability
   - Discrete speaker count
   - Speaker locations
   - Seating locations
   - Room acoustics

2. **Dynamic Range** — a system's ability to deliver sounds from the very softest to the very loudest. A quiet room is a prerequisite to hear soft sounds, whilst achieving high sound pressure levels (SPLs) at low levels of distortion is a result of speaker specification and placement, along with the correct amplifier power. Factors affecting dynamic range, as referenced in Section 3.1.6, include:

   - Room noise floor
   - Max SPL capability with low distortion at all seats

3. **Timbre** — the ability of the system to reproduce accurate harmonic structures that define the tonal quality of a sound. Factors affecting timbre include:

   - On- and off-axis frequency response
   - Phase coherence
   - Low distortion
   - Smooth sound power frequency response
   - Broadband system energy/time and impulse response
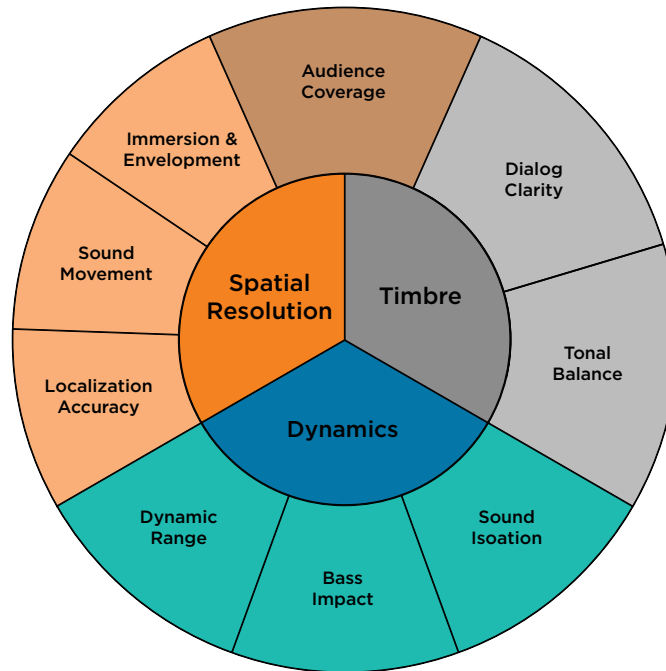
Figure 3-1: Balancing performance objectives (outer) by broad characteristic (middle)

3.3.1 COMPROMISING OBJECTIVES

When specifying a system, it is necessary to balance spatial resolution, dynamics, and timbre. Some examples of constraints that can lead to the need for compromise include:

- Budget
- Interior design
- Room size and proportions
- Intended use

As an example of how such constraints may impact the balance of objectives, consider the outcome of increasing the number of discrete speaker feeds within a fixed budget. This will improve spatial resolution, however, having more speaker feeds (including amplification) means less money per feed that may, in turn, lessen the performance (timbre and dynamics) of each. It is important to discuss compromise options with the customer.

Some examples of compromise include:

- Budget constraints at the initial build, but include the possibility for future upgrades. An approach to balancing performance objectives and budget might be to initially specify a system with fewer speakers, but make provision for adding more later by running cables to the respective future locations, also allowing for future mounting requirements. For instance, start with a 5.1 speaker layout that preserves dynamic range and timbre but sacrifices spatial resolution (see figure 3-2). This way, the system's spatial resolution can be upgraded over time whilst initially preserving timbre and dynamics.
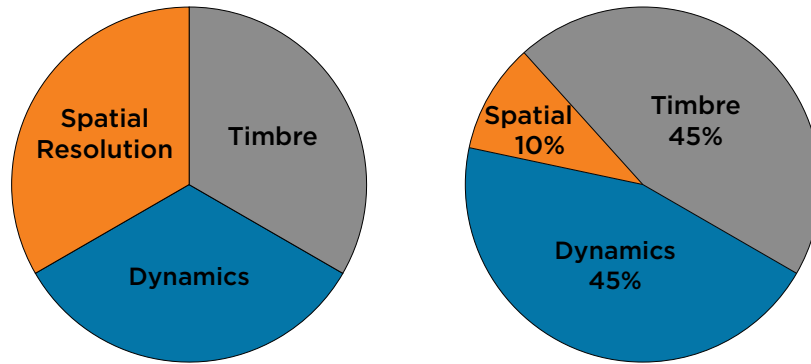
Figure 3-2: Balanced approach to objectives (left) vs compromise (right)

- A room where high SPL and/or a low noise floor is not possible. This will compromise dynamic range.

- A room where optimum speaker positioning is not possible. This will compromise spatiality.

- A large room with multiple seats but a limited budget. This will potentially compromise all aspects.

- A client request for the best possible 2-channel performance within a multichannel system. The timbre and dynamics of the 2.0 system (within the greater speaker layout) will need to be maximized.

- A client request for a multi-modal space that can be used as a nightclub environment. This scenario will require SPL being maximized.

A special case would be large rooms that require speaker and amplifier combinations that can produce the desired SPL. When budget is a consideration, it may be the right design choice to limit the quantity of speaker feeds, and thus spatial resolution, to deliver the required dynamic range at the seating positions.

Delivering excellent spatial resolution, with excellent timbre at beyond reference dynamic range in a large space will typically be the most costly scenario. In any case, more speakers does not necessarily equal "better" sound quality because spatial resolution is only one part of the sound quality equation.

3.4 PERFORMANCE LEVEL PARAMETERS

This recommended practice defines 21 Performance Level parameters, all of which are indexed in Table 3-1 below and grouped by characteristic — spatiality, dynamics, or timbre. The numbering (first column) is provided to simplify referencing and is tabled mostly in order of appearance throughout this document. The last column contains links to where each parameter is documented in its relevant section hereon, with all compiled in Appendix A.

Table 3-1: Performance Level parameters index

#	Description	Section Link
Spatial Resolution		
1	Minimum distance between the listening area and the room walls (meters, min)	4.1.4
2	Decoder/renderer capability and discretely rendered speaker configuration, excl. subwoofers (min # discrete speakers)	5.4
3	Number of screen wall speakers allowed outside of recommended zonal locations	5.5.4
4	Maximum SPL difference between screen wall speakers (dB max)	5.5.4
5	Maximum allowable horizontal angle between adjacent surround speakers (° max)	5.6.2.1
6	Maximum SPL difference between surround speakers (dB max)	5.6.2.1
7	Wide speakers maximum allowable horizontal deviation from median angle (± °)	5.7
8	Upfiring/elevation speakers allowed? (yes/no)	5.8.2
9	Maximum allowable vertical angle between adjacent height speakers (° max)	5.8.2
10	Maximum SPL difference between upper/height speakers (dB max)	5.8.2
11	Number of surround/wide/upper speakers allowed outside of recommended locations	5.9.3
Dynamics		
12	Screen Speakers SPL capability at RSP (dBC SPL, min & recommended)	6.1.4
13	Non-screen Speakers SPL capability at RSP (dBC SPL, min & recommended)	6.1.4
14	LFE frequencies total SPL capability at RSP (dBC SPL, min & recommended)	6.1.4
15	Background noise floor (NCB level, max and recommended)	8.5
Timbre		
16	Seat-to-seat frequency response variance across all screen wall speakers	5.5.4
17	Seat-to-seat frequency response variance across all surround and height/elevation speakers (± dB, max)	5.9.3
18	In-room bass extension -3dB cut off frequency (Hz, min & recommended)	7.5
19	Frequency response below the room's transition frequency (± dB, max)	7.5
20	Seat-to-seat frequency response variance below the room's transition frequency	7.5
21	Level of early reflections relative to direct sound (dB, min)	9.2.2

SECTION

4

SEATING LAYOUT

4.1   SEATING LAYOUT GUIDELINES

In the design of a high-performance entertainment space, seating type and layout is the first conversation that needs to happen with the client and their design team. Aspects of the design that need to be discussed include:

- What are the use modes of the space? What will the room be used for? For example, watching movies, watching TV, playing games, listening to music, practising yoga, reading a book, watching sports with friends.

- What type of audiovisual content will the space be used to play most often, and what else might be played on occasion?

- How many people will the room be able to accommodate, and how will accommodating more people potentially compromise the performance of the room?

- What type of seating will be used? For example, cinema recliners, sofas, bar stools, and chaise lounges? Will there be temporary seating such as beanbags brought in for occasional use?

- Are there any inclusive design requirements, such as accommodating people with disabilities?

Seating layout guidelines assume the room is rectangular and that wall constructions are reasonably uniform. Entertainment spaces engineered for high quality immersive AV presentation should always have at least one primary seating location where the minimum possible design compromises are made for both sound and image performance. This is both the main listening position and the main viewing position and shall be referred to as the **Reference Seating Position** (RSP).

4.1.1   REFERENCE SEATING POSITION (RSP)

The starting point is to define the RSP according to the **CTA/CEDIA-CEB23-B Home Theater Video Design** recommended practice.

In practice, the RSP is determined by a careful analysis of the subjective viewing preference of the user after being informed of the technical trade-offs (pixel resolution, brightness, contrast, screen size and aspect ratio, preferred content aspect ratio, and vertical or horizontal masking, etc.) and their impact on visual satisfaction. In a commercial cinema, such analysis can include tests at different seating positions.

In a rectangular room layout with reasonably uniform wall construction, the RSP should ideally be on the perpendicular axis of the front center speaker, as shown in figure 4-1. Avoid aisles in the middle of the room.
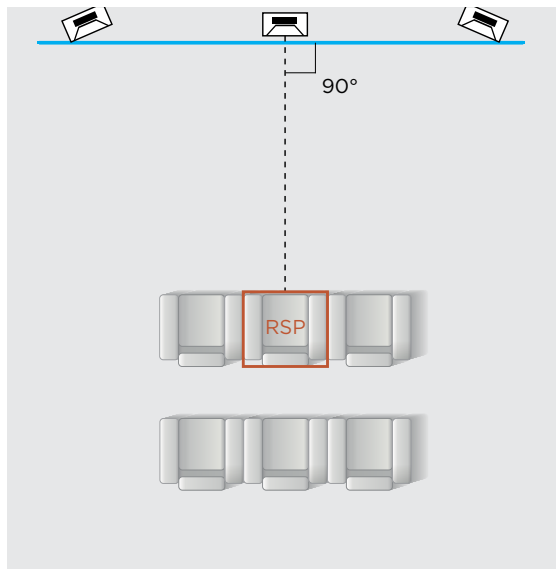
Figure 4-1: Reference Seat Position (RSP) perpendicular to the front center speaker
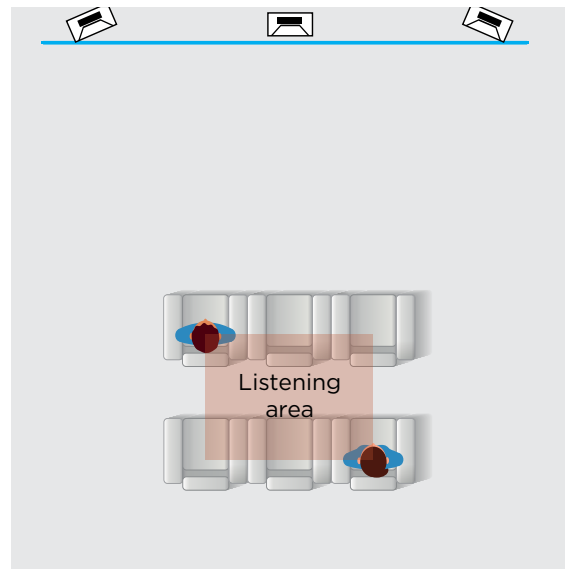
Figure 4-2: Listening area

4.1.2   LISTENING AREA

The **listening area** encompasses all seats in the entertainment space. Its perimeter runs through the middle of where the outermost listeners' heads will be located (encompassing aligned or offset rows) to account for the left-right, front-back sound perception. The resulting rectangle, depicted in figure 4-2, ultimately defines the limits for placement of speaker groups, as detailed in Section 5.6.2.

4.1.3   SEAT-TO-SEAT CONSISTENCY

A primary goal when designing an immersive audio system is to achieve **seat-to-seat consistency**. That is, the experience at the RSP should also be recreated as closely as possible at all other seats. It should be noted that many of the performance objectives listed in Section 3 can be substantially met by proper configuration of the seats with respect to the room and to the installed speakers.

4.1.4   SEATING PROXIMITY TO WALLS

When a seat is positioned close to a wall and therefore a surround speaker attached to that wall, there is a high risk that this specific speaker becomes a dominant source causing distracting localization. The result for the listener will be an unbalanced sound stage and loss of envelopment.

For this reason, it is strongly recommended to avoid placing a row of seats or a sofa/couch against the back wall. If seating must be placed against the back wall due to space constraints, it is then recommended to not use back speakers at all, as these speakers will be very close to listeners' ears and become the dominant sound sources. Side surrounds are acceptable, and, in this situation, a 5.1 speaker arrangement is preferable to 7.1, plus the upper speaker layer.
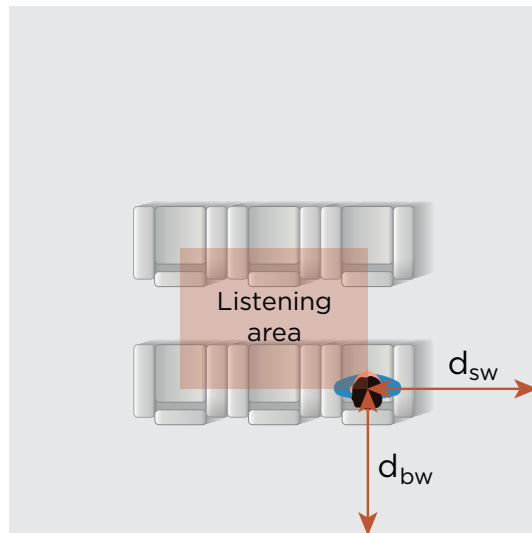
Figure 4-3: Minimum seating distance from walls

The recommended minimum distances of any seat from a wall are represented by d_{sw} (distance side wall) and d_{bw} (distance back wall) as shown in figure 4-3, the respective values for each Performance Level of which are below.

PERFORMANCE LEVELS — SEATING LAYOUT

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
1. Minimum distance between the listening area and the room walls (d_{sw}, d_{bw})	meters (m)	Min.	**>0.5**	**>0.8**	**>1.2**	**>1.5**	Seat

This parameter helps avoid speakers being too loud for some and too quiet for others, whilst simultaneously minimizing wall boundary interference. Design prediction requires measuring from the proposed center of each listener's head to the nearest boundary wall or protruding speaker baffle.

4.1.5   AVOIDING NULL POINTS

Try to avoid putting listeners' heads at or near the null points of the low-order (1st, 2nd, and 3rd order) axial length and width standing waves (also called room modes, See Section 7.2). The end result will depend upon a combination of:

- Seat locations
- Room dimensions (see Section 7.3.1)
- Subwoofer quantity and layout (see Section 7.3.2)
- Room bass absorption (see Section 9)
- Electronic electro-acoustic optimization (see Section 11)

SECTION

5

SPEAKER LAYOUT

5.1　SPEAKER LAYOUTS INTRODUCTION

Immersive sound is introducing a paradigm shift in speaker layouts. While different formats (Dolby Digital and DTS) fundamentally agree on the optimal speaker locations for the 5 or 7 main channels, there is no such consensus with respect to the additional upper layer speakers for immersive audio.

There are several immersive audio formats for home reproduction, including Dolby Atmos®, Auro-3D®, DTS:X® (also as a subset of IMAX® Enhanced), and MPEG-H 3D Audio. The developers of each have some differing speaker placement recommendations with horizontal and vertical angles for each speaker relative to the RSP, typically with large tolerances. However, these should not be interpreted as absolute requirements resulting in incompatible speaker layouts. When chosen wisely, the same speaker layout can work for all formats.

Moreover, all of the immersive audio formats recommend that speakers be ideally placed relative to a singular RSP. This can cause potential problems when an audience is spread over a larger listening area.

The optimal speaker placement for the various immersive sound formats needs to consider many practical requirements of home entertainment spaces around the RSP. These include the size and proportions of the room, the size and aspect ratio of the screen, the size and shape of the listening area, and presence of seat risers to ensure head clearance in multiple seating row configurations.

This section establishes guidelines that resolve all of these considerations — having a single, sensible arrangement of speakers that works well for all formats and all listeners, and provides a methodology suitable for real home entertainment spaces.

5.2　IMMERSIVE SOUND FORMATS

The immersive sound formats can each be summarized by general recommendations as described in this section. Each has scalable system sizes ranging from 5 discrete speaker feeds to as many as 34, plus LFE.

5.2.1　DOLBY ATMOS

For Dolby Atmos in the home, Dolby recommends speaker positions for various system sizes ranging from 5 (3.1.2) up to 34 (24.1.10) discrete speaker feeds, plus LFE, with 9 (5.1.4) and 11-channel (7.1.4) systems being most common. Three of these configurations are depicted in figures 5-1 to 5-3. For more specific information, links to Dolby Atmos setup guides are provided in Appendix E.3. Note that these include some options for speakers in height locations on the same vertical plane as the listener-level speakers, either in addition to, or instead of top speakers along ceiling lines.

In commercial cinema, Dolby Atmos can provide up to 64 discrete speaker feeds delivered by a maximum 7.1.2 bed and up to 118 audio objects.
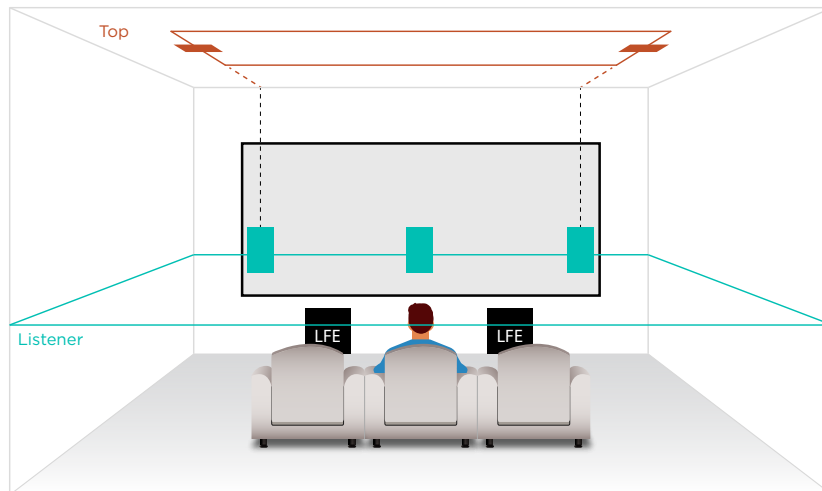
Figure 5-1: Smallest Dolby Atmos 3.1.2 layout with only 3 front speakers and 2 top/overhead
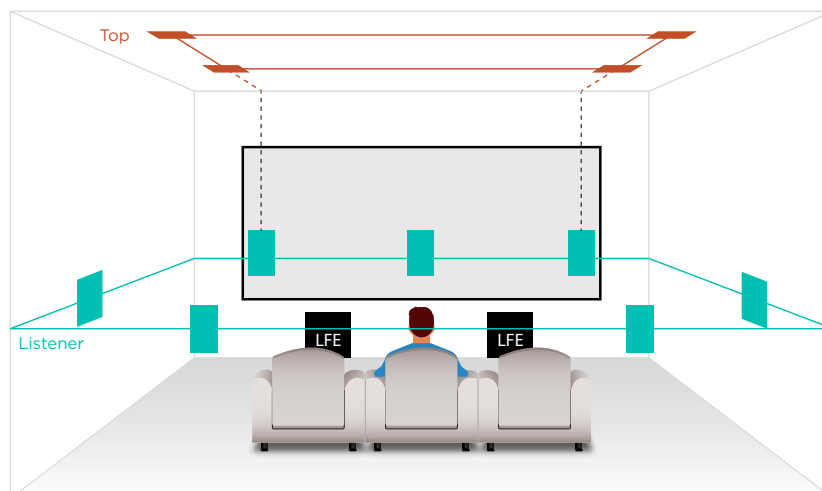
Figure 5-2: Dolby Atmos 7.1.4 layout including 4 top/overhead speakers along ceiling lines
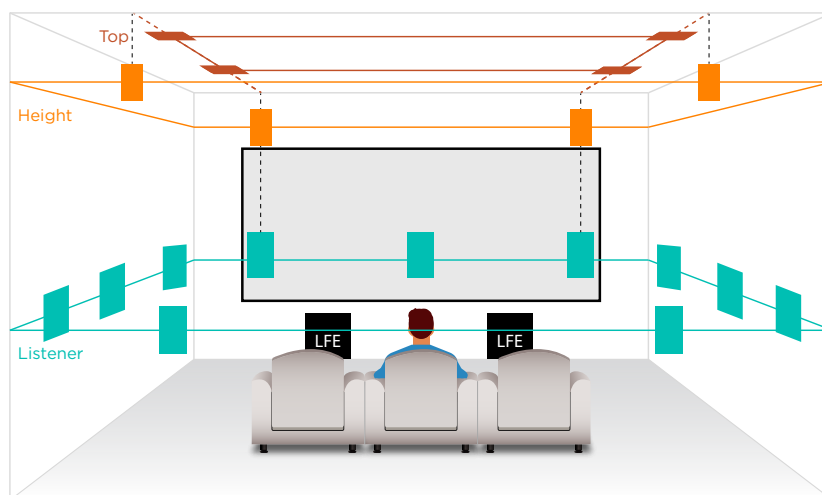
Figure 5-3: High spatial resolution Dolby Atmos 11.1.8 layout with optimized upper layer

5.2.2   AURO-3D

Auro-3D provides up to 13 discrete speaker feeds (plus LFE) corresponding to predefined speaker layouts. It utilizes a traditional 5.1 or 7.1 listener-level layer of speakers for backward compatibility with surround sound, with the addition of at least 4 height speakers vertically aligned with the corresponding listener-level speakers. Auro Technologies describes the 9.1 configuration (comparable to 5.1.4 in other formats) as the recommended minimum setup for the full Auro-3D experience, as depicted in figure 5-4. The optimal configuration is 13.1 (comparable to 7.1.6) including a central single top speaker directly over the listeners, as shown in figure 5-5.

Auro-3D is optimized to produce a dome of sound around and over the listeners to achieve an enveloping vertical spread of the sound image. Therefore, the elevation angle between the listener-level and upper layers is of primary importance and should always be between 25° and 40°, with 30° as the optimal target. Links to Auro-3D setup resources are provided in Appendix E.3.
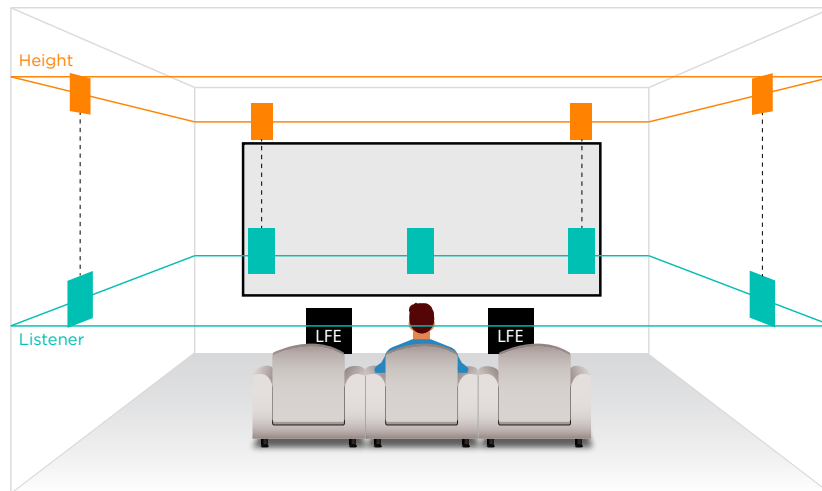
Figure 5-4: Auro-3D 2-layer 9.1 (5.1.4) speaker layout is the minimum recommended configuration
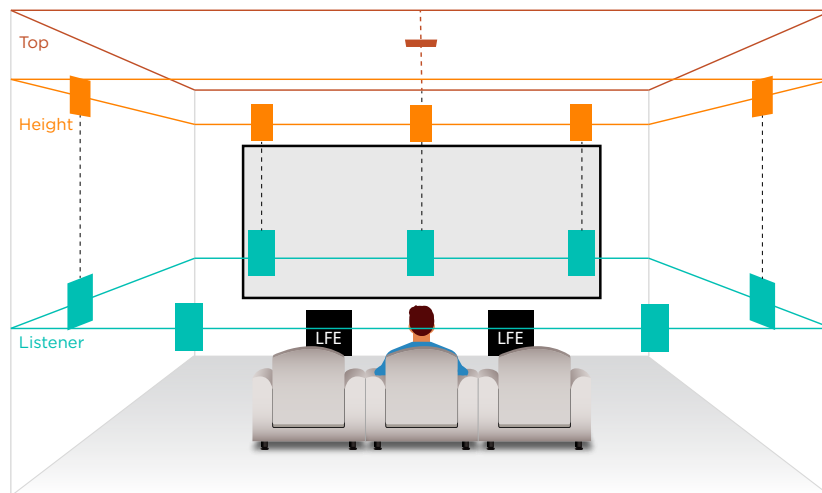
Figure 5-5: Auro-3D 3-layer 13.1 (7.1.6) speaker layout for the complete experience

5.2.3 DTS:X

The standard **DTS:X** renderer delivers up to 11 discrete speaker feeds (plus LFE) corresponding to a 7.1.4 layout. Guidelines advise a flexible range of upper speaker azimuth angles as low as 20° (high on wall) and up to 45° (on/in ceiling, angled towards listener), with advice to favor higher angles. Best immersion is achieved when the upper speakers are placed where a figurative dome intersects the ceiling, with each speaker equidistant from the RSP.

By comparison, **DTS:X Pro** provides up to 30 discrete speaker feeds including numerous listener-level and upper layer locations for more uniform resolution in a more spherical sound field. Figure 5-7 depicts a system utilizing 23 of these locations (excluding the lower layer and some other locations not included in the recommendations of this document), resulting in a conceptual 13.1.10 system.
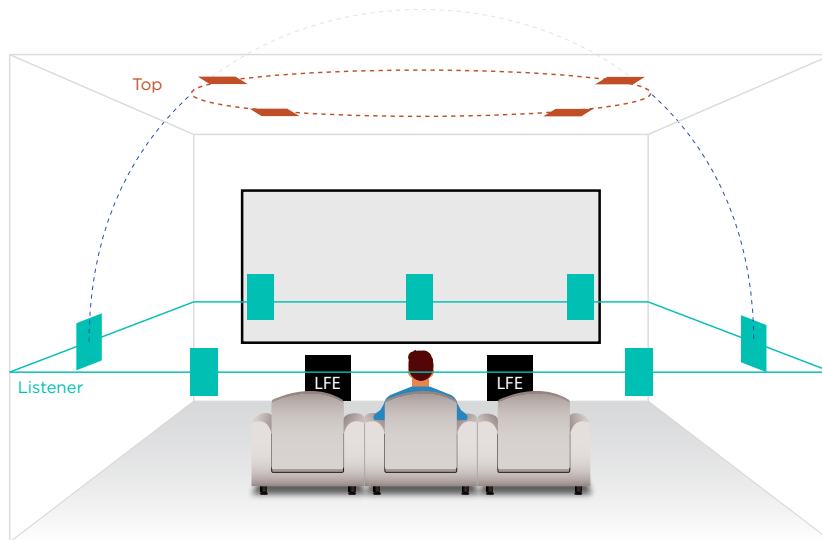
*Figure 5-6: **DTS:X** in a standard 7.1.4 layout*
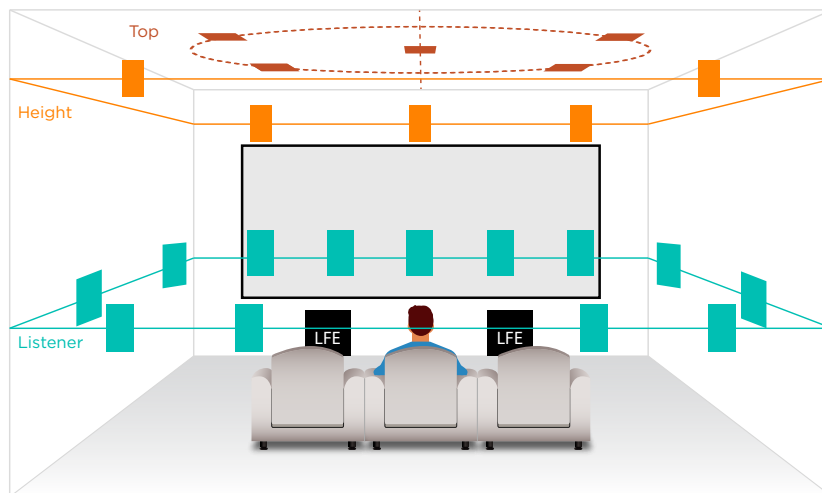
*Figure 5-7: **DTS:X Pro** in conceptual 13.1.10 layout,
scalable to 30 discrete speaker feeds*

5.2.4 MPEG-H 3D AUDIO

MPEG-H 3D Audio (ISO/IEC 23008-3) is an open standard for audio encoding that is flexible to various speaker layouts, however it references ITU-R BS.2051-3 for several standardized configurations and angles. The four most notable are:

- "System C" consistent with Dolby Atmos 5.1.2
- "System D" consistent with Dolby Atmos 5.1.4
- "System G" that approximates Dolby Atmos 9.1.4
- "System H" *Advanced Sound System* consistent with NHK 22.2 (Japanese *Super Hi-Vision*)

Integrators should be cognizant of MPEG-H, particularly due to its inclusion in the Digital Video Broadcasting (DVB) and ATSC 3.0 (NEXTGEN TV) systems, including compatibility with streaming media. However, the work of this recommended practice to unify speaker layouts for Dolby Atmos, DTS:X and Auro-3D should be considered as fully adaptable to MPEG-H applications.

5.3 LABEL KEY FOR DISCRETE SPEAKER FEEDS

Consistent labeling of speaker locations based on discrete processor output feeds is important for interpretation of design documentation. There are several standards with some different ideas and methods, but a more consistent approach is recommended in figure 5-8 and the accompanying table on the following pages.

This method of labeling leads with function, being either front (F) or surround (S) at listener-level (the "x" in the x.y.z syntax) and top (T) or height (H) for the upper layer (the "z" in x.y.z). A cross-reference to other formats is tabled in Appendix E.

Note that when using multiple pairs of side surround speakers to accommodate multiple seating rows (as recommended in Section 5.6.2), the pairs in addition to the primary SL/SR should each be appended with a number for differentiation. The recommended method is to label the forwardmost pair in the surround speaker zone (refer to Section 5.6.1) as SL1/SR1, with the next pair back carrying the primary SL/SR label, then SL2/SR2 for the third row pair.
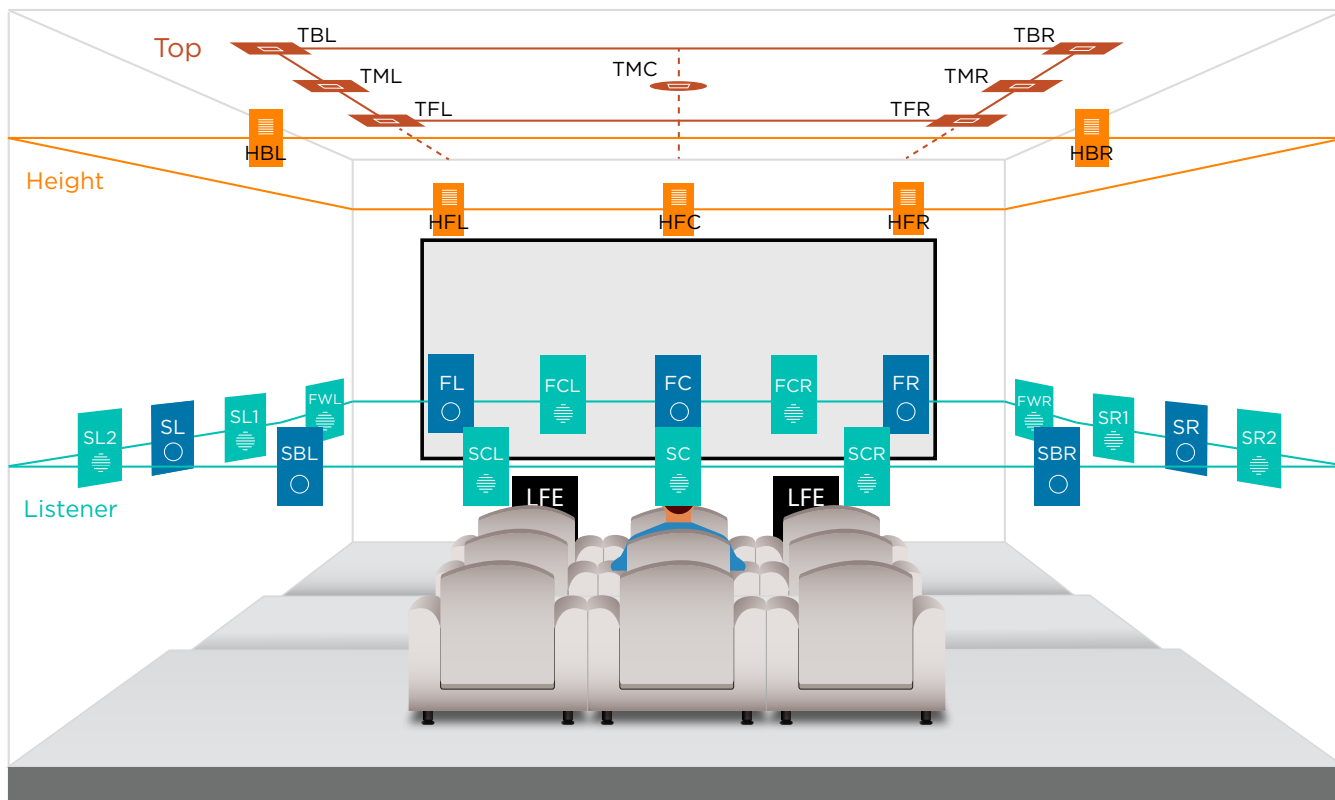
Figure 5-8: Discrete speaker feed nominal locations and corresponding labels (as tabled below)

Color code	Label	Description	Notes	Processor Support
Listener-level standard ⭘	FL	Front Left	Primary front speakers	Commonly used and supported
	FC	Front Center		
	FR	Front Right		
	SL	Surround Left	Use with 5.1	
	SR	Surround Right		
	SBL	Surround Back Left	Additional for 7.1	
	SBR	Surround Back Right		
Listener-level expanded	FWL	Front Wide Left	Additional listener-level speakers for higher spatial resolution	
	FWR	Front Wide Right		
	SL1	Surround Left 1		Less commonly supported
	SR1	Surround Right 1		
	SL2	Surround Left 2		
	SR2	Surround Right 2		
	FCL	Front Center Left	Additional front speakers for large screens	
	FCR	Front Center Right		
	SC	Surround Center	Additional surround speakers central zone behind listeners	Not commonly supported
	SCL	Surround Center Left		
	SCR	Surround Center Right		

Color code	Label	Description	Notes	Processor Support
Upper (Top)	TFL	Top Front Left	Use with x.1.4 and above	Commonly used and supported, including x.1.2 soundbars
	TFR	Top Front Right		
	TBL	Top Back Left		Commonly used and supported
	TBR	Top Back Right		
	TML	Top Middle Left	Use with x.1.2, and x.1.6 and above	Commonly used and supported, including in 3.1.2 AV receivers
	TMR	Top Middle Right		
	TMC	Top Middle Center	"Voice of God" for DTS:X Pro and/or Auro3D	Supported by Auro-3D and/or some DTS:X processors
Upper (Height)	HFC	Height Front Center	Use with: • Auro 11.1 and 13.1 • Optional for DTS:X Pro	
	HFL	Height Front Left	Use with: • Auro-3D (all variants) • DTS:X Pro • Dolby Atmos x.1.8, x.1.10 and x.1.12	Supported by Auro-3D and/or some DTS:X processors. Less commonly supported in Dolby Atmos hardware
	HFR	Height Front Right		
	HBL	Height Back Left		
	HBR	Height Back Right		

5.4 UNIFIED SPEAKER LAYOUT DESIGN METHODOLOGY

The intention of an immersive audio speaker system is to produce a three-dimensional sound field in which all the speakers contribute to creating a unique immersive experience. However, when a video screen is used, the primary goal of sound in an entertainment space is to support the image for listeners sitting at known positions with their heads oriented toward the center of the screen. As a result, all possible directions from which sound may be heard are not equivalent.

Different speaker groups are defined according to their functions, and their positions need to be specifically optimized: front (screen and wide), surround, and upper (height and top) speakers.

The recommended methodology for designing an immersive sound speaker layout is:

- STEP 1: Place screen speakers to match the viewing angle to preserve sound-to-picture coherence.
- STEP 2: Define surround speakers (number and positions) based on the listening area and the room.
- STEP 3: Place the front wide speakers to bridge the screen and surround speakers.
- STEP 4: Define upper speakers (quantity and positions) based on ceiling height and listening area.

Comprehensive speaker layout recommendations are provided in Appendix E. Each requires the use of an immersive audio processor with the capability to discretely render the appropriate number of speaker feeds.

PERFORMANCE LEVELS — SPATIAL RESOLUTION

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
2. Decoder/renderer capability and discretely rendered speaker configuration, excl. subwoofers	Number discrete speakers	Min.	**5**	**11**	**15/13***	**15/13***	Room

Includes all listener-level and upper discrete processor outputs, though there are multiple combinations of speaker locations possible therein, depending on the room design and characteristics. * Auro-3D specific room design requires 13 discrete feeds; for other formats the minimum should be 15 for Levels 3 and 4.

5.5 RECOMMENDED PLACEMENT FOR SCREEN SPEAKERS

5.5.1 SCREEN WALL SPEAKER ANGLES

The various immersive audio formats propose a broad range of horizontal angles for screen wall speakers, ranging between 44° and 60° relative to the RSP. This range closely approximates the recommended SMPTE viewing angle for film projection (43°), the recommended maximum viewing angle for UHD 4K digital video (61°), and the optimal angle for 2-channel music reproduction (60°).

Above everything else, **the angle between front left (FL) and front right (FR) speakers should match the visual angle of the screen to achieve sound-to-picture coherence**. Immersive sound formats allow more accurate sound positioning and subtle mixes in which the coherence between sound and picture is more critical than ever. Sound-to-picture coherence is a requirement of Recommendation ITU-R BS.1909. For guidelines on correctly sizing a screen, refer to CTA/CEDIA-CEB23-B Home Theater Video Design recommended practice.

The FL and FR speakers should be placed as close as practical to the edges of the screen. If the entertainment space is used mainly for movies with front projection video, the FL and FR speakers should be placed behind an acoustically transparent screen (see Section 9.4). In this case, the FL-FR angle is slightly narrower than the viewing angle. It is also possible to place the speakers beyond the sides of the screen, though this practice is less common and results in the horizontal audio angle being slightly wider that the viewing angle. Decisions can be made to accommodate specific constraints such as floorstanding speakers, reduced space behind the screen, or possible obstruction of speakers by the screen structure and/or masking mechanism. A slight mismatch between sound and visual angle is no cause for alarm as the "ventriloquist effect" — the phenomenon of human perception correlating sounds to plausible rather than actual sources — will help a listener's brain reconcile the sound to on-screen activity.

If the system is used primarily for music reproduction, it is advised to place the FL and FR speakers to form the ideal stereo angle of 60° relative to the RSP. If the speakers are not behind the screen, it mitigates all possible losses associated with acoustically transparent screens. However, note that placing the FL and FR speakers close to the side walls increases the need for appropriate, passive acoustic treatment (see Section 9).

5.5.2 NUMBER OF SCREEN WALL SPEAKERS: 3 OR 5

Some immersive audio formats can utilize additional "inter" speakers between the front center (FC) and front left and right (FL/FR) speakers, labeled front center left (FCL) and front center right (FCR), respectively. Use of these speaker positions is only appropriate if the processor is capable of discretely rendering these output feeds.

The number of screen wall speakers depends on the width of the visual angle from the RSP:

- If the visual angle is less than or equal to 40° (±20° from center, indicating a narrow screen), then 3 screen speakers are enough, regardless of the other speakers.

- If the visual angle is greater than or equal to 70° (±35°, wide screen), 5 speakers are recommended, regardless of the other speakers. It is recommended to position the additional FCL/FCR speakers either at the half angle or the half distance between the front center and FL/FR speakers. This uniform angular distribution of speakers across the screen guarantees smooth, uniform panning of sound sources across the picture.

- If the visual angle is between 40° and 70° (most cases), the following guidelines may apply:

  o 3 screen speakers are recommended if the number of surround speakers is less than or equal to 8.

  o 5 screen speakers are recommended if the number of surround speakers is greater than or equal to 10.
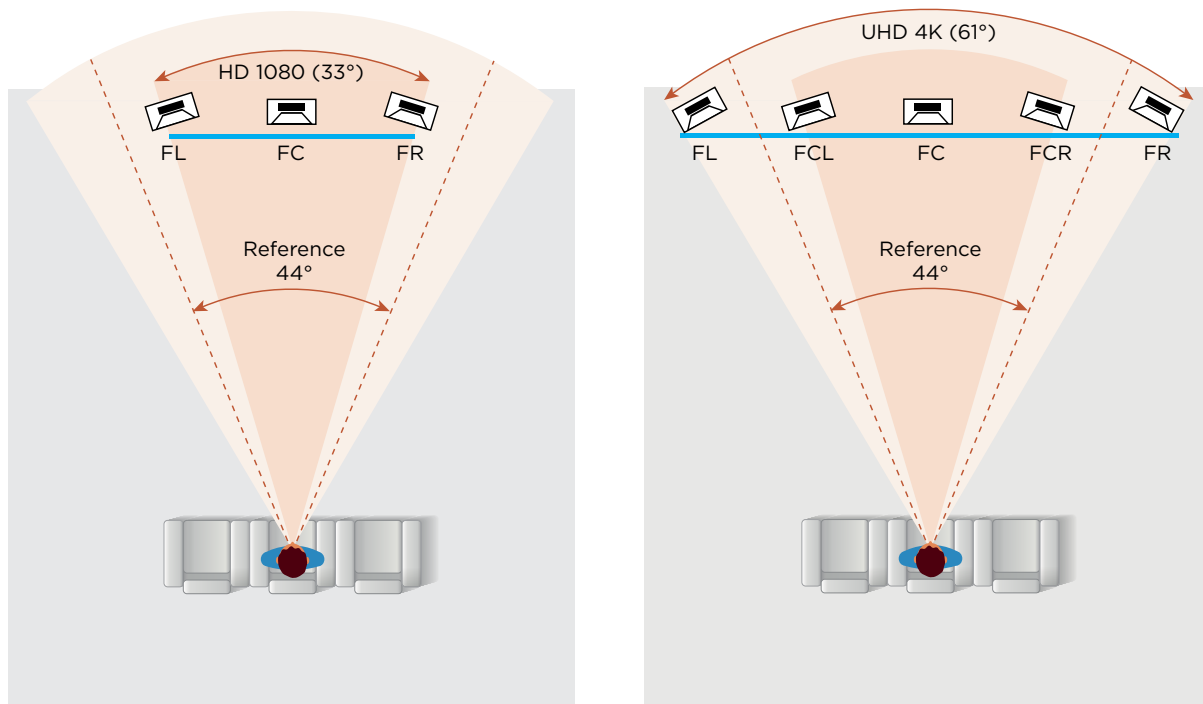
Figure 5-9: 3 screen speakers if visual angle is ≤40° (left) or
5 screen speakers (right) if visual angle is ≥70° or if ≥ 10 surround speakers

5.5.3 VERTICAL ALIGNMENT OF SCREEN WALL SPEAKERS

As the available resolution of the picture increases, the trend is to use larger screens with a vertical viewing angle ranging between around 18° to 34°. Refer to CTA/CEDIA-CEB23-B for recommendations on screen size and position.

In order to maintain the sound-to-picture coherence, it is recommended to maintain acoustic centers of the screen wall speakers within the middle one-third of the screen's height. This improves subjective audible comfort for the listeners, improves height effects (if used), and all while maintaining good vertical coherence of the center channel audio with the picture.
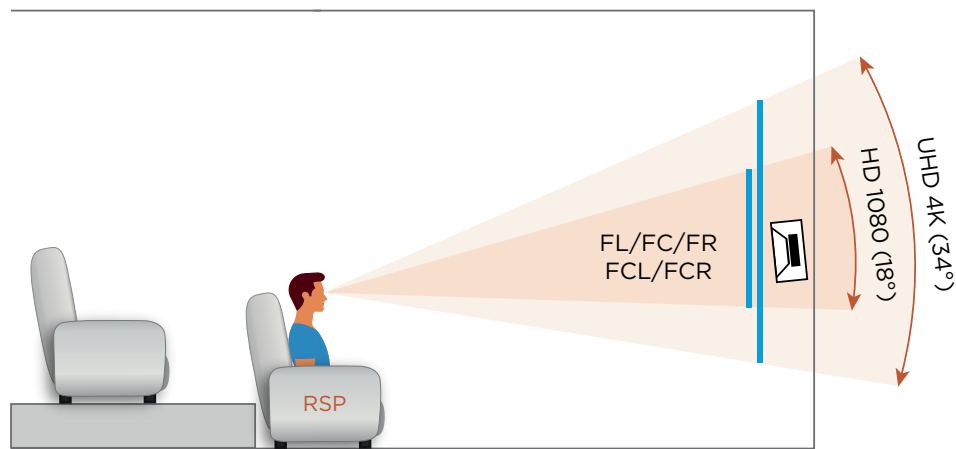
Figure 5-10: Vertical alignment of screen wall speakers

5.5.4 VERTICAL POSITION OF CENTER SPEAKER

Where the front center channel speaker cannot be positioned on the same horizontal plane as the FL/FR speakers, it is recommended that it be positioned as close as possible to the top or bottom of the screen. The choice of top or bottom is influenced by the following factors:

- Distance to a room boundary. It is recommended that the center speaker be located away from any boundaries or furniture that will cause strong early reflections.

- Clear sound path (free of occlusion) to listeners

- Screen size and position

- Center speaker dispersion and coverage

PERFORMANCE LEVELS — SCREEN SPEAKERS

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
3. Number of screen wall speakers allowed outside of recommended zonal locations	Number speakers	-	**0**	**0**	**0**	**0**	Room
Speaker locations are not strict angle numbers. They are zones/areas resulting from multiple trade-offs and defining acceptable possible locations for a given screen wall speaker. Defined zones are wide enough to allow some flexibility in speaker locations within the recommended zone.							
4. Maximum SPL difference between screen wall speakers	dB	Max.	**6**	**5**	**4**	**2**	Seat
Normalised to RSP (where levels will be set to have a 0dB variation). Individually for every seat, the maximum predicted SPL difference (using anechoic propagation loss) between any two screen wall speakers.							
16. Seat-to-seat frequency response variance across all screen wall speakers normalized to measured RSP response between 500 Hz and 16 kHz (1 octave smoothing)	± dB	Max.	**5**	**3**	**1.5**	**1.5**	Seat
Predicts how similar the experience and performance level will be across multiple seats. Design prediction should consider correct speaker alignment, off-axis frequency response on both the horizontal & vertical axes, and the effect of the room.							

5.6 RECOMMENDED PLACEMENT FOR SURROUND SPEAKERS

The various immersive audio formats provide very similar recommendations for the listener-level surround speaker layouts — they all recommend speakers to the sides and behind the listening area **with equal spacing**.

Format specific recommendations are applicable for a single seat situation but need to be adapted to the multi-seat context of a home entertainment space. The surround image will be distorted as the listener moves away from the RSP, and other seats within the listening area are invariably of varied distance to the numerous surround speakers.

However, optimal surround performance can be achieved within the listening area by carefully adjusting the **number** and **position** of surround speakers according to the listening area and the room to ensure that minimal image distortion is achieved for all listeners.

5.6.1   SURROUND SPEAKER PLACEMENT ZONE RECOMMENDATIONS

One fundamental goal for immersive audio is to ensure that all listeners in the audience share the same experience. In other words, when an effect is mixed to one side, every listener should perceive it from that side. Likewise, when an effect is mixed to the back, every listener should perceive it as coming from the back.

Since the introduction of 7.1 discrete multichannel sound, the belt of surround speakers is traditionally segmented into two sub-groups: the surround (side) speakers and the surround back speakers. This distinction between side and back effects remains valid with object-based audio thanks to the coordinate system for object positions (three-dimensional cartesian X, Y, Z model to form a box).

As a result, in a multi-seat entertainment space, the fundamental localization is preserved for all seats if the placement of all surround speakers is adjusted relative to the listening area.

1. **Surround** (side) speakers should all be located to each respective side of the space, avoiding the zone directly behind the listening area to ensure proper left-right orientation for all listeners.

   - In some circumstances the left and right placement zones can extend forward of the front row of seats by up to 500 mm (20 in.), such as for placement of SL1/SR1 speakers, or to mitigate the significant gap that otherwise results between front L/R and first surrounds in a long, narrow space.

   - If implementing a 5.1 listener-level layer with no surround back speakers, a greater angle is typically used for more rearward placement of surround L/R. Depending on the size and shape of the space, this may extend placement onto the back wall, but not directly behind the listening area.

2. **Surround Back** speakers should all be positioned behind the rear line of the listening area. This rule ensures that none of the listeners can perceive a back speaker from in front of them.
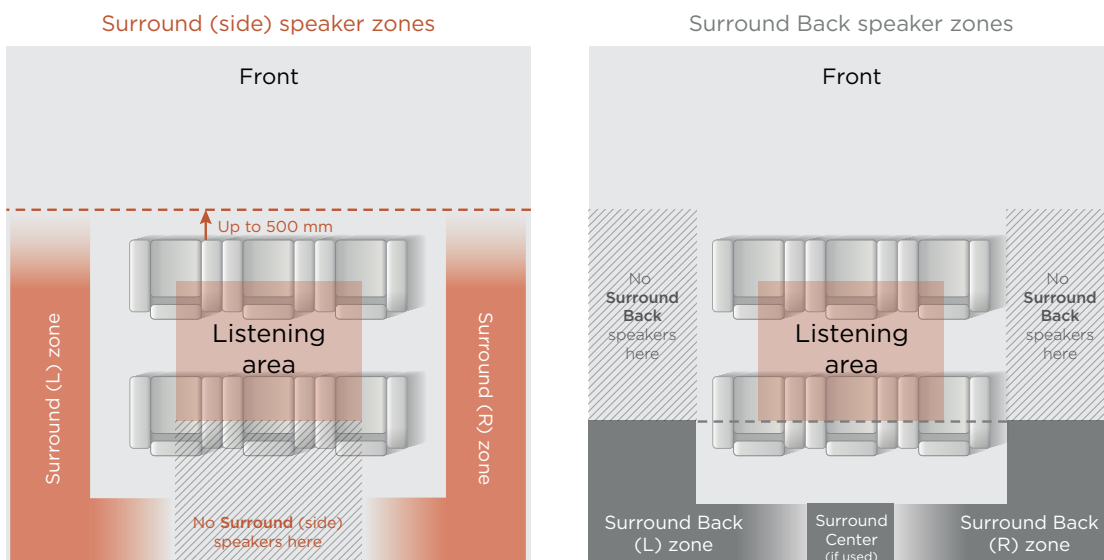
Figure 5-11: Placement zones for surround side and surround back speakers
(fade areas represent less common extremities)

5.6.2 ADAPTING THE NUMBER OF SPEAKERS FOR THE LISTENING AREA

Recommendations for the number of surround speakers are a function of the following factors:

1. **The size of the listening area**. As a general rule, larger spaces with greater expanses of walls will logically require more speakers.

2. **The distance from the listening area to the room walls**. When a listener is positioned close to a wall (see minimum distances in Section 4.1.4) they may then be too close to one speaker while even further away from others, relative to the RSP. Using more surround speakers will reduce the dominance of a singular close speaker by reducing the differential between speaker distances and angles, improving spatiality and immersion for all listeners.

3. **The number of seating rows.** If there are multiple seating rows but only one speaker on each side wall (such as in a discrete 7.1 system), the localization perception will vary with each row. For example, if the side speaker is aligned with the middle row, the people seated there would hear sounds coming from beside them as intended, but the front row would hear the sounds as coming from slightly behind, and the back row would hear them coming from slightly in front. The experience would be inconsistent across the listening area. The closer the seating is to the speakers, the more evident this becomes.

Increasing the number of surround speakers can lead to greater consistency and higher spatial resolution across the listening area. How the increased number of surround speakers are specifically employed is discussed further in Section 5.6.4.
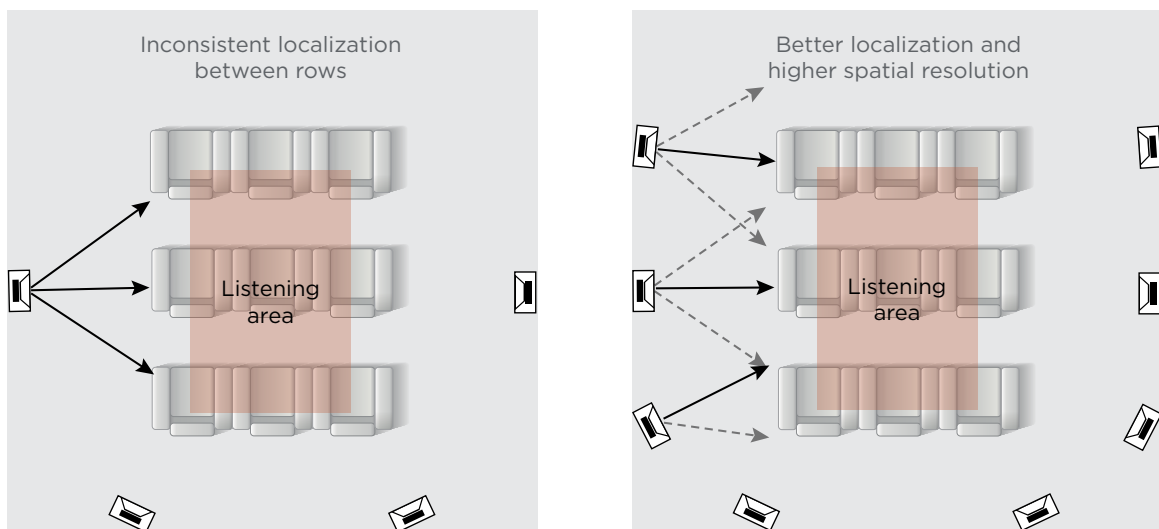
Figure 5-12: Minimal surround speakers (left) in which localization will be inconsistent across multiple seating rows, versus additional surround speakers (right) for higher spatial resolution and seat-to-seat consistency

5.6.2.1 MAXIMIZING SPEAKER USAGE THROUGH PROCESSING

Following the recommendations in section 5.6.2 can result in a speaker count well beyond the standard 4 surround locations, depending on the size of the entertainment space and number of seats and rows. As discussed in section 2.2.3, a higher speaker count improves spatial resolution with object-based audio but may only see a limited number of speakers engaged with 5.1 or 7.1 channel-based content.

Use of an **upmixing** feature in a processor may be employed to expand channel-based content to be reproduced by the higher number of speakers. Upmixing is not limited to surrounds and can be used across all speaker locations, depending on processor capabilities.

Additionally, if there are multiple seating rows, the side surround speakers (SL/SR) may be "arrayed" for consistency between rows. **Speaker arrays** are created by feeding the same signal to multiple surround speakers so audio elements that should only trigger a single speaker will instead be reproduced across the group of speakers. However, it is important to distinguish two main methods:

- *Physical arrays* are created through shared processor outputs and wiring. All speakers wired in one array will reproduce the same content across a diffuse field; they cannot be employed separately for discrete content. This technique is commonly used in commercial cinema rooms to expand 2 or 4 surround channels for reproduction by multiple speakers distributed along the side and back walls for greater audience coverage. Physical arrays reduce localization of object-based content and therefore are not recommended.

- *Software-based arrays* are managed by a supporting processor, enabling its configuration to be content dependent while also providing separate adjustments to each speaker (such as level and delay). For example, the processor may employ discrete rendering to multiple side surround speakers with Dolby Atmos content but change to shared output feeds to effectively create side surround arrays with Dolby Digital 7.1 content.

Whether the immersive audio system is designed to utilize only upmixing, or a combination of upmixing and software-based (not physical) arrays, the number of speakers should not exceed the number of discrete outputs on the processor (with the exception of subwoofers and LFE).
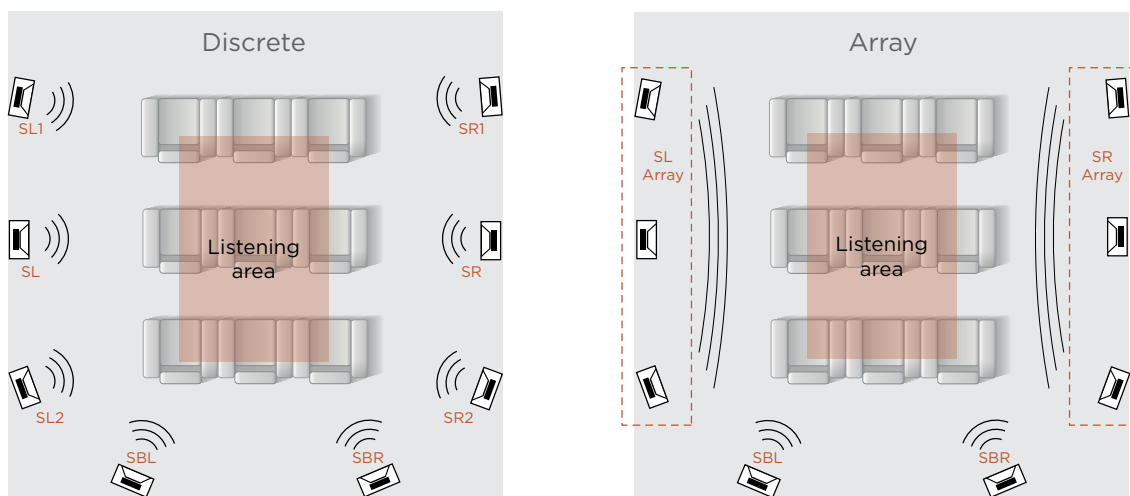
Figure 5-13: Full discrete surround speaker configuration (left) vs. arrayed side surrounds (right)

PERFORMANCE LEVELS — SURROUND SPEAKERS

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
5. Maximum allowable horizontal angle between adjacent surround speakers	Degrees (°)	Max.	N/A	80°	60°	50°	Seat
To ensure that sound movement is smooth and localization is accurate, this metric specifies the maximum horizontal angle between adjacent surround speakers at the seating location.							
6. Maximum SPL difference between surround speakers	dB	Max.	10	6	4	2	Seat
Normalized to RSP (where levels will be set to have a 0 dB variation). Individually for every seat, the maximum predicted SPL difference (using anechoic propagation loss) between any two listener-level surround speakers.							

5.6.3   SPEAKER POSITIONING FOR ACOUSTIC HEAD CLEARANCE

With a listening area comprising multiple seats, **sound occlusion** can occur as the direct sound paths from some surround speakers are obstructed for some listeners by the heads of others sitting beside or behind. This can lead to sound "shadowing" and can have a dramatic negative impact on both the tonal balance and the localization of sounds.

Where the seating area comprises multiple rows, **visual occlusion** can also occur for some viewers with the picture partially obscured by the heads of those sitting in front. **Visual head clearance** is usually achieved by creating tiered seating with *risers*, whereby the second row onwards is each raised in turn by an amount sufficient to afford an unobstructed view from every seat. As a consequence, the surround listening plane — the plane that intersects all listeners' ears — is no longer horizontal and becomes tilted downwards toward the front of the space.

Irrespective of whether a multiple-seat listening plane is level or tilted, **acoustic head clearance** is necessary to reduce seat-to-seat variation and preserve the artistic intent of played content. This can be achieved through a balanced combination of vertical and/or horizontal head clearance techniques, as depicted in figure 5-14.

- **Vertical head clearance** involves raising the entire surround speaker plane as minimally as required above the listening plane to enable all listeners to hear sounds from a given speaker over the heads of others. This typically results in elevation of around 300 mm (12 in.), but the amount can vary depending on the size of the listening area, distance to walls, and ceiling height. Raising the surround speakers too far risks merging the surround field with the upper layer for an undesirable all-above-the-head sound perception.

- **Horizontal head clearance** involves minimally shifting each surround speaker pair forward or backward to ensure they are not directly in line with seating rows to clear the direct sound path for all listeners. This should be balanced against the goal of preserving equal spacing between surround speakers.

As a general rule, ensure line-of-sight from every seating position to every speaker position.

Single Seat

Speaker plane should be at
or slightly above
the listening plane

Listening / Speakers plane

Single Row

Minimally raise level plane
and/or horizontally shift speakers
to ensure no occlusion

Speakers plane

Listener-level plane

Tiered Multiple Rows

Minimally raise tilted plane
and/or horizontally shift speakers
to ensure no occlusion

Speakers plane

Listening plane

Figure 5-14: Minimally shifting the surround speakers may be required to achieve acoustic head clearance

5.6.3.1 ACOUSTIC CLEARANCE AROUND FURNITURE AND FITTINGS

In mitigating sound occlusion it is also important to consider the height of seat backs and other furnishings, along with architectural, decorative, and/or functional elements (such as a bar) to ensure acoustic clearance for all listeners. For instance, while a very high seat back may be considered a premium comfort choice, having it too high can occlude the direct sound path of surround speakers for its occupant, thereby negating some of the efforts of optimal speaker positioning. Holistic design should maintain direct sound paths from all speakers to all listeners.

Seat backs too high

Sound path

Surround speakers plane

Appropriate seat back height

Sound path

Surround speakers plane
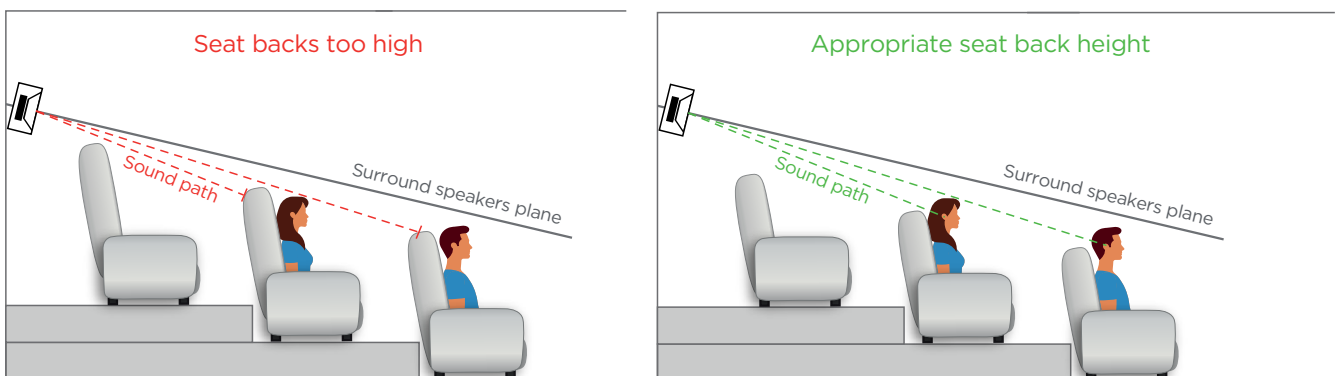
Figure 5-15: Seat back too high (left) occludes rear sound paths vs. appropriate seat back height (right)

5.7 RECOMMENDED PLACEMENT FOR WIDE SPEAKERS

Once the screen speakers have been positioned according to Section 5.5 and the surround speakers according to Section 5.6, the sizable gap between the outermost screen speakers and the frontmost surround speakers can be filled by **front wide** speakers. There are two methods for achieving this.

1. **Median angle** — The angle arising from the midpoint of the *distance* between the FL/FR speakers and their corresponding first side surround speakers. For example, if the distance between the front left (FL) and surround left (SL) speakers is 3 meters, the front wide left (FWL) speaker should be positioned along the RSP's sight line of the 1.5 m midpoint, such as on the wall beyond the physical midpoint. The median angle is derived from this.

2. **Bisector angle** — The midpoint between the angle of the FL/FR speakers and the angle of the first corresponding surround speakers. For example, if the FL speaker is at 30° from the front center and the SL speaker is at 90°, the bisector angle is (90°-30°)/2 = 30° beyond the FL speaker, or 60° from center. This can be expressed as 120° between the two wide speakers.

The median angle is preferred over the bisector angle as it keeps the wide speakers slightly closer to the screen, which is more consistent with their cinematic use. Note that both Dolby and DTS recommend placing the front wide speakers on the listening plane at 120° (±60° from the front center speaker, consistent with the example above).

The front wide speakers should be mounted on the same horizontal plane as the front left and right speakers, and pointed toward the RSP. This may require either special mounting or pre-angled speakers. Flush mounting in the side wall is not recommended as it would result in the sound path pointing across the front width of the room at extreme off-axis from the listener, unless the speakers feature appropriately pre-angled baffles.
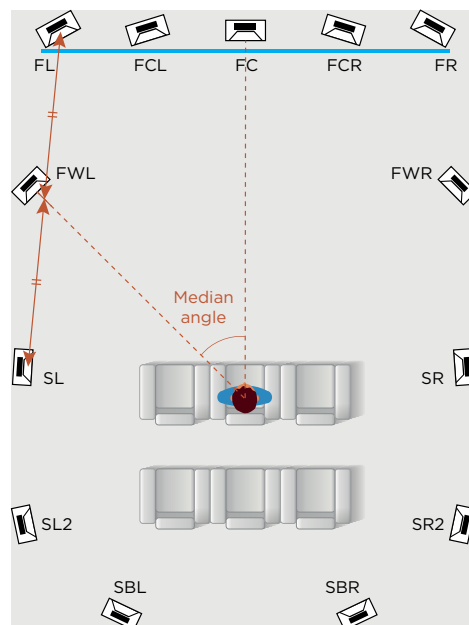
Figure 5-16: Front wide speaker placement according to the midpoint between front L/R and first side surround speakers

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
7. Wide speakers (If implemented) maximum allowable horizontal deviation from median angle	Degrees (°)	±	**10°**	**7°**	**5°**	**2°**	Room
To ensure localization accuracy, this metric is the maximum horizontal anglular deviation allowed from the ideal median angular location for wide front speakers.							

5.8 RECOMMENDED PLACEMENT FOR UPPER SPEAKERS

Nowhere is the disparity of speaker placement recommendations between the main immersive audio formats more evident than with the upper layer. Yet, even here, carefully thinking through the immersion goals of all formats can lead to some specific placement recommendations that can work well for all.

All immersive audio formats utilize upper layer speakers with varying angles ranging from 20 - 45° elevation from the listener's ear level, as described in Section 5.2. For instance, Dolby Atmos recommends 30 - 45° with top (overhead) locations preferred along two ceiling lines (vertically aligned or slightly inside of front left and right speakers), DTS:X advises a broader 20 - 45° but recommends angles higher in the range, and Auro-3D specifies from 25° to a maximum of 40°, with 30° being the target, high on the walls in the same vertical plane as the front left/right screen speakers.

These recommendations are directly applicable for a single seat situation but need to be adapted to the multi-seat context of an entertainment space. Upper sound localization will be compromised as the listener moves away from the RSP. Optimizing localization for all seats can be achieved by carefully adjusting the number and position of upper speakers and the resulting vertical angle between L/R rows of upper speakers, according to the listening area and the ceiling height.
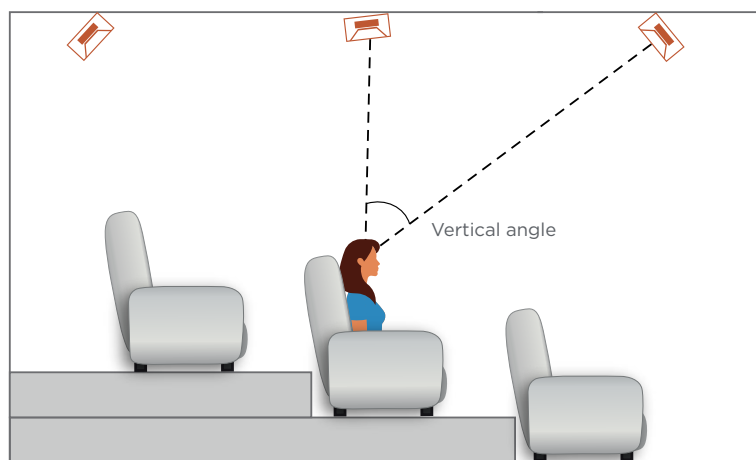
Vertical angle

Figure 5-17: Vertical angle between adjacent rows of upper speakers

5.8.1   UPPER SPEAKER PLACEMENT ZONE RECOMMENDATIONS

One fundamental goal in immersive audio is to ensure that all listeners in the audience share the same experience — when an effect is mixed to the upper front, every listener should perceive it from high in front, and when an effect is mixed to the upper back, every listener should perceive it as coming from high in the back. This obvious statement can be easily missed if speaker positions are determined based only on the RSP without factoring the length of the listening area.

As a result, in a home entertainment space with multiple seating rows, the fundamental localization is preserved for all seats if the placement of all upper speakers is adjusted relative to the listening area, according to the following guidelines:

1. All upper front speakers should be at or forward of the front of the listening area. This rule ensures that none of the listeners can hear an upper front speaker as coming from high behind.

2. All upper back speakers should be to the rear of the listening area. This rule ensures that none of the listeners can hear an upper back speaker as coming from high in front of them.

3. It is preferred that all upper left/right speakers should be aligned along front-to-back ceiling lines with spacing not narrower than the listening area or wider than the main front L/R speakers. This rule ensures that none of the listeners can hear an upper left speaker as coming from the right, or vice versa. However, in the instance of a wide listening area relative to the front main speakers, this rule could lead to an excessive distance between upper left and upper right speakers, resulting in a compromise at the RSP. In this case, it is preferable to exclude the far left and far right seats from the rule.

4. The band of the top middle zone traversing left to right (to include the top center speaker) should be centered above the RSP, ± 500 mm (20 in.) towards the front or back of the space.
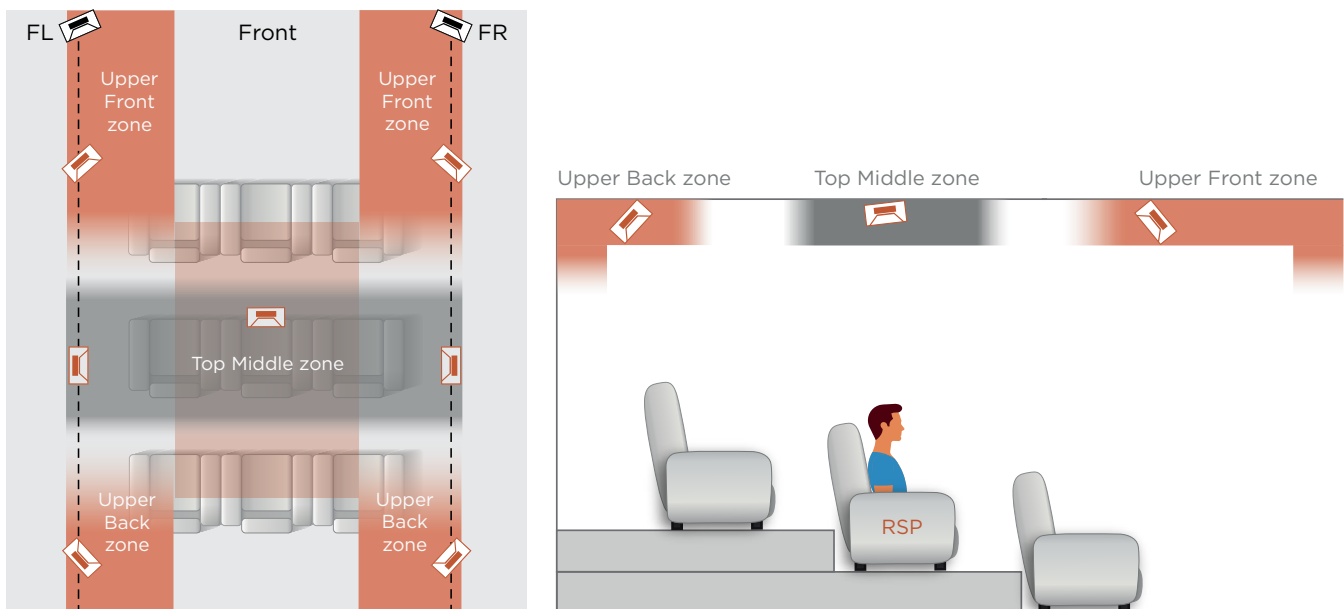
Figure 5-18: Approximate placement zonal recommendations for upper (top/height) speakers

5.8.2 ADAPTING THE NUMBER OF SPEAKERS FOR THE LISTENING AREA

The recommended number of upper speakers is a function of:

- **The length of the listening area**. It stands to reason that a long listening area needs to be covered with more upper speakers. A general guideline is to use at least 4 upper speakers. The Performance Level parameter for vertical angle between upper speaker pairs nominates a range from 80° (fewer rows of upper speakers) to 50° (more rows of upper speakers).

- **The distance from the listening plane to the ceiling**. The lower the ceiling relative to the listeners, the greater number of top/overhead speakers will be required. Having more speakers provides additional sound anchor points but also reduces the span needed to present phantom images, thereby better maintaining accurate localization and immersive experience for most of the audience.

  Note that ceiling height and reflectiveness are also important factors if using upfiring/elevation speakers, as the sound reflection angle should encompass the listening area.

PERFORMANCE LEVELS — UPPER SPEAKERS

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/ Seat
8. Upfiring/elevation speakers allowed?	Yes/No	-	**Yes**	**Yes**	**No**	**No**	-
Absent the ability to install top (overhead) speakers, one solution is to employ upfiring/elevation (e.g., "Atmos Enabled") speakers aimed at a reflective ceiling surface to reproduce immersive content and audio objects. These speakers should have a suitable mechanical and electrical design.							
9. Maximum allowable vertical angle between adjacent (L/R rows of) upper speakers	Degrees (°)	Max.	**N/A**	**80°**	**60°**	**50°**	Seat
To ensure that sound movement is smooth, and localization is accurate, this metric specifies the maximum vertical angle between adjacent upper speakers at the seating location. Excludes top middle center ("Voice of God") and height center speakers.							
10. Maximum SPL difference between upper speakers	dB	Max.	**12**	**8**	**5**	**2**	Seat
Normalized to RSP (where levels will be set to have a 0 dB variation). Individually for every seat, the maximum predicted SPL difference (using anechoic propagation loss) between any two height/upper speakers.							

5.8.3 MAXIMIZING UPPER SPEAKER USAGE ACROSS ALL FORMATS

Even though there are differences in the number and placement of upper speakers among immersive formats, common locations may be shared to good effect.

- **Dolby Atmos** provides up to 10 discrete upper speakers:
    - o   1 pair front height (wall/ceiling), 3 pairs top (ceiling), 1 pair back height (wall/ceiling)

- **Auro-3D** provides up to 6 discrete upper speakers:
    - o   Front L/C/R height (wall), 1 pair rear height (wall), single top center ("Voice of God")

- **DTS:X** provides 4 discrete upper speakers:
    - o   1 pair front height/top, 1 pair back height/top

- **DTS:X Pro** and **MPEG-H** each provide up to 13 discrete upper speakers:
    - o   Front L/C/R height, 3 pairs top (ceiling), back L/C/R height, single top center

By aligning these processor feeds to cross-format shared speaker positions as shown in Appendix E, the system will make best use of every speaker resource for the benefit of the listeners.

5.9 SPEAKER DIRECTIVITY AND OPTIMAL ORIENTATION

Besides the speaker location, the speaker directivity pattern has a substantial impact on spatial uniformity over the listening area, both in terms of localization accuracy and sound pressure uniformity.

The vast majority of speakers are point sources, as described in Section 6.1.4.1. Several speaker orientation methods are possible, depending on the project requirements and budget. The three most popular are:

1. Pointing towards the reference seating position
2. Non-angled surface or flush mounting
3. In-wall or baffle mounting

These are discussed in Sections 5.9.1 - 5.9.3 on the following pages.

5.9.1 POINTING TOWARDS THE REFERENCE SEATING POSITION

To achieve truly high-end immersive sound reproduction, the general recommendation is that, whenever possible, **all speakers should point toward the reference seating position** (RSP), as specified for professional cinemas and professional studios designed for immersive sound.

Orientating speakers this way will achieve a wide listening area, the most accurate source positions and uniform tonal balance as the sound elements move around. Where speaker mounting to achieve the exact orientation is difficult, it is instead reasonable to use in-wall or in-ceiling speakers with pre-angled front baffle aimed as closely as possible towards the RSP. This method provides a result that is (slightly) less dependent on room acoustics as the energy projected outside of the listening area is minimized.
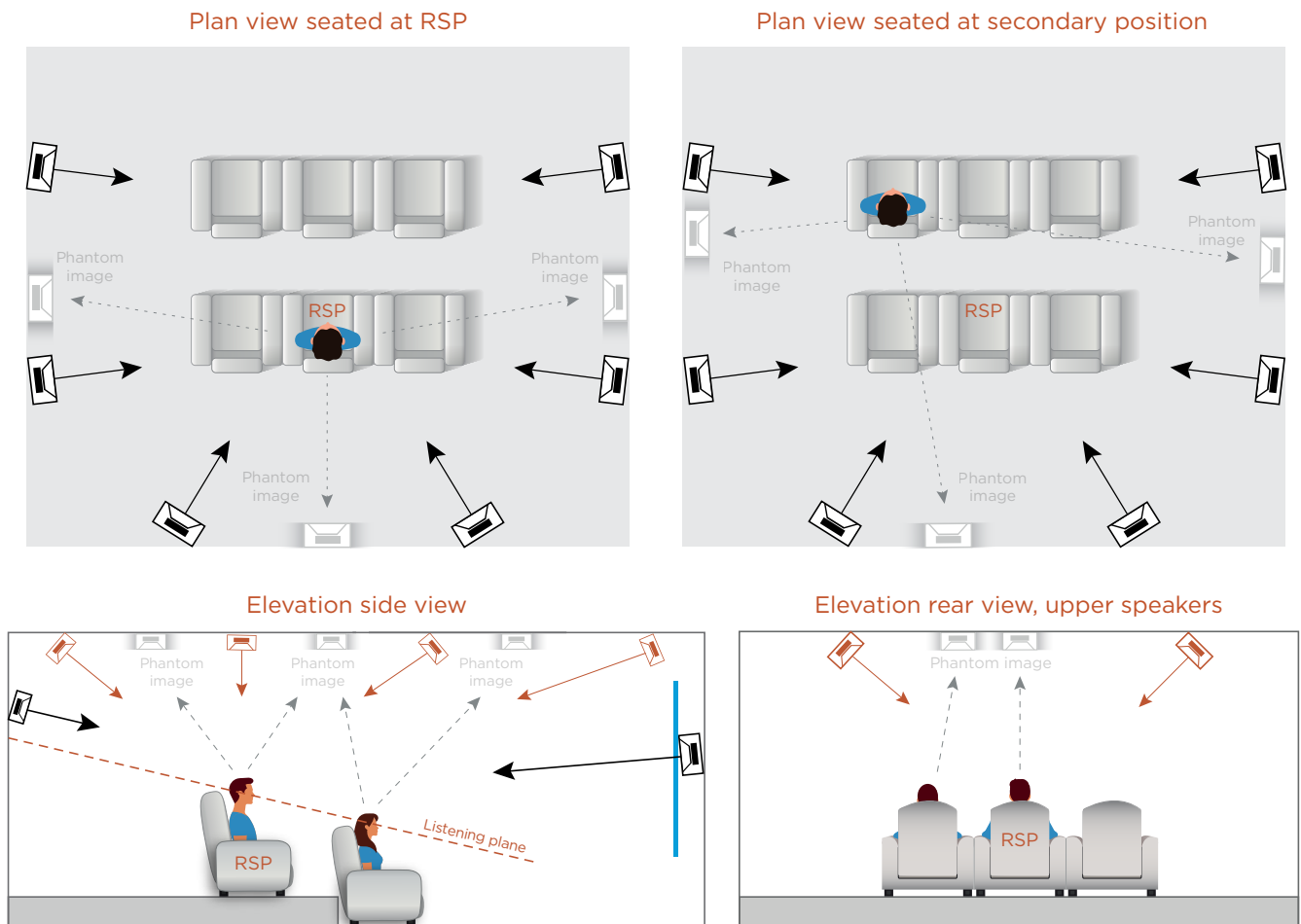
Figure 5-19: Speakers pointing toward the RSP optimizes localization perception throughout the listening area

5.9.2 NON-ANGLED SPEAKER MOUNTING GUIDELINES

With a less high-end approach it is also acceptable to mount non-angled speakers (sometimes called "shower" mounting) on or in the ceiling and walls. However, the speakers used should have wide dispersion characteristics.

The localization and immersive experience will be compromised for listeners sitting away from the RSP as sounds appear to be drawn more towards the nearest speakers, with phantom (perceived) images between adjacent speakers also being skewed accordingly. Additionally, use of non-angled speaker orientation is more sensitive to the room acoustics as much of the speaker energy is reflected off the adjacent and opposite walls, resulting in stronger reflections and flutter echo. Conversely, a non-angled approach can greatly facilitate the integration and often leads to a cleaner aesthetic. However, flush mounting should always be avoided for front wide speakers, as this would result in them being used drastically off axis (30° to 50°), relative to the listening area.
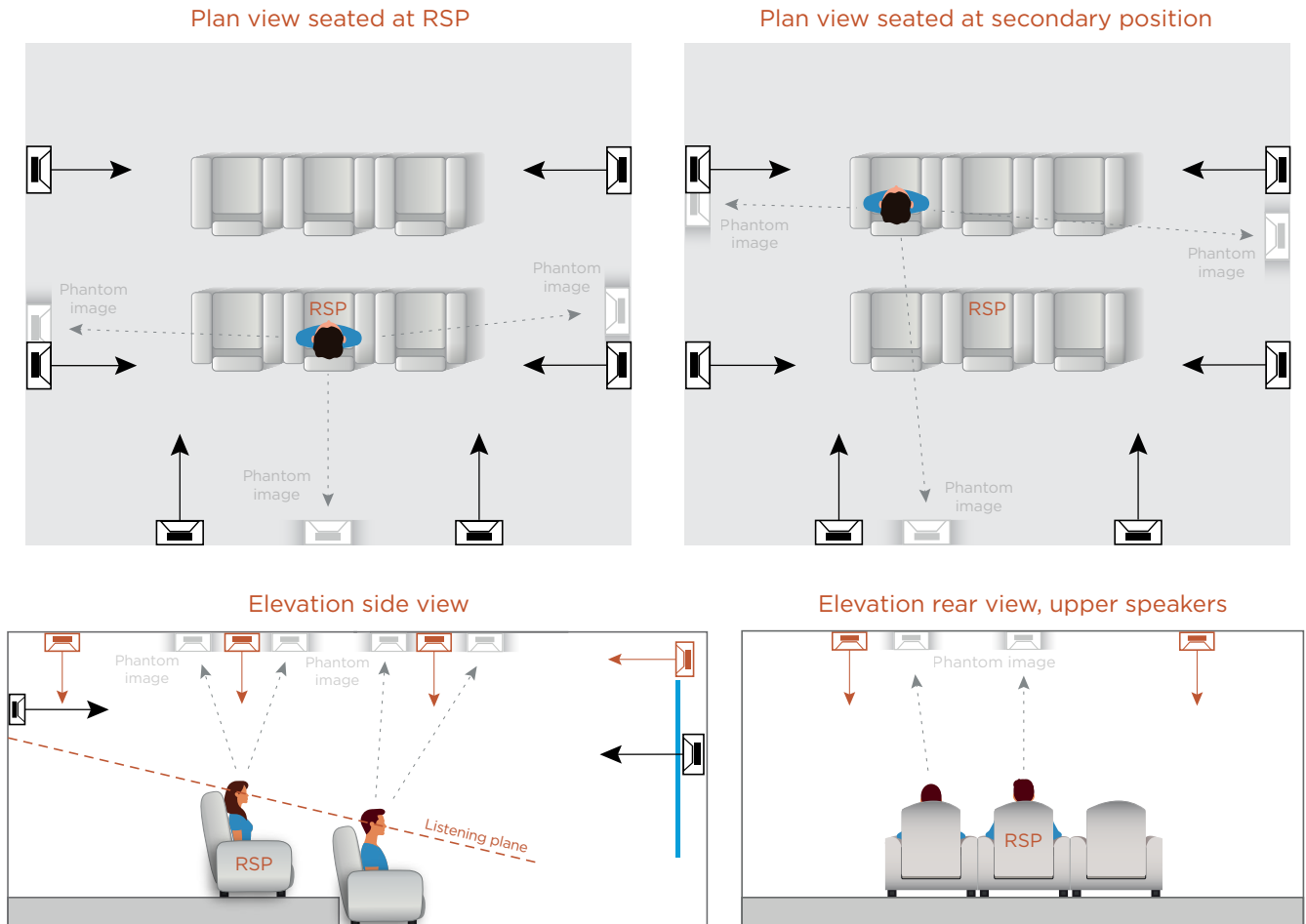
Figure 5-19: Non-angled speakers can skew audio imaging towards the nearest speaker

5.9.3 IN-WALL OR BAFFLE MOUNTING GUIDELINES

In-wall or baffle mounting improves the smoothness of low-frequency response and provides increased sensitivity in the region below 300 Hz.

Speakers specifically designed for in-wall mounting (including in-wall subwoofers) should be flush-mounted in the wall (possibly angled) with minimal obstructions or cavities in their vicinity. Conventional box speakers should preferably be located either in a baffle wall or at more than 1 m (3.28 ft) in front of the wall. Speakers that are not designed for this kind of mounting will require equalization to reduce the excessive bass created by the baffle or in-wall mounting.

Speakers, and in particular, subwoofers, should not be mechanically coupled to surfaces which can themselves radiate energy. This can produce unwanted effects such as additional resonances, cancellation, and non-linear distortion including rattles. This applies to room walls and screen baffle walls, and needs to be very well executed.

If in-wall or baffle mounting is used:

- the baffle material should be very inert and well damped, able to absorb or dissipate vibrational energy. It is usually a stiff and heavy material with a reinforced internal structure.
- the speakers should have no direct mechanical contact with the baffle. They should sit on vibration isolating pads, should be gasketed into place with closed cell foam weather stripping, and the cutouts should be oversized.

If a proper baffle wall execution is not possible, it is better to avoid its use and simply use absorption materials around the screen speakers.

PERFORMANCE LEVELS — SPEAKER LAYOUT GENERAL

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/ Seat
11. Number of surround/wide/upper speakers allowed outside of zonal recommendation locations	Number speakers	-	**N/A**	**0**	**0**	**0**	Room
Speaker locations are not strict angle numbers; they are designated zones/areas for speaker groups resulting from multiple trade-offs. Zones are broad enough to allow some flexibility in speaker locations.							
17. Seat-to-seat frequency response variance across all wide/surround/upper speakers normalized to measured RSP response between 500Hz and 16kHz (1 octave smoothing)	± dB	Max.	**N/A**	**N/A**	**3**	**1.5**	Seat
Predicts how similar the experience and performance level will be across multiple seats. Design prediction should consider correct speaker alignment, off-axis frequency response on both the horizontal & vertical axis, and the effect of the room.							

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SECTION

6

SPEAKER SELECTION

6.1 SPEAKER PERFORMANCE

Most performance parameters outlined in Section 3 "Audio Performance Objectives and Levels" are affected by the choice of speakers, including subwoofers. When selecting speakers, the following performance parameters should be considered:

- Speaker frequency response
- Speaker directivity index
- Speaker sound power
- Speaker dispersion
- Speaker audience coverage
- Inter-speaker timbre, spectral and phase accuracy
- Speaker and subwoofer output sound pressure level capability

In order to make the selection based upon the performance requirements of the system, the following data should be known and used:

- ANSI/CTA-2034-A (Spinorama)
- Speaker dispersion heat map
- Speaker maximum short and long term sound pressure level capacity

6.1.1   "SPINORAMA"

Various standards exist to determine the frequency response, polar radiation patterns, directivity, and maximum output of a residential speaker (see Informative References). One such standard is ANSI/CTA-2034-A, colloquially known as "Spinorama." Based on research conducted by Dr. Floyd E. Toole, Spinorama is widely considered to be an accurate test method to predict the overall performance of a speaker as auditioned in acoustically typical residential rooms.

The method involves measuring a speaker at 1/20-octave resolution with 70 microphone locations at 10° increments on both vertical and horizontal orbits surrounding the speaker. The raw data can be examined in several different ways, but the Spinorama configuration is intended to reveal the nature of direct and reflected sounds arriving at a listening position in entertainment spaces.

Once collected and aggregated, the Spinorama data graphically represents speaker performance in six metrics, as follows:

1. **On-axis frequency response** — The response of the speaker's amplitude across the audible frequency range using 1/20 octave resolution. This describes the first-arriving direct sound for listeners seated on this axis.

2. **Listening window** — Spatial average of nine amplitude responses where the microphone relates to the speaker, between ±10° vertical and ±30° horizontal angles. This curve describes the average direct sound for listeners at multiple seating locations. It also reduces effects of audibly insignificant acoustical interference ripples that may only appear in a single anechoic on-axis curve.

3. **Early reflections** — The estimate of all first reflections arriving at the RSP in a typical room. These are often the second loudest sounds (direct sounds are loudest) arriving at the listening location and therefore the off-axis sounds contributing to this curve are important components of sound quality predictions. The early reflection curve is a good predictor of the steady state room curve above about 500 Hz, although such a curve, by itself, is not a reliable indicator of sound quality.

4. **Sound Power** — A representation, shown as a frequency response, of the total sound power radiated by the speaker, all of which arrives at the listener position from many directions. It is calculated using the 70 microphone measurements, each one weighted to estimate the energy passing through different areas of an imaginary sphere surrounding the speaker. Sound power is the ultimate "spatial average," and as such is an important factor in identifying possible resonances in a speaker.

    Significant bumps that are prevalent across the Spinorama frequency response curves represent anomalies, and as such are a potential source of coloration in reproduced sound. The absence of such bumps is a desirably strong indicator of a potentially neutral sounding speaker.

5. **Sound Power Directivity Index (SPDI)** — The difference between the listening window and sound power curves. The higher the SPDI, the more directional the speaker.

6. **Early Reflection Directivity Index (ERDI)** — The difference between the listening window and early reflection curves. The nature of small room acoustics and the interactions of sound reflections within have a large effect on perceptual sound quality. The smoothness of the ERDI curve is an important indicator of speaker sound quality.
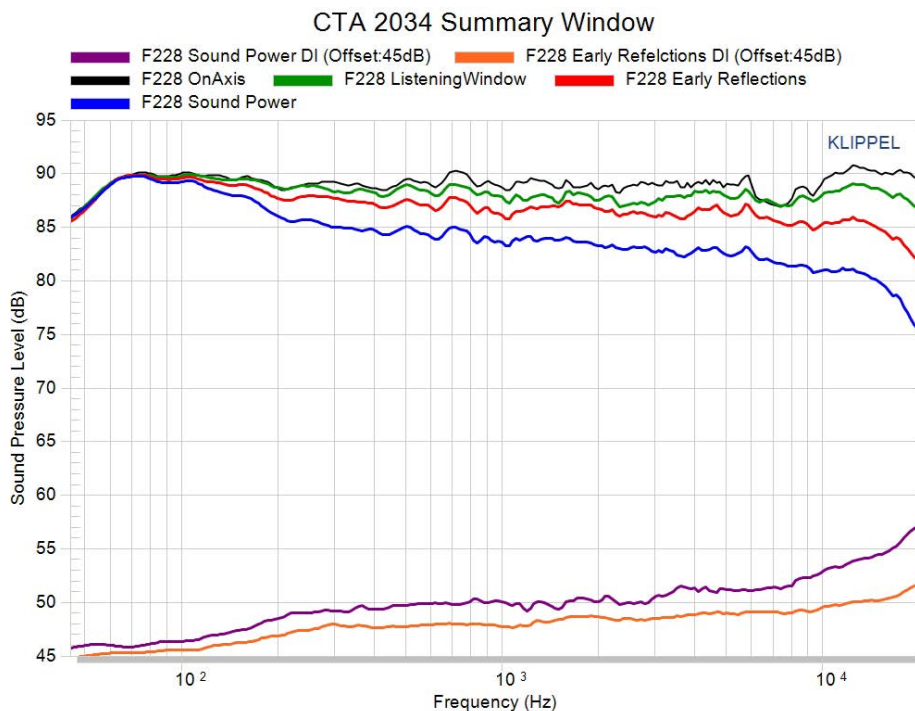
Figure 6-1: Example Spinorama data [1]

6.1.2 SPEAKER DISPERSION HEAT MAP

The graphical plot of a speaker's dispersion and directivity pattern is colloquially known as a "heat map," or sometimes "polar plot" or "polar map." The heat map is so-called because of its colors, wherein warmer colors signify higher amplitude. This is useful for predicting the audience coverage and room interaction of a given speaker, and the resulting consistency of frequency response at all seating locations (±3 db, ±6 db, etc.).

The heat map can also be used to ascertain the need to angle a speaker towards the listening area. This should always be considered for any speaker where the listeners are positioned off-axis to the speaker's listening window (as per ANSI/CTA-2034-A). Wide and height speakers mounted flat to a surface are examples of this.

Be aware that attempting to compensate for listening to a speaker off-axis by applying electronic EQ may result in the maximum sound pressure level capacity of the speaker being reduced, together with other unintended consequences on sound quality.
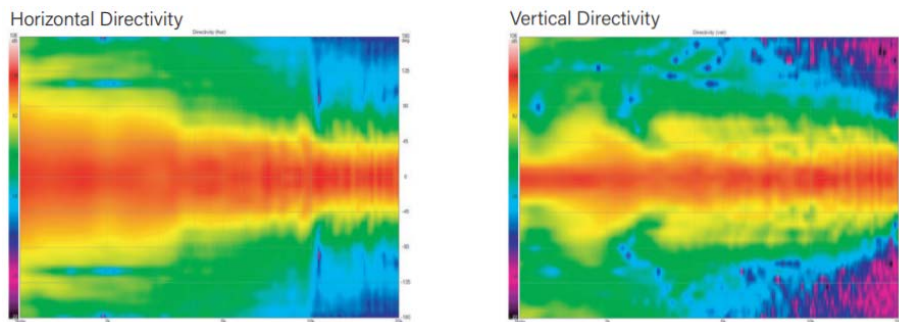
Figure 6-2: Example speaker directivity heat maps [2]

6.1.3 INTER-SPEAKER PHASE COHERENCE

In audio, "spatial resolution" describes the ability of a sound system to create highly focused and localizable sound sources at any position in space including the positions in the room where there is no physical speaker. This resolution results from different speakers combining to form focused and localized sound sources. Such sources are called **physical sources** when presented directly from the speaker locations, and **virtual sources** or phantom images when they are perceived from the space between speakers. Collectively, they form a soundstage or a spatial image.

Accuracy of spatial resolution is directly related to how well speakers match in both amplitude and phase — the inter-speaker characteristics.

6.1.3.1 INTER-SPEAKER POLARITY MISMATCH

An inter-speaker mismatch due to absolute polarity reversal, namely a speaker wire connected such that the positive lead is connected to the negative amplifier terminal and the negative lead is connected to the positive terminal, will result in that speaker completely losing its ability to form a phantom image with any other correctly connected speaker.

6.1.3.2   INTER-SPEAKER PHASE MISMATCH

The same sound wave coming from two in-phase speakers will combine to a particular amplitude, but if the inter-speaker phase is misaligned at any given frequency it will cause a loss of amplitude between the two now-offset peaks. The amount of amplitude loss, or "destructive interference," corresponds to the degree of phase rotation; 45° ≈ 1.4 dB loss; 60° ≈ 2.5 dB loss; 90° ≈ 3 dB loss. Discomfort starts at 90° phase shift and increases toward 180° (full polarity mismatch as described in Section 6.1.3.1).

An inter-speaker phase mismatch within a limited frequency range may be audible throughout the entire room. At the RSP, it can create significant discomfort. Unfortunately, such phase mismatches can happen at certain frequency bands when speakers with different characteristics are combined. For instance:

- Mixing 3-way speakers with 2-way speakers
- Similar looking speakers using different crossover topologies
- Speakers from the same manufacturer but different models
- A speaker being used in a vertical orientation versus being used horizontally
- Poor sample-to-sample consistency between similar model speakers

6.1.3.3   INTER-SPEAKER GROUP DELAY MISMATCH

Group delay is a measure of how fast the acoustic phase changes at different frequencies, and any resulting delays in sound waves at those frequencies. Factors include things like driver type and alignment, and crossover high- and low-pass filters. While group delay as a speaker characteristic is generally regarded as mostly affecting low frequencies, mismatching speakers with different group delay characteristics results in an audible, time-based offset across more groups of frequencies. This is called **group delay misalignment**, and it shifts and blurs the image and introduces timbre changes.

For instance, the mismatch of using screen speakers with a waveguide while the surround speakers utilize a shorter waveguide or dome tweeter.

Inter-speaker phase mismatch is related to group delay misalignment. For instance, a 0.1 ms delay at 200 Hz corresponds to a 7° phase shift. Inter-speaker phase mismatches always happen when different speakers are used together.

6.1.3.4   ACHIEVING PHASE CONSISTENCY

The best results will be achieved when speakers with a similar phase response are used throughout the system. As such, using the same speakers all around will provide consistency at all frequencies above the transition (Schroeder) frequency. Unfortunately, however, this is often not practical because different characteristics are commonly needed for different speakers. Examples include:

- High SPL screen speakers
- Compact surround speakers
- Wide dispersion ceiling speakers
- Pre-angled front wide and front height speakers

Most rooms will end up using different speakers with different phase characteristics. As phase characteristics are usually not published, it is difficult to match by design. This is where choosing an electroacoustic optimization system with "rephasing" or "retiming" capability is beneficial.

The way the speakers match, and their placement, will predominantly define the spatial resolution achievable at the RSP. With few speakers and a large listening angle between surround speakers, localization may degrade rapidly when the listener moves away from the RSP. Adding more discretely rendered speakers can broaden the area in which multiple listeners have a similar experience.

6.1.4   SPEAKER MAXIMUM SPL CAPACITY

Speaker and amplifier specifications can be used to loosely predict post-installation system short- and long-term SPL capability within ±3 dB of target levels. These estimates allow for basic engineering where SPL capacity is predicted relative to the challenging dynamics of cinema sound.

The SMPTE commercial cinema standard specifies a calibrated level of 85 dB with peak SPL capability set to 105 dB(C) at a position two-thirds of the way towards the back of the room for screen speakers and 102 dB peaks for all other speakers. Peak SPL capability of the LFE channel is set to 115 dB(C), being 10 dB more than main speaker levels.

6.1.4.1   SPEAKER ACOUSTIC SOURCE AND PROPAGATION LOSS

The SPL at any given seat is influenced by the acoustic source of the speakers, and the resulting propagation loss as the sound spreads over distance. For the purposes of design, it is typical to employ the inverse-square law to predict propagation loss, as if the speakers were operating in free-field space. Speakers can be generalized into one of two types of acoustic sources:

- **Line sources** — These produce a *cylindrical wave* expansion that, when implemented in a true floor-to-ceiling configuration, attenuates at only 3 dB per doubling of distance in free field with virtually no floor or ceiling interaction. However, in practice, speakers may be hybrid in size and function with some vertical dispersion, resulting in somewhere between 3 dB and 6 dB loss per doubling of distance. Line source speakers are typically only suitable for the horizontal listener-level plane.

- **Point sources** — These produce a *spherical wave* expansion that attenuates at 6 dB per doubling of distance in free field. In practice, directivity typically increases with frequency, however, speaker manufacturers can tailor directivity characteristics by using specific drivers (or possibly multiple drivers), waveguides, and crossovers. Point source speakers are suitable for both listener-level and upper layers in immersive audio systems.

In a finished room, the measured steady-state maximum SPL will likely be higher due to the contribution of reflected sounds. A conservative estimate may be obtained by concentrating only on the direct sound and the linear distance from the speaker to the listening position.

> ℹ **Calculation Example: SPL at seating positions based on speaker sensitivity and peak power**
>
> A speaker in the front of a room has a sensitivity of 96 dB (meaning it produces 96 dB SPL at 1 m with a 2.83 Vrms test signal). The RSP is 4 m away, and the last row of seats is 8 m away. If the speaker can handle a 500 watt peak power without audible distortion, dynamic compression, or failure, the calculation for predicting the maximum SPL capacity would be as follows:
>
> i. 500 watts is approximately a 9-step doubling sequence (2 to the power of 9, or 2^9) from 1 watt. 9 x 3 (dB increase per doubling of power) = **27 dBW** (dB relative to 1 W into an 8 Ω load)
>
> ii. Therefore, 96 dB SPL at 1 watt (speaker sensitivity) + 27 dBW of power beyond 1 watt = **123 dB SPL of peak sound at 1m** for that speaker
>
> iii. Doubling the distance to 2 m loses 6 dB due to propagation loss, and doubling again to 4 m loses another 6 dB, meaning **12 dB loss** at 4 meters.
>
> iv. The maximum peak SPL at 4 meters would be 123 - 12 = **111 dB at the RSP**. This would provide 6 dB of headroom over the 105 dB peak reference level.
>
> v. Another doubling of distance to 8m results in a maximum peak SPL of **105 dB at the back row**.

The Performance Level parameters for recommended SPL capability for residential spaces are tabled below. These should be considered post-calibration/EQ (see).

PERFORMANCE LEVELS — DYNAMICS

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/ Seat
12. Screen Speakers SPL capability at RSP (post calibration EQ, within assigned bandwidth) without clipping	dB SPL (C)	Min.	99	102	105	108	Room
		Rec.	102	105	108	111	
13. Non-screen Speakers SPL capability at RSP (post calibration EQ within assigned bandwidth) without clipping (includes amplifier headroom)	dB SPL (C)	Min.	96	99	102	105	Room
		Rec.	99	102	105	108	

Sound Pressure Level at the Reference Seating Position is the recommended minimum long term SPL according to AES75-2022 or ANSI-CTA-2034-A, Section 8. Consideration should be given to the following:
1. Additional speaker SPL capability at bass frequencies to allow for bass contours
2. Additional speaker SPL capability to allow for +EQ

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/ Seat
14. LFE frequencies total SPL capability at RSP, plus bass management if used (post calibration EQ, within bass extension spec for the level) without clipping (includes amplifier headroom)	dB SPL (C)	Min.	109	112	115	118	Room
		Rec.	114	117	120	123	

Total system SPL capability at LFE frequencies for speakers and/or subwoofers. Can include room/boundary gain and gain resulting from summing multiple speakers/subwoofers acting as one virtual subwoofer.

6.1.4.2 LOW-FREQUENCY SPL ADDITIONAL CONSIDERATIONS

At low frequencies, the following should be taken into consideration:

- Room dimensions and volume have more impact at low frequencies where room modes dominate.

- Where multiple subwoofers are used for the **LFE channel only**, the required peak SPL capability is achieved by the combined output of all subwoofers. The additional SPL capability provided by multiple subwoofers depends on the system and room design, but is typically +10 dB per 1/3 octave band across the LFE operating range (nominally 20 - 120 Hz).

- Where subwoofers are used for combined **LFE + bass management** (see Section 7.3.2.3), additional SPL capability will be required, typically an extra (approximately) 4 dB of SPL.

- If a bass contour is part of the target frequency response, consideration should be given to ensure that the SPL capacity of both subwoofer(s) and all other speakers is adequate.

For example, in a system targeting reference 105 dB, the LFE needs to target 115 dB. When bass management is employed, this increases another 4 dB to 119 dB. However, with a 10 dB bass contour this becomes 129 dB total for the subwoofers and 110 dB for the speakers (in the bass region, depending on crossover settings). Therefore, the SPL capability of the speakers and subwoofers at bass frequencies is likely greater than may be initially calculated.

SECTION

7

SUBWOOFERS AND LOW-FREQUENCY ROOM OPTIMIZATION

7.1 LOW-FREQUENCY ROOM OPTIMIZATION OBJECTIVE

The primary objective with low frequency audio reproduction in a room is for the overall level of bass and its frequency response to be consistent across all seats, with no audible resonances. This should be achievable without a large loss of efficiency.

In this context, **optimization** specifically refers to the reduction of seat-to-seat variation in the magnitude of the frequency response from 20-80 Hz, as reproduced by the subwoofers. Making the frequency response relatively flat or achieving a couple of extra decibels of bass output are not directly included in this definition of optimization, though these goals may be achieved during the optimization process or should be easier to achieve once the system is optimized.

7.2 ROOM MODES

Room modes (standing waves) are determined by the dimensions and shape of the room. These resonant frequencies create significant differences in amplitude for the same frequency at different locations in the room, often by as much as 20 dB or higher. All modes peak at the room boundaries, with nulls and peaks distributed throughout the room, based on the mode order, being multiples of the fundamental mode. In cuboid rooms with parallel walls, the positions of the room modes can be predicted with a fairly high degree of accuracy based on the distance between two walls and the speed of sound. Wall construction, doors, windows, seating risers, etc., will each impact the exact location and frequency of the room modes.

Given the large differences in frequency response across the listening area, and the goal of achieving a smooth and consistent seat-to-seat response, some EQ will be necessary. However, without an optimized design defining seating and subwoofer placement, EQ may not achieve positive results for all seating locations.
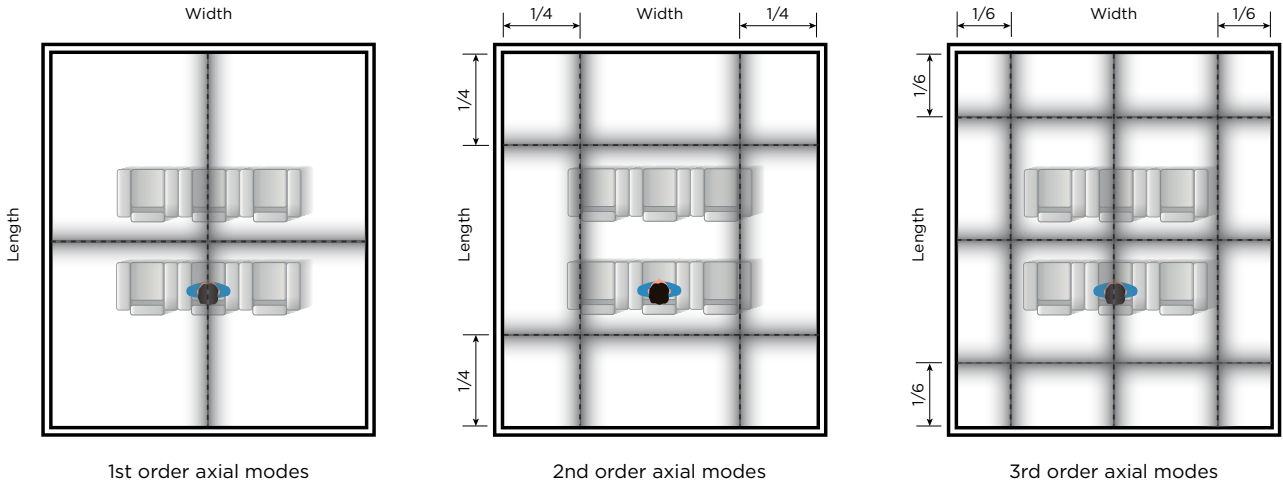
Figure 7-1: Approximate depiction of 1st, 2nd, and 3rd order axial room modes centered on the dashed lines and diminishing through the shaded areas (each within approximately 450mm [18"] of the modal lines).

7.3 ROOM OPTIMIZATION APPROACHES

Two approaches, used in combination, can achieve optimal low frequency performance in a room:

- **Dimensional Optimization** — working with or specifying room dimensions to lessen the impact of room modes.
- **Positional Optimization** — using multiple subwoofers in specific arrangements and applied in conjunction with bass management to improve seat-to-seat consistency.

While it is preferred that all aspects of the system — room dimensions, seating locations, subwoofer location(s) — be specified by the designer to optimize low frequency performance, even if one starts with a fixed value for some parameters, the choices for the others may be optimized. For example, if room dimensions are fixed, an optimized setup of subwoofers and seating area may be chosen. If both the room dimensions and seating locations are fixed, it may still be possible to optimize the subwoofer layout/positioning. Conversely, if the room dimensions and subwoofer locations are fixed, the seating layout may be adjusted to minimize the effect of room modes to improve seat-to-seat consistency.

There are several factors to consider when selecting an optimization approach, as outlined in table 7-1. This provides suggestions for optimization in various cases, the most relevant for which involve multiple subwoofers in a small (residential) room with multiple seats.

Table 7-1: Optimization procedure selection criteria

Case	Recommended Optimization Procedure	
	Rectangular Room	Non-Rectangular Room
Large room. Large rooms, such as auditoriums, cinemas, etc., likely do not need to be optimized. Even at low frequencies there will be a large number of active room modes, effectively smoothing out the response across the seating area.	None	
Only one subwoofer in room with multiple seats. In this case, optimization options are limited. In a rectangular room, the midpoint of the front wall or quarter-point on a side wall are good subwoofer locations to start with.	**Positional Optimization** Expected result: slight to moderate improvement	Trial and Error Expected result: slight to moderate improvement
Room with multiple subwoofers, room dimensions and seating area not known. For example, a room is not exactly dimensioned yet but subwoofers need to be located.	**Positional Optimization** Expected result: moderate improvement	None

Case (continued)	Recommended Optimization Procedure	
	Rectangular Room	Non-Rectangular Room
Room with multiple subwoofers, room dimensions are known or (preferably) can be specified.	**Positional + Dimensional Optimization** Expected result: moderate to considerable improvement	None
Room with multiple subwoofers, impulse response measurements from each subwoofer to each listening location are available, and any of the following apply: • Subwoofer locations flexible • Individual subwoofer level can be adjusted • Individual subwoofer delay can be adjusted • Individual subwoofer filtering available	**Advanced Optimization** Expected result: Excellent improvement	

7.3.1   DIMENSIONAL OPTIMIZATION

The idea of optimizing room dimensions for audio has been around for a long time. The influence of the ratio of room dimensions upon the frequency distribution of room modes has been extensively studied. EVERY room will have room modes. There are, however, certain ratios of the room's length, width, and height that spread the modes apart to minimize issues at specific frequencies and given seating locations.

If the system designer has the freedom to choose the room size and dimension ratios, it is prudent to consider the modal response of the chosen dimensions. While many different models have been developed to identify an idealized room ratio (the so-called "golden ratio") they are often not applicable due to the many variables that occur between projects. The final outcome of precisely how the low frequencies respond in a space is affected by multiple factors including room volume, number of subwoofers and respective locations, and the materials and methodology of construction that determines wall impedance to bass frequencies.

Although no perfect ratio can be universally relied upon, as a general recommendation, it has been found that a length-to-width ratio within 1.15-1.45:1 will typically achieve a reasonable spacing of room mode frequencies, which may then be further improved by additional bass optimization/management techniques. The height can be chosen more freely without compromising the acoustical quality. Width-to-height ratios should be greater than 1.1:1 while avoiding integer multiples of the width and height (for instance, 1:1, 2:1, etc.).

If non-optimum room ratios are unavoidable, a more advanced combination of subwoofer number, subwoofer positioning, and electro-acoustic optimization can partially mitigate many negative outcomes.

Non-rectangular rooms are extremely difficult to model, so rules-based recommendations are impossible.

One may assume that all room modes have the same impact on audience experience, whereas, in reality, some modes will be a factor and some not, depending on where the subwoofers and seats are located. Additionally, dimensional optimization is aimed at achieving a flat frequency response (without using equalization) and not optimizing seat-to-seat variation, but the latter is the goal here. As such, dimensional optimization is much more effective when used in combination with positional optimization.

The overall performance at bass frequencies is a combination of:

1. Room volume
2. Room proportions
3. Listener location(s)
4. Subwoofer quantity
5. Subwoofer location(s)
6. Absorption at bass frequencies
7. Electro-acoustic optimization of all speaker feeds reproducing bass

7.3.2   POSITIONAL OPTIMIZATION

Due to room modes, seat-to-seat differences will remain unless multiple subwoofers are employed in specific arrangements to smoothen the standing wave patterns and allow subsequent equalization to be more effective. Once the seating layout has been designed with consideration given to avoiding room modes, then *positional optimization* refers to a method of choosing optimal locations for subwoofers in rectangular rooms, relative to room proportions.

7.3.2.1   MULTIPLE SUBWOOFERS

Systematic research[3] suggests that configurations with symmetrical subwoofer layouts composed of two or four subwoofers are preferable when the seating area is in the center of the room (preferred) or between the center and rear of the room, and with the subwoofers located near or in the walls. Furthermore, configurations where the subwoofers are located at wall midpoints tend to work best. With positional optimization, even rooms where one dimension is an integer multiple of the other (often maligned in the past) can be successfully optimized.

Seven arrangements of 2 or 4 subwoofers are shown in figure 7-2, applying to a rectangular room. The configurations are ranked in descending order from best (a) to good (g) for multiple seating locations, by which four subwoofers are generally preferred over two.
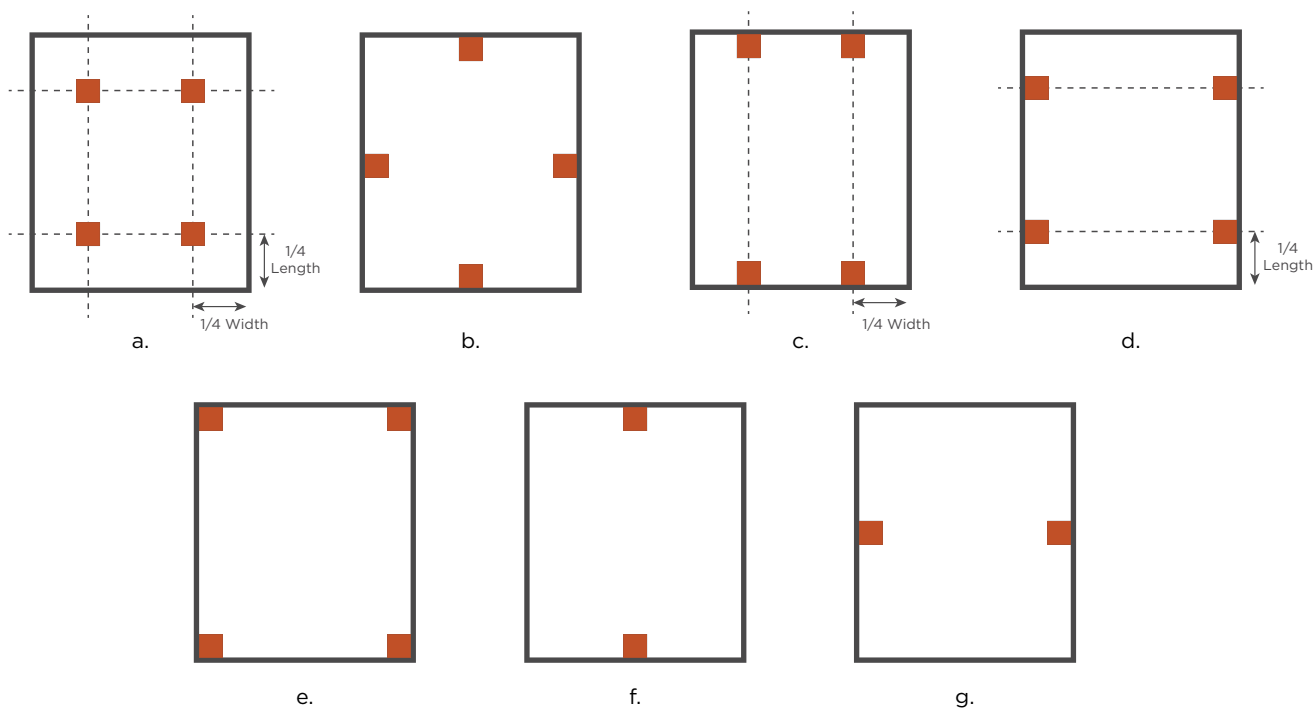
Figure 7-2: Arrangements of two or four identical subwoofers, driven by the same signal, that generally give optimal results for multiple seating locations in rectangular rooms.

- Configuration (a) requires subwoofers to be located away from the walls, possibly in or on the ceiling. Though likely not practical, this option is included because it provides almost perfectly flat and consistent bass throughout most of the room.

- Configuration (b) exhibits the lowest seat-to-seat variation of all the boundary placement options.

- All others, particularly (c) and (d), give good combinations of bass efficiency and seat-to-seat variance.

- Configuration (e) tends to produce slightly higher low-frequency output levels (higher efficiency) than the others, typically in the order of 1 – 3 dB increase due to corner loading.

- Configurations (f) and (g) require approximately double the individual subwoofer's output capacity at each location to approach the sound levels of the other configurations shown. However, placing double subwoofers (two of the same subwoofer side-by-side) at the mid-wall positions in these locations can result in acoustical output comparable to that of arrangement (e).

Keep in mind that these configurations are not guaranteed to work better in every case, but they produce more seat-to-seat consistency, on average.

The subwoofers should typically be identical, mounted similarly with respect to the room boundaries, connected in the same polarity and set to the same output levels. Subwoofers are assumed to be on the floor. In-wall subwoofers located above floor level should work similarly, assuming they are each at the same height.

Note that, in this context, a rectangular room is assumed to have reasonably similar wall construction for all four walls. For example, a room with brick construction on one wall and single layer gypsum board on the other walls may not behave as a symmetrical rectangular room, or may behave as a rectangular room with dimensions moderately different than its actual physical dimensions.

A caveat also applies in that positional optimization results for a room with seats on risers may be somewhat unpredictable — this case has not yet been systematically investigated.

7.3.2.2 ALTERNATIVE SUBWOOFER LOCATIONS

Subwoofers may be placed at locations other than at the outer boundary of the room and at floor level. In a rectangular room with no seat risers, it is assumed that moving the subwoofers vertically would affect only the height modes (as opposed to width and length room modes), which to a first approximation should not cause seat-to-seat variation if the ear height is the same over the seating area. However, in real, non-ideal rooms, this may not be the case.

Unfortunately, adding another degree of freedom in subwoofer placement greatly increases the complexity of the problem. At this time, a systematic survey including subwoofer height and possibly in-ceiling locations has not been performed, however there is anecdotal evidence that such configurations can be useful.

7.3.2.3 BASS MANAGEMENT

The use of full-range speakers at the front and surround locations is generally not the best way to deliver uniform bass to multiple listeners, but neither is a single subwoofer. Optimum bass uniformity is achievable when the low frequencies from ALL speaker feeds are combined through bass management, together with the LFE signal, and delivered equally to multiple subwoofers arranged in specific patterns, as described in Section 7.3.2.1. If the signals going to various subwoofers are different, then optimization will be virtually impossible.

7.3.3 ADVANCED OPTIMIZATION

Some advanced methods including double bass arrays (DBAs) and other active acoustic technologies for addressing room modes are emerging and may be included in future revisions of this document.

Other, more sophisticated methods based on detailed measurements in built rooms are also possible. These methods are not constrained to rectangular rooms, and include electronic modification of the audio signal to each subwoofer. This type of optimization is by far the most powerful, but requires a built room and measured responses from each subwoofer to each seat.

Finally, rooms may be modeled using acoustical modeling software. This is very labor intensive and expensive, but does not require a built room or measurements. Also, obtaining accurate acoustical impedance values for room boundaries may be difficult.

Additional resources are provided in Appendix B.1.

7.4   ROOM OPTIMIZATION PROCESS

1. **In the most general case where room dimensions and seating area are not known and cannot be influenced, select a preferred subwoofer layout** (Section 7.3.2.1). Otherwise, proceed to point 2.

2. **Select optimal combination of subwoofer layout, seating area, and room dimensions. If any one or two of these are fixed, select best options for the other.**

3. **Modest damping of low-frequency room resonances is always desirable.**

   This may be achieved by using certain forms of wall construction, but only if it does not interfere with requirements for sound isolation. For example, a wall with high transmission loss tends to be massive and stiff, and as such will absorb less acoustical energy within the room. Consider the use of specially constructed low-frequency absorbers in appropriate locations to dampen low-frequency sound waves.

4. **Choose designs that allow further optimization during calibration.**

   Designs that allow control of individual subwoofer level and delay are particularly helpful in optimizing any acoustical space. Judicious variation of levels and delays between multiple subwoofers can reduce audibility of resonances. Free and commercially available software may be utilized to allow this type of optimization.

5. **Include a high-resolution parametric equalizer in the design, dedicated to the main subwoofer feed.** See Section 11: Calibration of Electro-acoustics.

   The equalizer should be able to place the filter's center frequency with a resolution of 2 Hz or better, and have at least six independently adjustable filters. Separate equalization channels for each subwoofer can also be useful. Final equalization should be made at the RSP with all subwoofers operating simultaneously.

The objective is to place the subwoofers so that they do not couple excessively into any room mode that causes variation in sound levels in the seating area, and/or place the seats so that they do not sit in the dips of any modes. The accuracy of this approach may be affected by factors that are not accounted for in simple modal calculators, such as non-ideal wall construction, or low-frequency absorption from upholstered furniture. If the space is substantially non-rectangular, it is much more difficult to optimize, however following steps 1-5 above is still recommended.

7.5 | LOW-FREQUENCY RESPONSE RESULT

Low-frequency room optimization, both physical and electroacoustic, should apply from the room's transition (Schroeder) frequency down to the lower limit (-3 dB cut-off point) enabled by the subwoofers. The goal of optimization is to achieve extended and smooth bass reproduction with good seat-to-seat consistency. This should be subject to final calibration — see Section 11.

PERFORMANCE LEVELS — LOW FREQUENCY RESPONSE

Parameter	Unit	Target		Level 1	Level 2	Level 3	Level 4	Room/ Seat
18. In-room bass extension -3 dB cut off frequency point	Hz	Min.		35	30	20	18	Room
		Rec.		30	25	18	15	
In-room predicted -3dB bass extension frequency with no perceptible distortion or audible mechanical resonances (e.g., rattles) at the specified minimum SPL according to performance parameter 14 (LFE frequencies total SPL capability at RSP). To include speaker coupling, boundary and room gain.								
19. Frequency response below the room's transition frequency at the RSP relative to target curve (1/3 octave smoothing). "The Result"	± dB	Max.		5	4	3	2	Seat
Predicts a smooth frequency response at the RSP, relative to a predetermined target curve.								
20. Seat-to-seat frequency response relative to measured RSP response below the room's transition frequency per seat (1/3 octave smoothing). "The Consistency"	± dB	Max.		N/A	4	3	2	Seat
Predicts how similar the experience and performance level will be across multiple seats.								

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SECTION

8

SOUND ISOLATION

8.1   SOUND TRANSMISSION RATINGS

Achieving **sound isolation** is to provide an effective acoustic barrier to block sounds from passing between adjacent spaces. It is required for two purposes:

1. To prevent external noise from compromising the carefully engineered low background levels in the listening space.
2. To prevent high sound levels inside the listening space from being audible in adjacent spaces.

Quiet passages in a movie, such the rusting of leaves or a quiet whisper can measure 30 dB or less, whereas the interior of a home in a quiet neighborhood may typically be around 50 dB, and the use of some household appliances can push that to 80 dB or more. If there isn't sound isolation in the home entertainment space, there will always be a risk of sounds from other rooms or outside penetrating the space and collapsing a listener's *suspension of disbelief*.

The lower the noise floor in the entertainment space, the larger the acoustic dynamic range the space will achieve. The level of sound isolation required is then based on whichever is deemed more important — the quality of dynamic sound in the space, or sensitivity of sound to adjacent spaces. In some cases, a legal planning requirement will set out a maximum noise level that can be transmitted to an adjoining property; for example, a basement conversion in a London street.

The main point to be aware of for reference level sound isolation is dedication to detail. There absolutely must not be any weaknesses left in the design or implementation.

Recording studio designers refer to a phenomenon they call the "keyhole effect." This occurs when a recording studio is impeccably built with impeccably verified performance, only for complaints to be received a short time after handover that external noises can be heard from within. Upon investigation, the cause is found to be a locksmith having been brought in to put a keyhole through the door, the point being that sounds will come through any small gap and be heard.

8.1.1   SOUND ISOLATION MEASUREMENTS

The materials and components used to achieve isolation are popularly referred to as "soundproofing," but may more accurately be considered *sound reduction* as they typically reduce sound transmission but not block it completely. How much such apparatuses can reduce sound transmission is measured as **transmission loss (TL)** at any given frequency, expressed in decibels (dB). However, to quantify sound reduction performance across a range of frequencies, there are two indices commonly in use:

- **Sound Transmission Class (STC)** — US scale standardized by ASTM E413, STC is a single integer number to rate transmission loss, measured in 1/3 octaves or full octaves from 125 Hz – 4 kHz, weighted around a center frequency of 500 Hz.

- **Sound Reduction Index (SRI)** — standardized globally under ISO 10140 (formerly ISO 140), SRI is a single integer number resulting from A-weighted measurements at 1/3rd octaves from 100 Hz to 3,150 Hz and logarithmically calculated to generate a single figure denoted by the value R_w (R for reduction, w for weighted).
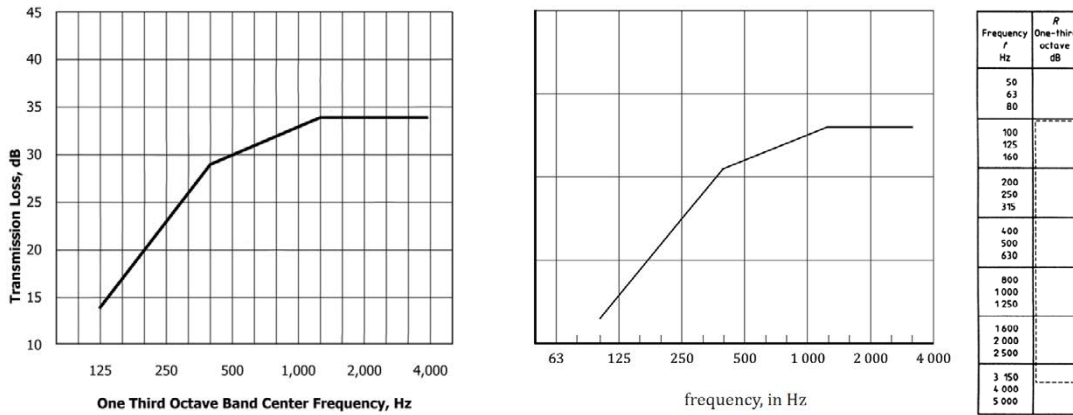
Figure 8-1: STC reference curve (left) based on ATSM E413, compared to SRI reference curve (right) based on ISO 10140

R_w 35

f, Hz	R ,dB
50+	25.9
63+	18.0
80+	17.8
100	25.8
125	28.7
160	31.2
200	27.9
250	31.6
315	30.3
400	31.4
500	33.9
630	34.0
800	34.4
1000	34.1
1250	33.4
1600	33.7
2000	34.6
2500	36.4
3150	38.8
4000	40.2
5000	40.2
AAD	-30.9

Frequency range for rating in accordance with ISO 717-1

Rating Curve (ISO 717-1)

Sound Reduction Index, R, in dB

R_w 41

f, Hz	R ,dB
50+	20.5
63+	19.1
80+	18.0
100	24.5
125	30.9
160	31.2
200	32.9
250	34.7
315	35.8
400	36.7
500	38.3
600	37.9
800	39.9
1000	41.6
1250	41.1
1600	42.0
2000	42.4
2500	43.1
3150	45.0
4000	45.5
5000	44.3
AAD	-28.0

Frequency range for rating in accordance with ISO 717-1

Figure 8-2: Examples of two doorsets with very different R_w but comparable bass (≤ 160 Hz) reduction [4]

Figure 8-1 shows the transmission loss reference curve for both standards, from which the single integer index is derived. The reason the curves start low and rise with frequency is because the longer, more powerful wavelengths of bass frequencies are harder to block than the much shorter wavelength, relatively lower power high frequencies. In practice, even though the frequency range and weighting of the STC and SRI indices differ, the resulting STC or R_w value may be the same for some products or may differ by several decibels.

Figure 8-2 shows an example of measured results using the SRI standard for two single-leaf doorsets with very different R_w ratings (35 vs. 41). Deviations above the curve indicate better sound reduction at those frequencies, while below the line indicate lower than reference relative reductions. However, observing the corresponding measurement chart for each shows these two samples to be similar in the sub-160 Hz range, if not slightly better for the lower R_w sample!

Immersive audio systems will deliver large amounts of bass energy, so understanding the TL measurements in this range is very important. As the single STC or R_w value may not necessarily reflect this, it may be an unreliable indicator when designing the overall sound isolation requirements. When considering products, the full range of TL measurements at every 1/3 octave (or full octave) frequency is more informative.

When the room is complete, the airborne sound insulation properties of the finished building elements can be measured for the sound level difference between adjacent spaces. This is determined as a *weighted standardized level difference*, denoted by $D_{nT,w}$ (where D is for difference).

> *Application example — if a room achieves a rating of 45 dB $D_{nT,w}$ then a sound level of 85 dB*
> *in the home entertainment space will result in it being heard in the adjoining room at 40 dB.*

These measurements involve generating a sound in the source room, then measuring the level simultaneously in both rooms. This is performed multiple times across the 1/3rd octave bands at multiple locations. The ISO 16283-1 standard describes this process of measurement, and ISO 717-1 describes the calculations to reach the weighted standardized value. Importantly, it is generally regarded that $D_{nT,w}$ will be approximately 4 - 6 dB lower than R_w values due to the inherent realities of measuring completed building elements onsite compared to measuring products in lab conditions.

8.2 BUILDING CONSTRUCTION ISOLATION LEVELS

Wall, ceiling, and floor construction techniques are discussed in Appendix D. The results they combine to achieve can be considered in any of five isolation levels. Building products will typically have acoustic properties measured using STC and/or SRI values on which the designer can determine suitability, but using the same index across a complete design is advisable.

Standard Construction

Typical, non-acoustically rated construction is adequate for rooms adjacent to the entertainment space where the noise level is low, and the adjacent room is not noise sensitive. This would be appropriate for rooms such as storage rooms, hallways, basements (assuming no loud machinery operating), etc.

Typical STC or R_w is 34.

Isolation Level 1

This is recommended for rooms adjacent to the entertainment space where the noise level is moderate, or the adjacent room is moderately noise sensitive. This is the typical situation, and includes rooms such as kitchens, dining rooms, etc.

Typical STC or R_w is 52.

Isolation Level 2

This is recommended for rooms adjacent to the entertainment space where the noise level may be significant, or any adjacent rooms are noise sensitive. This is also a typical situation, and includes rooms such as living rooms, dining rooms, bedrooms, etc.

Typical STC or R_w is 60.

Isolation Level 3

This is recommended for rooms adjacent to the entertainment space where the noise level is high, or the adjacent room is very noise sensitive. This would include the need to reduce noise transmission *into* rooms such as bedrooms, or *from* spaces like gaming rooms, kids' playrooms, etc. Note that extreme measures may be required if very noisy areas, such as a shop area, are located next to the home entertainment space. Special care should be used for rooms with exterior exposure to traffic, airports, railway lines, night clubs, concert venues, or other sources of high-level noise. The services of a competent acoustical consultant are recommended in such cases.

Typical STC or R_w is 70.

Isolation Level 4

This is recommended for Level 3 or 4 entertainment spaces. It should be a floating room-within-a-room design (see Appendix D). All mechanical and electrical services have to be silenced, all penetrations sealed with acoustic sealant, and absolutely no rigid connection between the inner and outer layer. A video projector system should be external to the space and use a specially designed projection porthole. The services of a competent acoustical consultant are mandatory in such cases.

Typical STC or R_w is 80.

> **ℹ Application Example: Determining target sound isolation level**
>
> An entertainment space is targeting a noise floor of 24 dB and the designer is referencing STC values. Sounds from outside the space are expected to reach around 80 dB (vacuum cleaner, coffee grinder, outside traffic, etc.). According to the methods described in this section, the room would need to achieve a $D_{nT,w}$ of 56 (80 minus 24), equating to an STC of approximately 60, being isolation level 2.
>
> On the other hand, if the goal is to only be able to hear the sound from the entertainment space minimally from noise sensitive adjacent spaces, the isolation requirements will typically be higher. For instance, if the entertainment space contains a Performance Level 2 system that can achieve 105 dB SPL, then hearing it at, say, 40 dB (average across the frequency range) from the next room would require a $D_{nT,w}$ of 65. This equates to an STC of around 70, being isolation level 3. However, consistent with the STC reference curve, bass transmission would still be relatively prevalent, requiring isolation level 4 to reduce further.

8.3   ISOLATION GUIDELINES

Use appropriate door construction and installation

All doors into the entertainment space should be a minimum 45 mm (1 ¾ in.) solid core door with rubber weather stripping and sealed thresholds. It is recommended to use specialty acoustic door thresholds, astragals, and sound sealing around the entire jam.

It should be noted that a door alone cannot be rated for sound reduction; it must be a doorset. That means the complete assembly comprising door, frame, seals, and threshold. It is always advisable to purchase a doorset that is acoustically rated to meet the target. The seals on a door can quickly wear with age, so attention should be given to how the manufacturer has designed and constructed the seal.

A communicating doorset (two interfacing doors with an air gap in-between) is always far more effective than a single door. It is advisable to design for such a door from the start. Better still, the use of a lobby area that has no direct acoustic path between doors will increase the transmission loss effectiveness. A further benefit is that each door can be rated slightly lower. Ensure the lobby space is well damped acoustically.

For an STC/SRI 75 class wall, an acoustically rated door with a transmission loss (TL) effectiveness of 40 dB or more at 125 Hz is recommended. Products rated using an independent accredited acoustical testing laboratory are preferred.
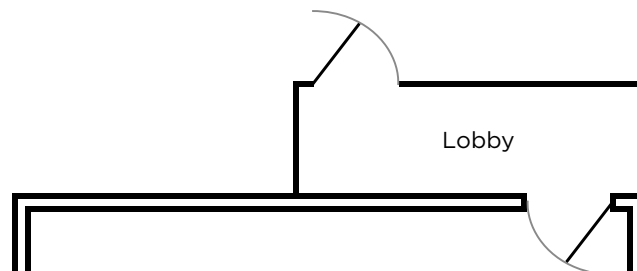
Figure 8-3: Constructing a lobby as an entrance to a home entertainment space using an anteroom and two 45mm (1 ³/4 in.) solid core doors instead of a single STC-62 rated acoustical door

Use appropriate windows

The windows should all be of sufficient minimum rating to meet the sound isolation requirements of the room and wall class, with STC/SRI 60 for typical applications. If windows are required in an STC 75 class wall (try to avoid this), they should be acoustically rated with a minimum of STC/SRI 58, preferably with a TL of 40 dB or more at 125 Hz. Products rated using an independent accredited acoustical testing laboratory are preferred. This guideline assumes small windows; large windows will need to meet the target STC rating for the finished wall. Consult with an acoustician to calculate the overall loss to ensure the design of the space is not being compromised.

Acoustic double glazing uses a larger spacing than thermal double glazing — always use acoustically rated glazing frame sets.

Completely caulk and seal all joints in any common wall(s)
Avoid oversizing penetrations and use specialty acoustic seals/sealant.

Prevent penetrations from contacting the gypsum board
Any penetrations through the walls by electrical outlets, wire penetrations, HVAC ducts or plumbing should provide a 6 mm (¼ in.) gap around the penetration to decouple it from the plasterboard. The resulting gaps should then be thoroughly sealed with a 50-year flexible caulking material.

Control break-in noise from exposed HVAC ducts
Enclose exposed ducts or add silencer units before the supply register in the room. Silencers on common ductwork is essential. Use of half round duct where noise can break into or out of a duct may be required. Refer to the 2019 ASHRAE Handbook — HVAC Applications, Chapter 49 for TL data on half round duct, and ISO 14163:1998 Acoustics — Guidelines for noise control by silencers.

Control flanking paths between adjacent rooms
A flanking path is a noise path created by gaps and cracks in and around building elements. Failure to mitigate even one significant flanking path can negate all other sound isolating efforts.

1. Direct transmission as measured in a lab test
2. Flanking noise via flanking walls or conduit/piping
3. Flanking noise via duct work etc
4. Flanking noise via ceiling void
5. Flanking noise via flooring void or concrete slab
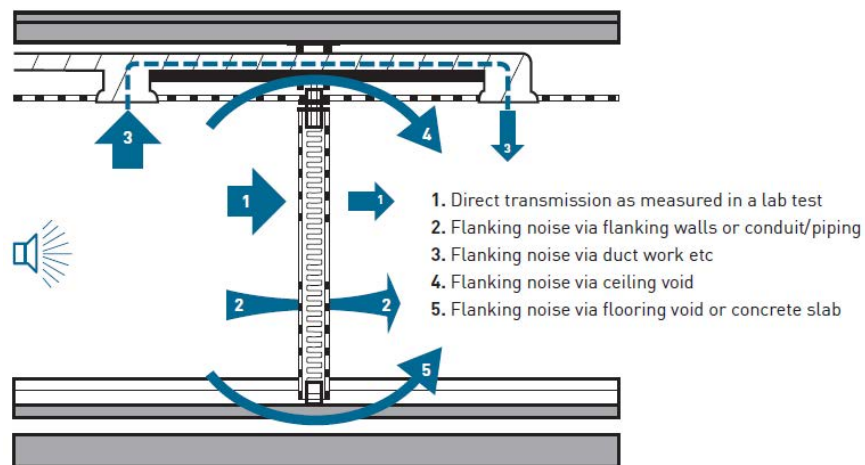
Figure 8-4: Flanking paths [5]

Flanking paths can be:

- **Electrical outlets**
  Where outlets are located on both sides of a wall, stagger their location by at least one stud width so that they are not opposite each other. Seal/caulk outlets and boxes as codes allow.

- **Gaps in walls, ceiling, floor structure and/or ventilation systems**
  Seal all gaps with acoustically rated resilient caulking or other approved material.

- **Ductwork**
  Ducts with a direct path from the entertainment space to an adjacent room or any room with expected high noise levels should include mitigation such as a silencer, duct lining and multiple 90-degree turns, lined plenum (ventilation void), or other approved technique — refer to CEA/CEDIA-CEB24: Home Theater HVAC or the 2019 ASHRAE Handbook — HVAC Applications, Chapter 49.

8.4 GUIDELINES FOR AVOIDING MECHANICAL NOISE

There should be no audible rattles in the room. Any audible vibrations should be damped. Examples of sources of rattles include:

- Metal lath wire used to suspend building elements
- Electrical wiring, conduit, screen frame, and mounting hardware
- Improperly suspended gypsum board
- Storage of loose material within the room
- HVAC diffusers and grilles
- Light fixtures, furniture, equipment cabinets, in-room bars, etc.
- Cabinet doors

Use oversized ducts
HVAC ducts to the room should be oversized to allow for low noise levels. Flex duct may be used where break in/out noise (the noise that penetrates the walls a duct) is not an issue. Sound attenuators (silencer/muffler) need to be used to avoid sound transmission from other rooms and the fan system into the room.

There should not be a concentration of noise energy at any one frequency
Fan motors are tonal. Sound attenuators should be optimised to remove these frequencies.

Light dimmers and luminaires should be specified for low noise
Use dimmers that prevent the steeply chopped sine waveforms (as exhibited by less expensive units). Many LED lights use switch-mode power supplies, so care should be taken to use only low-noise units. Fluorescent and neon lighting can cause noise problems and should be implemented with extreme caution.

Acoustically treat plumbing in the surrounding area
Any plumbing within the walls, ceilings or floor of the room should be acoustically treated to prevent noises or vibrations being audible in the room or mechanically transmitted into the room spaces.

Any portion of plumbing pipe passing through room walls/ceilings/floors should be wrapped with an appropriate noise barrier material.

Piping through the room spaces should be resiliently decoupled from the structure. Pressure regulators and check valves should be of the silent operating design.

Isolate sump or lift pumps
Sump or lift pumps should be installed on isolators, and care should be taken to ensure proper balance of the pump impeller.

Isolate mechanical and HVAC equipment
Any mechanical equipment or HVAC equipment near the room should not have contact with common walls, floor or ceiling elements common to the room and should be resiliently suspended. Mechanical equipment sharing a common floor with the room should be mounted on resilient isolation pads with static deflection appropriate to the load.

Isolate structural noise

Noise transmitted through the building structure (walls, floors, etc.) should be controlled by isolating the noise source on appropriate shock mounts. Additionally, a break in the structure between the noisy device and the room boundaries is highly recommended.

Hinges and chairs should not generate squeak or other noises.

8.5   BACKGROUND NOISE OBJECTIVES

Background noise should be measured using the Noise Criteria, balanced (NCB) method, as described by the ANSI S12.2-2008 standard, *Criteria for Evaluating Room Noise*. The 2019 ASHRAE Handbook — HVAC Applications, chapter 49 references the ANSI standard and describes NCB as being "used to specify or evaluate room noise, including that from occupant activities, ... is based on the speech interference level (SIL) [500 - 4,000 Hz], ... with additional tests for rumble and hiss compliance."

The recommended and maximum levels of background noise should not exceed the NCB ratings as tabled below for each respective Performance Level.

PERFORMANCE LEVELS — SOUND ISOLATION

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
15. Background noise floor with all AV equipment and mechanical systems and building services switched on, at nominal operating temperatures	NCB rating	Max.	35	26	22	18	Room
		Rec.	26	22	18	15	
Noise floor indicates the level of general noise in the background — that which is discernible with all systems running (including HVAC) during regular operation of the entertainment space but while no multimedia content is being played (for instance, on pause or menu).							

A graphical depiction of NCB curves is provided in Appendix C.2.

Quick in-room measurements can be made with an SPL meter capable of measuring dB(A) to provide an indication of the noise in a space, but NCB is recommended as the final metric. However, if a noise criterion method other than NCB is preferred, it may also be acceptable with the following conditions:

- The criterion used can provide a comparable indication that the sound isolation objectives are being met across the frequency range of typical household noises (including HVAC systems, speech, general appliances, external sounds, etc).

- The method and findings are appropriately documented.

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9

ROOM ACOUSTICAL DESIGN

9.1   ACOUSTICAL TREATMENT OVERVIEW

Interior acoustical treatments provide an environment for the optimal reproduction of stereo and multichannel audio content, as well as for relaxed conversation. Acoustical treatments affect sound within a room rather than being intended to isolate a room from external sound. Their use is guided by two parallel requirements:

1. To deliver a clear direct sound that is well defined in the time domain. That is, a high direct-to-reflected (D/R) sound ratio.

2. To deliver a uniform **reflection decay time** (RdT) across the audible frequency range.

9.1.1   REVERBERATION TIME AND REFLECTION DECAY TIME

Traditionally, the first concern in room acoustics is to achieve a suitable reverberation time (RT). The standard measure for this is RT60 — the time it takes for sound to decay by 60 dB in a diffusive room after the sound source ceases. Large rooms such as performance halls and auditoriums are highly diffusive reverberant fields. However, residential spaces are too small to be reverberant fields, with increased prevalence of reflected sounds in relation to direct sounds. As such, in small rooms it is more useful to consider the **reflection decay time** (RdT).

The RdT is primarily determined by the amount of absorbing material in the room, its effectiveness, and where it is placed. A secondary influence is the amount of scattering or diffusion of sound that is caused by large objects in the room, such as chairs and tables, by ornamental surface irregularities on walls and ceilings, and by manufactured devices created for that purpose.

In a private entertainment space, the goal should be to control RdT and early reflections across the frequency range of approximately 32 Hz to 8 kHz, and the absorption used should be balanced across the audible range. While RdT will usually be greater at low frequencies, the aim is to keep its incline as linear and smooth as possible.

In general, RdT should be kept low enough to ensure that voice intelligibility is not impaired, balanced against the need for some reflections to create the requisite sense of space. If RdT is too low, the room will sound artificially muffled and "dead," making it uncomfortable to spend time in. A common outcome of this situation is poor integration of the front and surround sound fields, and a generally uninvolving experience. A longstanding guideline is to target RdT (RT60) between 0.2 - 0.5 seconds, but high channel count systems might benefit from being slightly lower again, for pinpoint localization.

An example of poor acoustic treatment design is the use of thin absorptive material (such as 20mm or 1 in. foam or fiberglass) across too much surface area within the space, placed behind acoustically transparent fabric. This approach will overly absorb upper midrange and high frequency reflections, but have little effect on frequencies below approximately 1.5 kHz. The result is an unbalanced sound that provides a poor experience for both audio reproduction and general conversation. Additionally, this can also lead to post-calibration equipment damage as attempts to electronically compensate for the loss of high frequencies can lead to overdriven tweeters.

9.1.1.1 REFLECTION DECAY TIME OBJECTIVES

The target for RdT is dependent on room volume. As room volume increases, target RdT times also increase. The formula for calculating the target RdT dependent on room volume is:

$$Tm = 0.3 \, (V / 100)^{1/3}$$

Where: **Tm** is the average RdT (RT60)
              V is room volume in cubic meters (m³)
              (conversion from cubic feet: cu. ft./35.315 = m³)

The RdT versus frequency curve when measured in 1/3 octave bands should be smooth within 100ms.
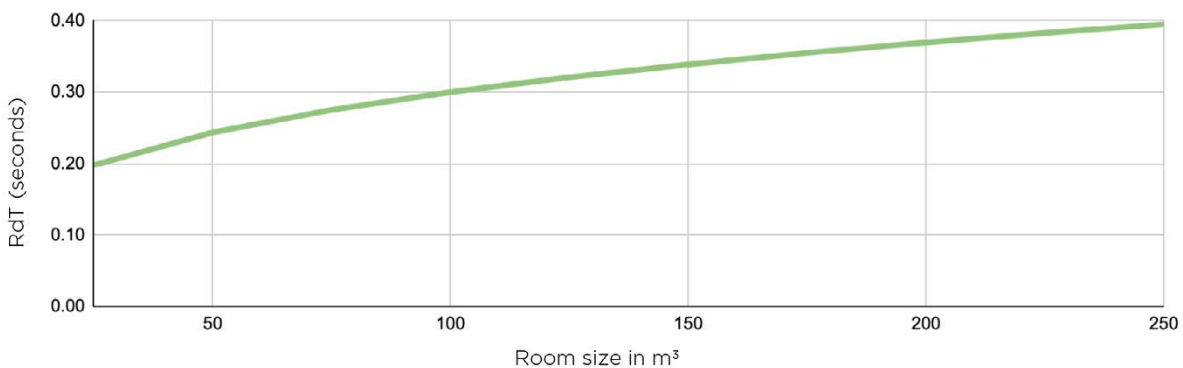
Figure 9-1: Reverberation time target in relation to room size (based on ITU research)

Though this formula provides a target, it is important to note that there is much debate around an "ideal" RdT for high performance entertainment spaces. In balancing audio performance with creating a human-centric environment, the RdT target may often be slightly higher than this formula provides.

Figure 9-2 illustrates the acceptable RdT range for a room of volume 100 m³ (3,530 cu. ft). For example, a room measuring approximately 7 x 4.8 x 3 m (23 x 15.7 x 10 ft.).
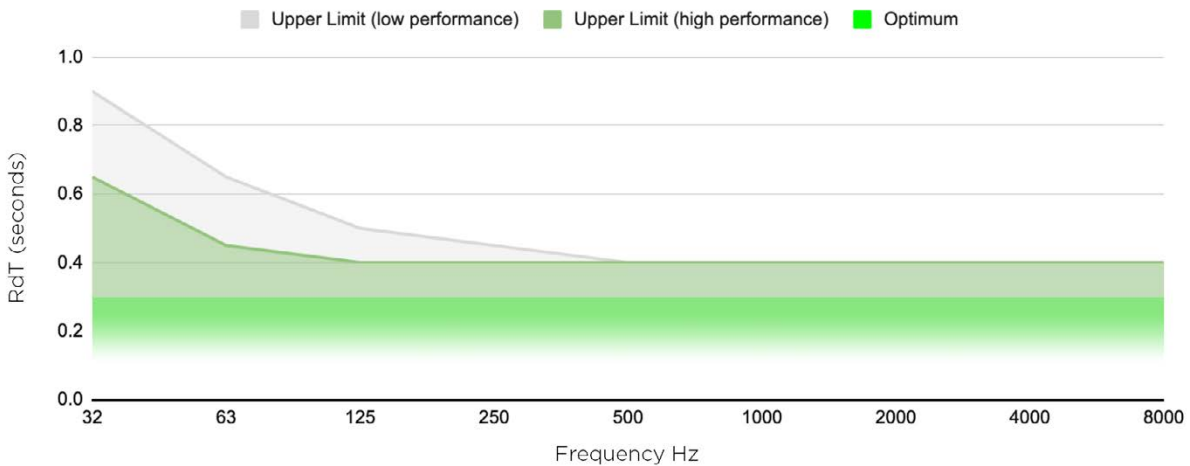
Figure 9-2: Target RdT with upper and lower bounds shown (for example room size of 100m³)

9.1.1.2 APPROXIMATION OF RDT USING THE CLASSIC SABINE EQUATION

RdT can be calculated to approximate RT60 across the audible frequency spectrum. Care must be taken with interpreting results, especially at modal region frequencies where low frequency behavior is difficult to predict. The technique is described in detail in Appendix D: Calculating Reverberation Time.

These calculations will provide a rough RdT estimate on which to base a plan for the required acoustic treatment, but best practice is to design the treatment method in a way that allows for fine tuning adjustments (adding or removing material) by ear, with reference to as-built measurements.

9.2 ACOUSTICAL DESIGN GUIDELINES

There is currently no single industry consensus approach to acoustic design and the application of acoustical treatments, with many different strategies for the delivery of target results. The performance specifications for direct-to-reflected (D/R) sound ratio and RdT should always be met, regardless of the chosen strategy.

9.2.1 LOW FREQUENCY ABSORPTION

Bass energy is the most difficult to control, so it is best to start the acoustical treatment design of the room with ensuring adequate bass absorption.

To achieve RdT targets at bass frequencies, it is important to consider acoustic products and materials that are effective at these frequencies. Many different types exist, each with different placement guidelines. Examples of strategies include:

1. Using bass absorbers (sometimes called bass traps) in the corners of the room, being the high-pressure regions of the low frequency standing-wave patterns in a room. The absorbers should preferably be of the membrane/diaphragmatic/panel type; foam type (velocity) absorbers are less suitable.

2. Tuned or tunable bass absorbers can be used to tackle specific modal frequencies. These need to be positioned in regions of high pressure at the required frequency to be most effective.

3. Bass absorption can be built into the room. Examples include under risers and steps, and into the construction of the walls.

4. Using an active configuration where the combination of specific subwoofer placement, setup, and calibration is used to effectively reduce room modal problems. This should be done in conjunction with a passive approach.

5. The construction of the room will have an effect on bass absorption:

   • Rigid concrete construction will have very little effect.

   • Single-layer gypsum board on a timber frame will have some effect, whereas multi-layered gypsum board will have a greater effect, particularly if damping compound is applied between layers. However, too many layers can increase the structural mass to the point that it forms a rigid isolator without absorptive properties.

- Gypsum board mounted on resilient channel or other decoupling devices during construction will have a significant effect.

Though some bass absorption can always be achieved from points 2 & 3 above, it can be unpredictable. Consideration should be given to strategies where additional bass absorption can be added once the system is complete and measured.

9.2.2 ACOUSTICAL TREATMENT RELATING TO SCREEN WALL SPEAKERS

The majority of sounds and nearly all dialog in a soundtrack comes from the screen wall speakers. The audience hears a combination of direct and reflected sounds that jointly influence the perceived size of the space, sound detail, and dialog intelligibility.

First order reflections from walls, ceiling, and floor, are so-called as they are the first sounds to arrive at the RSP after the direct sounds. They are generally also the next loudest after the direct sounds, but are more complex due to the different distances and reflectivity of various surfaces that the sounds bounce from on their path to the listeners. These longer paths cause an **initial time delay gap** (ITDG) — the delay from sound source to its arrival at the listeners' ears via the reflection point(s), which can have either helpful or harmful impacts on localization, timbre, and clarity of sound. As such, they should be addressed in the acoustic design of the entertainment space.

First reflections can positively reinforce the direct sound if the delivery time is short (generally <30 ms) and spectral shape is similar, providing good intelligibility and adding **apparent source width** (ASW). Conversely, first reflections can damage the listening experience if its arrival time is longer, its energy level remains relatively high, and/or spectral shape is dissimilar to the direct sound, producing image "smearing" or "blurring." Yet further increased ITDG (above approximately 60-80 ms) can start to produce echoes, significantly inhibiting localization where different spectral elements of a single voice, instrument, or sound object are perceived to be coming from two or more different locations.

Benefits to clarity result from the direct-to-reflected (D/R) sound energy ratio being reduced. Absorption or diffusion placed at the mirror points, (where a single bounce returns sound to the RSP) can mitigate the bad and elevate the good that these reflections may contribute to the listening experience. This benefit is most noticeable when the front speakers are operating alone, especially when sounds are "hard panned" to one of them. In movies and television, the center speaker operates alone much of the time, and some diffuse reflections can create a sense of spaciousness that is generally pleasing to the listener.

- For stereo sound or up to 7 listener-level speakers, using diffusing panels at the lateral first reflection (mirror) points reduces localizable reflections, allowing the listeners to perceive the room as larger. There is benefit from having some lateral reflections from the front side walls.
- Where front wide (FWL/FWR) speakers are located at the mirror points of screen speakers, use absorption around the front wide speakers.
- For high channel count systems (greater than 7 listener-level), it may be beneficial to use absorption at the first lateral screen wall speaker reflection points.

Refer to the Performance Level parameter below for level of direct-to-early-reflected sound. Careful consideration should be given where front speakers are located close to an adjacent surface. This may include vertical surfaces such as walls, horizontal surfaces such as furniture on top of which speakers (including the center speaker) sit, and/or coffee table(s) located between the front speakers and the listeners.

PERFORMANCE LEVELS — ACOUSTICS

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/ Seat
21. Level of early reflections relative to direct sound (0-15 ms, 1-8 kHz)	dB	Min.	N/A	-8	-10	-12	Room
Management of early reflections ensures an optimum balance of direct and reflected sound.							

9.2.3 ACOUSTICAL TREATMENT RELATING TO SURROUND AND UPPER SPEAKERS

Localizable sounds include channel-based and object-based effects in multimedia content as well as stable locations for musicians in "middle-of-the-band" recordings. These require strong direct sounds from the surround speakers to be delivered to all listeners in the room. However, the majority of the time, the intention is to envelop the audience with mood-setting music, atmospheric sounds, and acoustical ambience associated with what is happening in the front soundstage or on the screen.

Envelopment means being surrounded by sounds having no specific direction. It can create a sense of being in a different space. This perception is created when delayed versions (recorded reflections) of the front sounds arrive at the listeners' ears from the sides. Remember that sound is a three-dimensional experience, and the ceiling and floor are just as important as the walls.

The incorporation of upward firing "elevation" speakers generally assumes a room that is absent of overhead acoustical materials, and has a ceiling height of 4.5 m (15 ft) or lower (2.3 - 3.7 m [7.5 - 12 ft] is ideal) with the speakers located at a height at least that of the screen speakers. The optimal height effect requires the ceiling to be as reflective as possible in the location of the initial reflection. It is recommended to place the elevation speakers in their assigned locations and employ a laser sight/pointer to identify the primary reflective area on the ceiling. This is the area that must be free of any acoustical treatment. For optimum performance the ideal primary reflective surface for each elevation speaker should be a minimum of 1.5 m^2 (16 ft^2).

Surround and upper speakers are just as important for the creation of a coherent soundfield as the screen speakers. Within the overall objectives of achieving RdT and D/R specifications it is generally good practice for the acoustic materials placed in the back and upper parts of the room to support envelopment and immersion by providing for some managed reflection, diffusion, and scattering.

9.3 ACOUSTICAL MATERIALS GUIDELINES

9.3.1 APPROPRIATE SPECIFICATION OF ABSORBING PRODUCTS

Where additional absorption is required to achieve the desired RdT and to control the D/R, it should not affect the timbre of the reflections. Absorbers of sufficient thickness to absorb sound across the frequency spectrum are required. These materials can be used in combination to achieve more broadband performance by increasing their thickness. An air space behind an absorbent panel increases its low-frequency performance.

An example of how the thickness of an absorbing material can effect its performance is illustrated in figure 9-3.
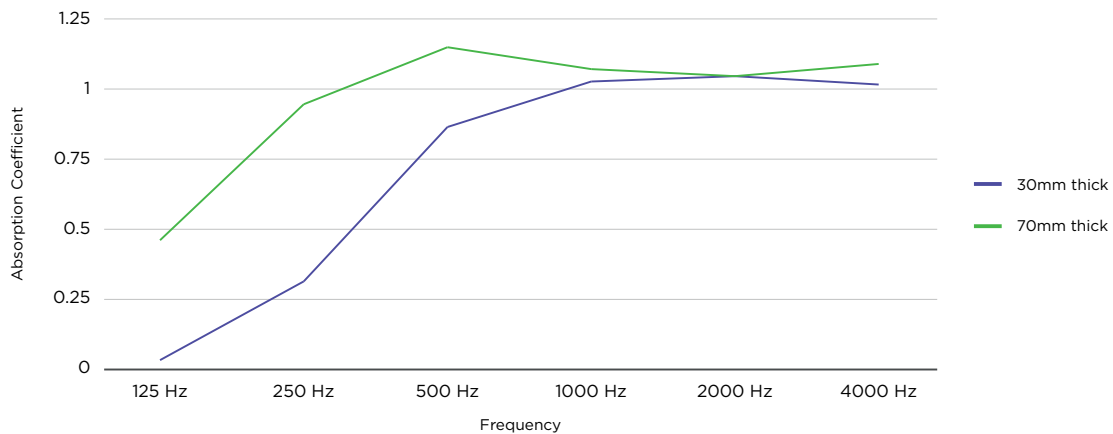
Figure 9-3: Example of absorbtion coefficient for different thickness materials at different frequencies

9.3.2 APPROPRIATE APPLICATION OF ACOUSTIC TREATMENTS

Many different approaches exist for the use and placement of absorption, scattering, and diffusion devices. Examples include:

1. Acoustical materials placed in the center portions of the front and rear walls are mostly absorbing, with scattering devices towards the sides of the rear wall.

2. Side walls can use a mixture of reflection, absorption, and scattering/diffusing devices. Diffusers designed to scatter the sound horizontally should be located in the region between about 300 mm (1 ft) below and about 1 m (3.28 ft) above ear level.

3. Diffusers can be of the engineered-surface type that are attached to, or are built into the walls, or they can be simple geometric shapes that can be attached to walls or constructed onsite using conventional building materials. To assist the illusion of immersion or envelopment, these devices should be effective at lower-middle frequencies. Check specifications with the acoustic treatment manufacturer.

4. Almost any curved or multifaceted convex geometric shape will scatter sounds, so considerable artistic freedom exists. For aesthetic effect, it may be desirable to have the geometric shapes extend from floor to ceiling, imitating columns. Engineered diffusing surfaces can be arranged side-by-side to cover an area.

5. Scattering or diffusion devices located on the ceiling should scatter sounds from the front speakers that would normally be reflected to the listeners' ears. This is most effective if it is an engineered surface designed and positioned to scatter the sound towards the sides of the room.

6. Phase grating diffusers that feature surface wells of varying depths to reflect sounds at slightly different times require minimum distances from the listeners. Ensure adherence to manufacturer guidelines.

9.3.3   AVOIDING FLUTTER ECHOES

There should be no audible flutter echoes at any of the listening areas of the room.

The room should not have large, untreated reflective surfaces that are parallel to each other. Such surfaces should be appropriately acoustically treated down to approximately 250 Hz. The total amount of absorbing material in the room should be calculated per octave of sound to meet the RdT objectives. Absorption should be brought down to at least 300 mm (1 ft) below the seated ear height.

9.3.4   FLOORING MATERIALS

Flooring materials have an effect on acoustical performance and should be considered. Where a carpet is used as an acoustic material, a carpet with an open back (breathable between weaves) should be chosen to allow sound to penetrate to a felt underlay, thereby maximizing the benefit of the carpet's absorption.

Alternative flooring materials and designs can be used, and the effects of these should be calculated for the room to achieve optimum results.

9.3.5   DECORATIVE FABRICS ON WALLS OR CEILING

When fabrics are used to cover wall or ceiling surfaces in entertainment spaces, their acoustical properties will need to be considered.

Fabrics covering acoustical design elements such as absorbers, reflectors, or diffusers, should be acoustically transparent over the frequency range for which the acoustical element is designed to be effective. For example, diffusers that operate in the vocal range from 500 Hz to 5 kHz should be covered by fabrics with a negligible insertion loss at 5 kHz and below.

The acoustical characteristics of fabrics are most critical when they are used to cover speakers. As with most hi-fi speakers' grille materials, these fabrics should have a specification that shows negligible loss up to the highest frequencies to be reproduced by the speaker. It is expected that modern surround

and immersive audio systems would be capable of reproducing the full frequency range to 20 kHz and beyond.

Specifications for acoustical fabrics can vary and often do not apply to high fidelity audio applications. As such, it is recommended to self-test or use third party test data to determine the acoustical suitability of any candidate fabric prior to specifying its use. It is important to be able to predict the performance outcome of acoustical design elements and speaker systems (both on and off axis) located behind any given material.

Equalization (EQ) can partially compensate for some losses caused by fabrics, but the preference is to use materials that do not inhibit performance in the first place. Refer to Section 11 for possible negative effects that can be caused by EQ applying excessive gain.

Subwoofers placed behind fabric wall or ceiling coverings present a special case. There is no insertion loss issue for fabrics at these frequencies, but the air movement produced by direct radiators and or the port of vented box designs can set fabric into motion. This can cause visual and noise events that detract from the immersive experience. High open area or stiffening mechanisms for the fabric can help, along with moving the sound source farther from the fabric surface whenever possible.

9.3.6   CONFORMITY TO FIRE AND BUILDING CODES

It is essential that all materials that compose the construction and acoustical treatment comply, as required, with the relevant local fire safety and building codes. This can include wall, floor, and ceiling construction and linings, including in-wall and on-wall materials, and all cabling that runs throughout. As such, it is imperative that integrators be aware of, and practice adherence to standards, regulations, and codes as they apply in the locality of a given project. It is recommended practice to document compliance notations as part of the design documentation process.

Furthermore, the completion of any residential space invariably requires involvement from adjacent trades, so regulatory requirements should form part of any clarification of responsibilities.

9.4   PROJECTION SCREEN ACOUSTIC CONSIDERATIONS

When designing a room, it may be desirable to locate the main front (screen) speakers behind a projection screen to improve localization of sound to the image area, or to maximize the screen area. In this case it is best to consider screen materials that are as acoustically transparent as possible.

Screens sold as "acoustically transparent" allow significant sound transmission. All screens will, to some degree, impede overall sound performance at frequencies from 2 kHz and above. The more open area the screen has, the less effect it will have on acoustic performance.

All screens will, to a greater or lesser degree, reflect some sound back to the speakers and surrounding surfaces behind the screen. This reflected energy will in some cases only be slightly reduced in level, and arrive soon after the direct sound. This creates complex *comb filtering* (when a sound adds to itself in a short time), and if not mitigated, will affect both on-axis and off-axis audio performance.

9.4.1   ACOUSTICALLY TRANSPARENT SCREEN MATERIALS

All acoustically transparent screen materials have highly variable acoustical properties relative to their material and weave/knit/perforation structure. This will affect the sound of the speaker at the seating positions. It is important to review relevant data regarding the on- and off-axis acoustical transparency of any candidate screen material.

9.4.2   PROJECTION SCREEN ACOUSTICAL RECOMMENDATIONS

1. Increasing the setback distance of speakers behind the screen will generally reduce the severity of acoustic artifacts.

    •   A setback of at least 150 mm (6 in.) is recommended. This may vary depending on the combination of speaker type, model, placement angles, listening angles, and screen technology.

    •   Setback distances of less than 150 mm (6 in.) may be acceptable for some speakers with horn or waveguide coupled tweeters.

    •   Figure 9-4 demonstrates the possible effects on frequency response when positioning speakers at various distances behind an acoustically transparent screen. Note this is not definitive, rather is representative of what may occur with some speaker and screen combinations.

Example effects of speaker setback distances behind an acoustically transparent screen
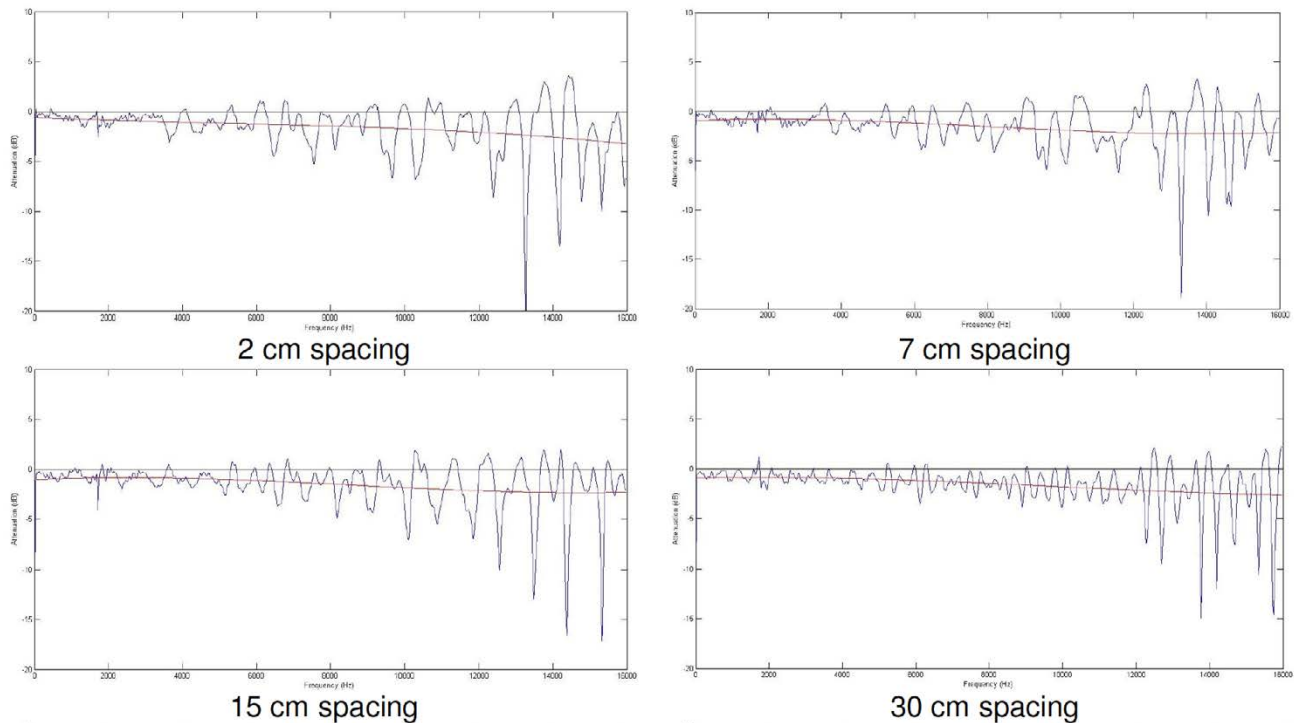
Figure 9-4: Example on-axis frequency response plots for a speaker spaced at various distances behind an acoustically transparent screen. Source: Newell, García, Holland [6]

2. Some speakers can be fitted with absorptive materials on their front baffle to mitigate comb filtering effects. Contact the manufacturer for availability.

3. It is suggested to treat the area behind the screen with absorptive materials to reduce the level of reflected sound, and in turn, reduce acoustic artifacts. These materials need to be effective

   • at frequencies down to a minimum of 500 Hz.
   • to fit into the overall acoustic treatment plan for the room.

4. Any overall sound level reduction due to screen transmission loss needs to be taken into consideration with regards to amplifier power and speaker capability. If any high-frequency attenuation is subsequently equalized, consideration should be given to any loss of maximum SPL capability that this will cause.

5. Projection screen selection (perforated vs. fabric) is a balance of compromises between the optimization of video and audio performance. Refer to CTA/CEDIA-CEB23-B for recommendations relating to screen material selection for optimizing video performance.

6. Placement of subwoofers or low-frequency devices behind a screen is not recommended. The high-excursion capability of these devices can create vibrations on the screen that may introduce artifacts in both audio and video.

   If no other location is possible then

   • take special care to leave enough space behind the screen. Positioning the subwoofer at least 300 mm (1 ft) behind the screen is recommended.

   • ensure there is enough air flow around the screen to avoid pressure build-up.

   The same precautions are also valid with speakers capable of reproducing low frequencies but used at full range, especially those with front vented ports. In any case, the objective is to ensure there will be no perceptible movement of the screen when all speakers are operating at the specified maximum SPL and frequency range.

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SECTION

10

EQUIPMENT GUIDELINES

10.1 EQUIPMENT LOCATION GUIDELINES

Optimal equipment performance

To achieve the performance goals outlined in this recommended practice, equipment should be installed in appropriate racks and equipment rooms that meet the manufacturer's requirements for proper operation.

Ease of access and use

A rack mount system should preferably be located in an adjacent space, but equipment located in cabinetry in the entertainment space can be acceptable with proper installation and environmental conditions.

No background noises

As above, remotely locating equipment away from the seating area or in a suitable enclosure will mitigate the issue of background noise caused by equipment.

If possible, equipment should be located to minimize its audible and visual impact

- Equipment presents both audible and visual ramifications — lights on the equipment, including user interface displays can be distracting to the visual field. Fan and mechanical noises from equipment will contribute to an increase in the noise floor of the entertainment space.

- Consider the connectivity range of wireless (RF, Bluetooth®, etc.) controllers and other devices when they are located away from the seating areas. This distance may vary due to conditions in the building.

10.2 EQUIPMENT INSTALLATION GUIDELINES

The environment in which equipment is installed should comply with manufacturers' specifications or recommendations for ambient heat and humidity.

- Equipment loses performance and life expectancy if operating temperatures extend above manufacturer specifications.

- The equipment room should be kept dry and as dust free as possible. Frequently cleaned and/or changed filters should be used where the ventilation system may introduce dust into equipment.

- Try to avoid installing equipment racks in areas where sources of humidity are present, such as sump pumps, unfinished exterior basement walls, etc.

- Refer to CTA/CEDIA-CEB24-A Thermal Management for Electronic Systems recommended practice for guidelines.

Equipment Rack Design Considerations

Recommended practice is to follow established industry standards for audiovisual equipment rack design, namely the EIA/ECA-310-E standard for Cabinets, Racks, Panels, and Associated Equipment.

Pre-built, welded racks are best for strength and stability. Rack selection should take into consideration:

- Access
- Weight of equipment
- Ventilation requirements
- Wiring considerations

Cable Management

- Cables should be organized, labeled, color coded, and referenced to a schematic to allow for ease of identification and servicing.
- Typically, the shortest possible signal path is the most desirable.
- Balanced or digital audio are the preferred methods of audio signal distribution, taking care to ensure adequate cable length, gauge, and impedance. Refer to CEDIA/CTA-RP28 HDMI® System Design and Verification Recommended Practice for guidelines pertaining to the specification and installation of HDMI cables and alternative technologies.
- TIA-570-D provides guidelines for running audio-video cables along with high voltage wiring.

System Power and Grounding

- The system should comply with all local electrical safety standards and codes.
- System grounding should be designed to be free from ground loops.
- Consideration should be given to protecting installed equipment from electrical power spikes, blackouts and brownouts.

Control Considerations

Control of the system should be provided through a user interface that simplifies its operation for the user.

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SECTION

11

CALIBRATION OF ELECTRO-ACOUSTICS

11.1   ROOM PERFORMANCE OPTIMIZATION

Sound reproduction in small rooms introduces complex electro-acoustics that can vastly compromise the listening experience. Room acoustics are typically composed of direct sound, early reflections, and late reflections/reverberation. The overall broadband steady state response arises from all of these, but mostly from reflected sound. This is also true for room resonances, but they are only significant below the transition (Schroeder) frequency. The performance of room acoustics can be optimized by a combination of the following steps:

1. Room size and proportions (see Section 7.3.1)
2. Seating layout (see Section 4)
3. Speaker selection (see Section 6), placement, and aiming (see Section 5)
4. Interior acoustical design and treatment of the room (see Section 9)
5. Electronic Optimization (equalization) as described below

Electronic Optimization of Electro-Acoustics

The electronic optimization of electro-acoustics, often simply called equalization (EQ), employs a set of filters that influence the signal frequency and phase response to compensate for specific electro-acoustic problems as identified with acoustic measurement tools. Filters are deployed using manual adjustment or automated procedures. To simplify, filters can be split into two groups: traditional frequency EQ, and time/frequency optimization.

Traditional EQ

Traditional EQ, such as graphic (fixed) or parametric (variable) EQ, works mainly in the frequency domain. Such methods are focused only on controlling the level of center frequencies and may have unintended side effects in the time domain. Traditional EQ might be applied as follows:

- At the low frequencies (below the room's transition frequency) to smooth the magnitude response of dominant room modes and adjust overall bass tonality.

- At the upper frequencies (above the room's transition frequency) to influence either the magnitude frequency response of the direct sound (called the speaker anechoic EQ), or the response of a speaker that has been positioned differently to that intended by the manufacturer (for instance, a speaker installed close to a corner), or to a lesser extent, the steady state frequency response of the system (called the target response) to adjust its tonality. Note that frequency filters do not allow control over direct sound and some reflections independently.

Time-frequency domain filters

Further optimization may be possible using filters that operate in both the time and phase domains. This can help normalize the performance of screen wall, surround, and upper speakers that may have significant differences in their amplitude as well as their time and phase attributes due to their direct and early reflected sound. This improves clarity and localization.

11.2 EQ RECOMMENDED PRACTICE

EQ is not a remedy for incorrect speaker and room acoustic design, rather it is a tool to fine tune the response of a well-designed and implemented system.

This includes proper speaker selection and positioning, optimized by effective acoustical design of the space, and basic adjustments (levels, delays, bass management). The result should produce minimal need for further electronic optimization of electro-acoustics in order to achieve the desired performance outcomes.

If applying EQ, it is recommended to regularly make comparisons to the non-equalized state by listening to confirm the progress of positive improvements. This should always be done at the typical volume level that the listeners would use.

Additional considerations for the use of electronic optimization of electro-acoustics are listed below.

1. Electronic electro-acoustic optimization is generally <u>not</u> suitable for the following:

    • Attempting to correct a room null (cancelling room mode) using just amplitude filters

    • Attempting to correct for flutter echoes or excess reverberation

    • Attempting to achieve the same off-axis response from a speaker as its on-axis response

    • Attempting to extend the frequency response of a speaker beyond its operating range

    • Attempting to correct the steady state system frequency response with narrow band, high gain filters above the transition frequency

    • Attempting to turn a poorly engineered speaker into a well-engineered one

2. Electronic optimization, especially when used to increase the level at certain frequencies, can reduce the overall sound pressure capability of a system and possibly exceed the capability of some drivers.

3. When using filters to achieve a particular target response, it is best to use filters that reduce gain, taking energy out of the system. When filters are applied with positive gain, these should be done minimally to preserve headroom.

4. In the case of a system using speakers with different phase/time characteristics, electronic phase/time alignment is recommended.

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APPENDIX

A

PERFORMANCE LEVEL PARAMETERS

A.1 TABLE OF PERFORMANCE LEVEL PARAMETERS

Parameter	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
Spatial Resolution							
1. Minimum distance between the listening area and the room walls (d_{SW}, d_{bW})	meters (m)	Min.	**>0.5**	**>0.8**	**>1.2**	**>1.5**	Seat
This parameter helps avoid speakers being too loud for some and too quiet for others, whilst simultaneously minimizing wall boundary interference. Design prediction requires measuring from the proposed center of each listener's head to the nearest boundary wall or protruding speaker baffle.							
2. Decoder/renderer capability and discretely rendered speaker configuration, excl. subwoofers	Number discrete speakers	Min.	**5**	**11**	**15/13***	**15/13***	Room
Includes all listener-level and upper discrete processor outputs, though there are multiple combinations of speaker locations possible therein, depending on the room design and characteristics. * Auro-3D specific room design requires 13 discrete feeds; for other formats the minimum should be 15 for Levels 3 and 4.							
3. Number of screen wall speakers allowed outside of recommended zonal locations	Number speakers	-	**0**	**0**	**0**	**0**	Room
Speaker locations are not strict angle numbers. They are zones/areas resulting from multiple trade-offs and defining acceptable possible locations for a given screen wall speaker. Defined zones are wide enough to allow some flexibility in speaker locations within the recommended zone.							
4. Maximum SPL difference between screen wall speakers	dB	Max.	**6**	**5**	**4**	**2**	Seat
Normalised to RSP (where levels will be set to have a 0dB variation). Individually for every seat, the maximum predicted SPL difference (using anechoic propagation loss) between any two screen wall speakers.							
5. Maximum allowable horizontal angle between adjacent surround speakers	Degrees (°)	Max.	**N/A**	**80°**	**60°**	**50°**	Seat
To ensure that sound movement is smooth and localization is accurate, this metric specifies the maximum horizontal angle between adjacent surround speakers at the seating location.							
6. Maximum SPL difference between surround speakers	dB	Max.	**10**	**6**	**4**	**2**	Seat
Normalized to RSP (where levels will be set to have a 0dB variation). Individually for every seat, the maximum predicted SPL difference (using anechoic propagation loss) between any two listener-level surround speakers.							
7. Wide speakers (If implemented) maximum allowable horizontal deviation from median angle	Degrees (°)	±	**10°**	**7°**	**5°**	**2°**	Room
To ensure localization accuracy, this metric is the maximum horizontal anglular deviation allowed from the ideal median angular location for wide front speakers.							
8. Upfiring/elevation speakers allowed?	Yes/No	-	**Yes**	**Yes**	**No**	**No**	-
Absent the ability to install top (overhead) speakers, one solution is to employ upfiring/elevation (e.g., "Atmos Enabled") speakers aimed at a reflective ceiling surface to reproduce immersive content and audio objects. These speakers should have a suitable mechanical and electrical design.							

Parameter (continued)	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
9. Maximum allowable vertical angle between adjacent (L/R rows of) upper speakers	Degrees (°)	Max.	**N/A**	**80°**	**60°**	**50°**	Seat

To ensure that sound movement is smooth, and localization is accurate, this metric specifies the maximum vertical angle between adjacent upper speakers at the seating location. Excludes top middle center ("Voice of God") and height center speakers.

10. Maximum SPL difference between upper speakers	dB	Max.	**12**	**8**	**5**	**2**	Seat

Normalized to RSP (where levels will be set to have a 0 dB variation). Individually for every seat, the maximum predicted SPL difference (using anechoic propagation loss) between any two height/upper speakers.

11. Number of surround/wide/upper speakers allowed outside of zonal recommendation locations	Number speakers	-	**N/A**	**0**	**0**	**0**	Room

Speaker locations are not strict angle numbers; they are designated zones/areas for speaker groups resulting from multiple trade-offs. Zones are broad enough to allow some flexibility in speaker locations.

Dynamics							

12. Screen speakers SPL capability at RSP (post calibration EQ, within assigned bandwidth) without clipping	dB SPL (C)	Min.	**99**	**102**	**105**	**108**	Room
		Rec.	**102**	**105**	**108**	**111**	

Sound Pressure Level at the Reference Seating Position is the recommended minimum long term SPL according to AES75-2022 or ANSI-CTA-2034-A, Section 8. Consideration should be given to the following:
1. Additional speaker SPL capability at bass frequencies to allow for bass contours
2. Additional speaker SPL capability to allow for +EQ

13. Non-screen speakers SPL capability at RSP (Post calibration EQ within assigned bandwidth) without clipping (includes amplifier headroom)	dB SPL (C)	Min.	**96**	**99**	**102**	**105**	Room
		Rec.	**99**	**102**	**105**	**108**	

Sound Pressure Level at the Reference Seating Position is the recommended minimum long term SPL according to AES75-2022 or ANSI-CTA-2034-A, Section 8. Consideration should be given to the following:
1. Additional speaker SPL capability at bass frequencies to allow for bass contours
2. Additional speaker SPL capability to allow for +EQ

14. LFE frequencies total SPL capability at RSP, plus bass management if used (post calibration EQ, within bass extension spec for the level) without clipping (includes amplifier headroom)	dB SPL (C)	Min.	**109**	**112**	**115**	**118**	Room
		Rec.	**114**	**117**	**120**	**123**	

Total system SPL capability at LFE frequencies for speakers and/or subwoofers. Can include room/boundary gain and gain resulting from summing multiple speakers/subwoofers acting as one virtual subwoofer.

15. Background noise floor with all AV equipment and mechanical systems and building services switched on, at nominal operating temperatures	NCB rating	Max.	**35**	**26**	**22**	**18**	Room
		Rec.	**26**	**22**	**18**	**15**	

Noise floor indicates the level of general noise in the background — that which is discernible with all systems running (including HVAC) during regular operation of the entertainment space but while no multimedia content is being played (for instance, on pause or menu).

Parameter (continued)	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/Seat
Timbre							
16. Seat-to-seat frequency response variance across all screen wall speakers normalized to measured RSP response between 500 Hz and 16 kHz (1 octave smoothing)	± dB	Max.	5	3	1.5	1.5	Seat
Predicts how similar the experience and performance level will be across multiple seats. Design prediction should consider correct speaker alignment, off-axis frequency response on both the horizontal & vertical axes, and the effect of the room.							
17. Seat-to-seat frequency response variance across all wide/surround/upper speakers normalized to measured RSP response between 500 Hz and 16 kHz (1 octave smoothing)	± dB	Max.	N/A	N/A	3	1.5	Seat
Predicts how similar the experience and performance level will be across multiple seats. Design prediction should consider correct speaker alignment, off-axis frequency response on both the horizontal & vertical axis, and the effect of the room.							
18. In-room bass extension -3 dB cut off frequency point	Hz	Min.	35	30	20	18	Room
		Rec.	30	25	18	15	
In-room predicted -3dB bass extension frequency with no perceptible distortion or audible mechanical resonances (e.g., rattles) at the specified minimum SPL according to performance parameter 14 (LFE frequencies total SPL capability at RSP). To include speaker coupling, boundary and room gain.							
19. Frequency response below the room's transition frequency at the RSP relative to target curve (1/3 octave smoothing). "The Result"	± dB	Max.	5	4	3	2	Seat
Predicts a smooth frequency response at the RSP, relative to a pre-determined target curve.							
20. Seat-to-seat frequency response relative to measured RSP response below the room's transition frequency per seat (1/3 octave smoothing). "The Consistency"	± dB	Max.	N/A	4	3	2	Seat
Predicts how similar the experience and performance level will be across multiple seats.							
21. Level of early reflections relative to direct sound (0-15 ms, 1-8 kHz)	dB	Min.	N/A	-8	-10	-12	Room
Management of early reflections ensures an optimum balance of direct and reflected sound.							

APPENDIX

B

LOW-FREQUENCY ROOM

OPTIMIZATION SUPPLEMENT

B.1 POSITIONAL AND DIMENSIONAL OPTIMIZATION

Figures B-1 and B-2 (next 2 pages) show the average seat-to-seat variation in frequency response from 20-80 Hz that results in rectangular rooms of various dimensions for several subwoofer configurations. This performance metric is called **mean spatial variance** (MSV). The higher the value, the higher the seat-to-seat variance. As such, a low value of MSV is desired, meaning that the frequency responses at the different seats are more similar.

The seat-to-seat variation is calculated on a theoretical basis but is a reasonable indicator of what can be expected in real rooms. If the room dimensions and seating area location (middle of room or between middle and rear of room) are known, the optimal subwoofer locations can be determined according to the configurations in Section 7.3.2.1.

- Figure B-1 (page 114) shows MSV plots measured with seating area centered in the room. Figure B-2 (page 115) is with the seating area positioned towards the rear of the room.

- In interpreting the MSV plots, the lighter the shaded area, the lower the MSV values, indicating more consistency in bass response from seat to seat. Conversely, darker areas indicate greater variation, being undesirable.

- The 6 plots include 3 configurations (config. 3, 5, and 6) from Section 7.3.2.1, but also includes 3 other lesser performing configurations (config. 1, 2, and 4) for comparison.

Note that if the subwoofer configuration is fixed and is one of those shown, the optimal range of room dimensions can be determined. Note that these figures assume an 2.4 - 3 m (8 - 10 ft) ceiling.

Additional analysis using modal calculators is possible, such as with the following resources:

- https://www.harman.com/audio-innovations
- https://www.hunecke.de/en/calculators/room-eigenmodes.html
- https://www.roomeqwizard.com ("Room Sim")
- https://amcoustics.com/tools/amroc

Software to assist with optimizing multiple subwoofers ("Multi-Sub Optimizer" by Andy C.) and additional resource links are freely available online at:

- https://www.andyc.diy-audio-engineering.org/mso/html/index.html

Mean Spatial Variance Plots: Centered Seating Area

Figure B-1: Predicted Mean Spatial Variance (MSV) for low frequencies (20-80 Hz) as a function of room dimensions, for six different subwoofer configurations – seating area centered in the room. Lighter areas in the plots correspond to lower MSV, which means less seat-to-seat level variation (good).

Source: "Low-frequency Optimization Using Multiple Subwoofers"[3], figure 6, T. Welti and A. Devantier, Harman International

Mean Spatial Variance Plots: Rearward Seating Area

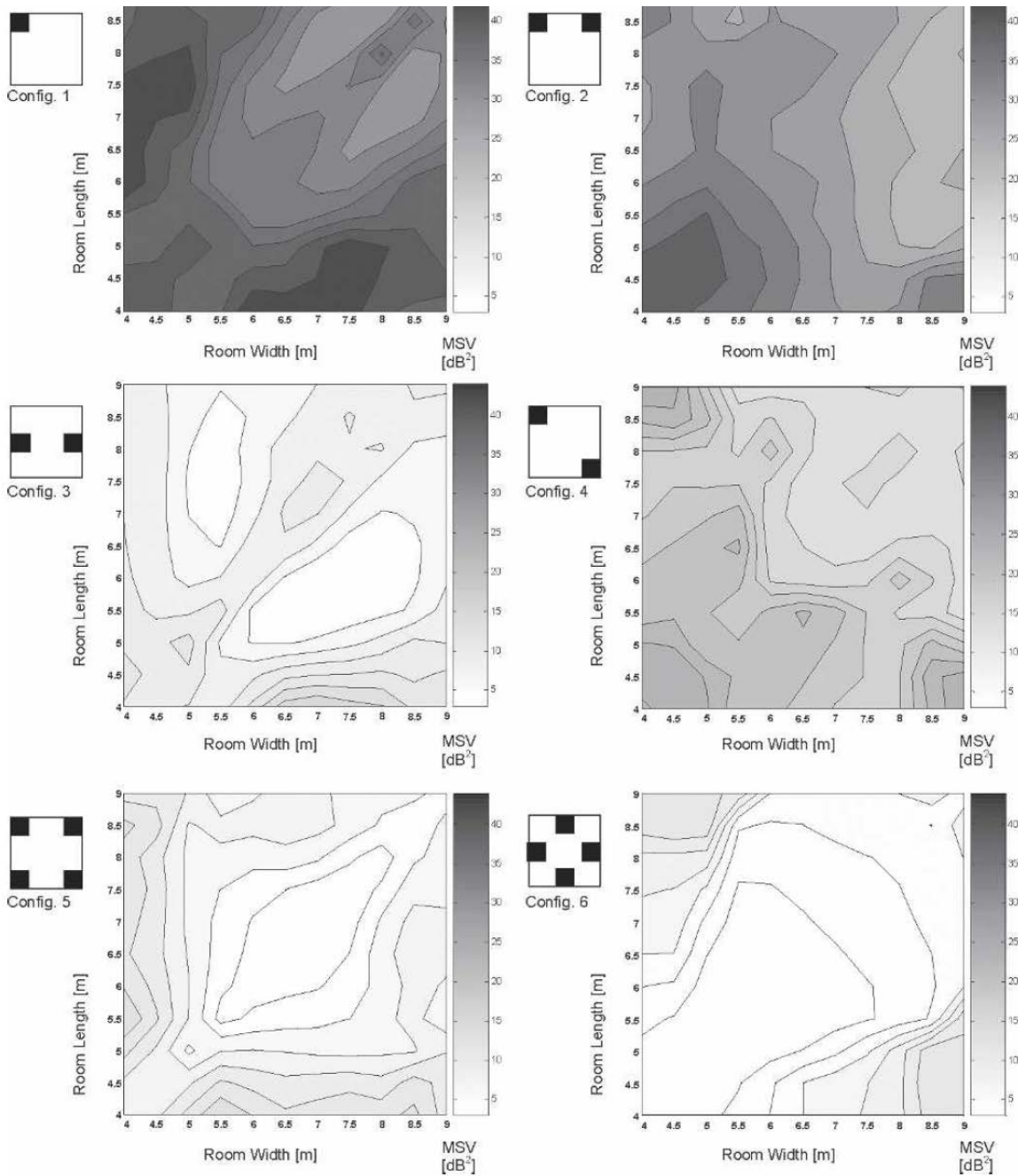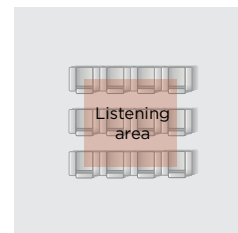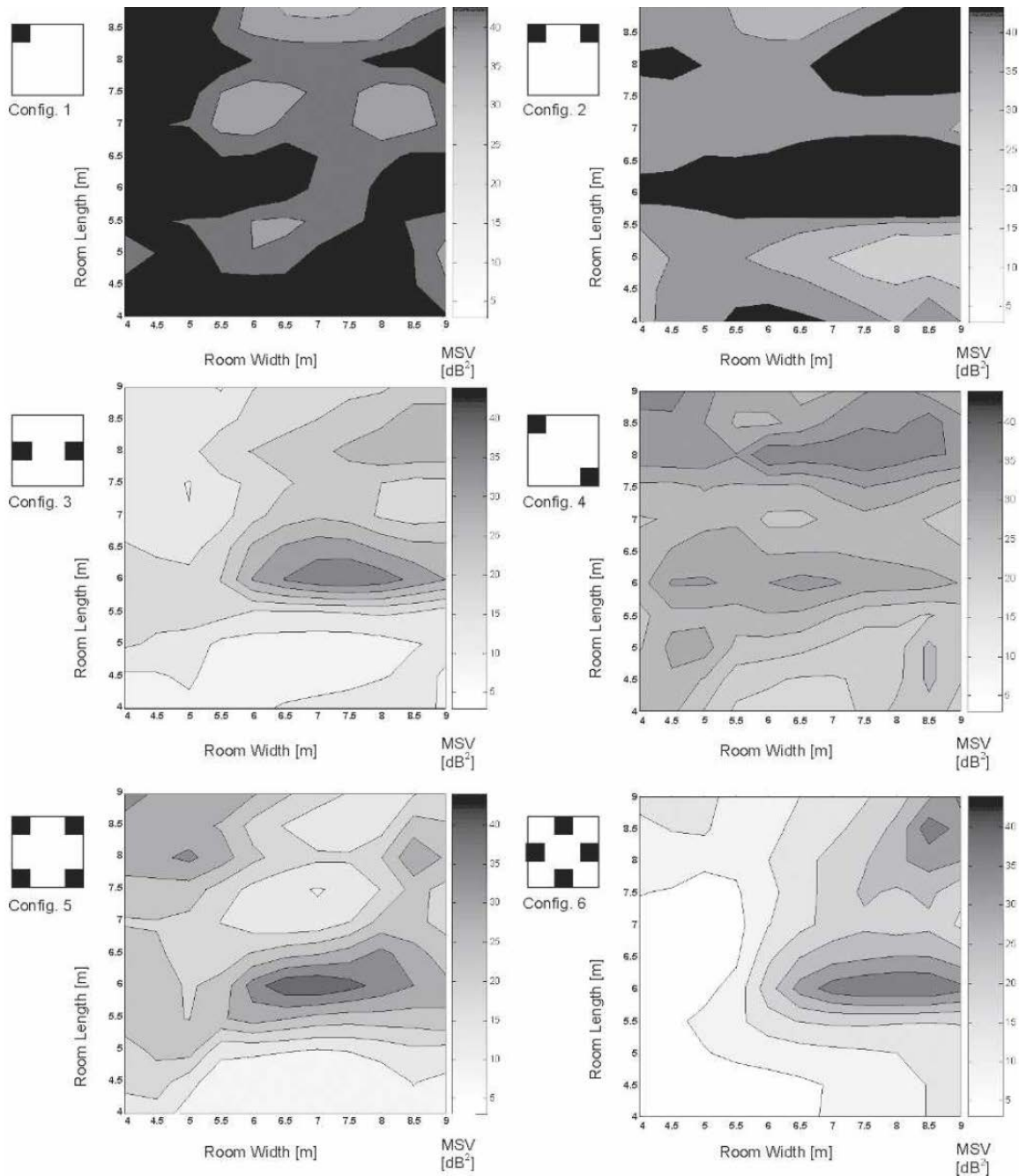Figure B-2: Predicted Mean Spatial Variance (MSV) for low frequencies (20 - 80 Hz) as a function of room dimensions, for six different subwoofer configurations – seating area moved back in room. Lighter areas in the plots correspond to lower MSV, which means less seat-to-seat level variation (good).

Source: "Low-frequency Optimization Using Multiple Subwoofers"[3], figure 7, T. Welti and A. Devantier, Harman International
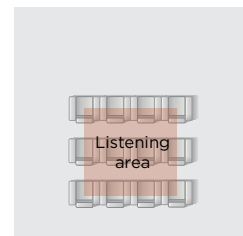
B.2   BASS MANAGEMENT AND SPATIAL LOCALIZATION

Published research[7,8] and white papers[9] indicate that spatial localization of bass below 80 Hz in 2-channel real world audio content in real rooms is subtle at best, and non-existent for the bulk of popular music which employs predominantly mono bass. Therefore, there is little justification for the argument that optimization methods that rely on bass management are inherently objectionable.

On the contrary, the listeners may experience seat-to-seat variation of 25 dB or more at some frequencies due the interaction of point-source bass and room modes. This can be the case whether the low-bass is coming from a full-range speaker or from a single subwoofer. Instead, employing bass management to redirect the bass information from all listener-level and upper layer speakers to instead be reproduced equally by all subwoofers in a multiple subwoofer configuration can harness room optimization and minimize seat-to-seat variation.

The general assumption so far has been that the subwoofers are located at reasonably similar distances from the listener. If a subwoofer is located very near a listener, there may be a moderate localization pull towards that subwoofer under certain conditions (listening to subwoofers only, distortion products or port noise from the subwoofer, etc.). In any case, when the seating area is a substantial fraction of the room, this may be an issue regardless of the how many subwoofers there are and whether they are bass-managed.

B.3   ADVANCED OPTIMIZATION

More advanced methods for optimization of subwoofers have been developed. These methods generally require subwoofer-to-listening location impulse response measurements and some type of signal processing for each independent subwoofer.

Welti and Devantier[3] show how a computer algorithm can be used to predict and evaluate thousands or even millions of possible settings of the signal processing equipment and/or potential subwoofer locations in the room, based solely on in-room measurements. These settings may be as simple as level or delay settings on each subwoofer. The best solution can then be implemented.

Other methods, such as those used by Kirkeby and Nelson[10] and Miyoshi and Kaneda[11], use more analytical approaches; for example, solving simultaneous linear equations to remedy the problem, which results in a single best solution generally implemented using sophisticated digital filters. An important advantage of all these methods is that they are not limited to rectangular rooms with typical seating configurations. They will work in virtually any room, and they work well. A disadvantage is that they require measurement data from a built room. Using this approach with a computer-modeled room does not work well in most cases.

Commercial products that use these more advanced approaches are just now becoming available. An alternate method, described in Celestinos and Nielsen[12], is simpler to implement but is not very flexible with respect to locating the subwoofers. (It uses one particular configuration of four subwoofers.) This method also only works in rectangular rooms.

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APPENDIX

C

SOUND ISOLATION SUPPLEMENT

C.1   WALL AND CEILING CONSTRUCTION

Immersive audio installation technicians can use multiple wall and ceiling construction applications to achieve sound isolation. Each method has its own inherent advantages and disadvantages. However, key considerations should incorporate high mass constructions, mechanical decoupling from the building's structure, and absorption.

C.1.1   FRAMING TECHNIQUES

There are three primary framing techniques to consider:

- **Room-within-a-room method**

  In the framing process, the room-within-a-room method is the most effective. However, this method may not be acceptable due to the amount of floor space consumed, local fire-code objections and loss of floor-to-ceiling clearance. A true room-within-a-room style of construction dictates an isolated floor, isolated base/top plates, and an isolated ceiling framing. Prior to proceeding with such a strategy, one is advised to seek professional input from either an architect or structural engineer.

- **Stagger-stud method**

  The least effective is the stagger-stud method of framing. While this method does provide mechanical isolation, neither the base nor top plates are isolated, and it can't be implemented to provide ceiling isolation. Additionally, stagger joist construction is usually not viable with existing mechanical and plumbing systems running through the joist space areas.

- **Isolation clips**

  The third method utilizes isolation clips installed onto the framing members (wall and ceiling), a metal "hat" or furring channel installed into the clips, and then the gypsum board is installed to the hat channel. The isolation clips consist of a rubber, or flexible material, which isolates, or damps, the wall and ceiling from the structure. This method can be very effective and is not cost or space prohibitive. Traditional "Z" channel, or resilient channel, is not an effective solution for music or cinema sound reproduction spaces.

  All joist and framing cavities should have fiberglass batts, blown-in wet cellulose, or similar insulation material in the cavities. Closed-cell foam insulation products are counterproductive. If open cell foam is to be used, the foam should not contact both sides of a wall or ceiling as it would re-couple the walls.

Instead of framing, some walls may be constructed from heavy, dense materials like concrete. While concrete is excellent at preventing airborne noise transmission, it will trap the acoustic energy inside the room. This is particularly the case with bass frequencies, which are the most difficult to absorb. Therefore, all the inner linings for the rooms that provide the layers of sound insulation should be more compliant, such as plasterboard, as these can be made to act as panel absorbers to aid the bass absorption in the room.

C.1.2   GYPSUM BOARD ISOLATION TECHNIQUES

Gypsum board is installed directly onto the framing for double wall or stagger-stud construction, or onto the hat/furring channel when isolation clips are utilized. Using two layers of gypsum board is highly recommended and provides a doubling of mass, reducing the resonant frequency of the wall assembly.

When multiple layers of gypsum board are used, each layer should be completely installed before applying any subsequent layer. In other words, ceiling then walls, followed by ceiling and walls again. This results in a lap joint in the corners rather than a butt style joint which, if not well sealed, will provide a flanking path and defeat the sound isolation efforts. Layers of gypsum board should have a viscoelastic coating applied between each layer. Such coatings have been shown to be very effective in damping (absorbing) low frequency energy.

Gypsum board products are available that have been manufactured with a constrained layer damping material that has been laminated into the panel at the time of manufacture. Special caution should be taken when electing to utilize such manufactured products. Firstly, two layers of the material may be required to achieve a wall with a mass equal to two layers of regular gypsum board sheets. Secondly, using such single-layer products will require careful attention to sealing any gaps or flanking paths where the sheets of material butt together.

For less critical applications, or where the existing space is already lined with gypsum board, a second layer can be installed over the existing walls and ceiling using a viscoelastic material applied between the layers. Do not install resilient channel or isolation clips over an existing wall surface and then install the new gypsum board. This form of construction will create a triple leaf, resulting in *more* transmission of sound through the barrier, not less.

To effectively seal the room, it is suggested that the installation of gypsum board occur before the installation of any architectural acoustical treatment elements such as columns, soffits, stages, or raised seating platforms. Columns can be used to house speakers, electrical outlets, and lighting control dimmers without the adverse effects associated with putting holes in the sound isolation barrier around the room. Installing wall-to-wall seating and stage platforms inside the barrier will also allow these items to be used as bass traps.

C.1.3   FLOOR ISOLATION TECHNIQUES

Floors should be decoupled from the structure of the building. Failing to do so will create a significant and undesirable flanking path. In a double wall construction method, floor framing can be isolated by using commercially available isolation pucks such as U-anchors or U-bases, floor suspension devices, or similar materials. Such methods will generally consume more height than is desirable in most residential situations. Concrete is an excellent transmitter of kinetic sound energy. Any temptation to avoid isolating concrete slab floors should be dismissed.

An effective method of floor isolation (without large structural impacts on upper floor rooms) is to install a high mass 7.5 - 12.5 mm ($^5/_{16}$ - ½ in.) rubber mat over the existing subfloor or slab. This mat should be installed after the gypsum board is installed, and any gap between the bottom of the gypsum board

and the subfloor should be thoroughly caulked. The mat should be installed 5 mm (¼ in.) short of the gypsum board and not make contact with it at any point. Oriented strand board (OSB) or structural particleboard/plywood is then installed over the mat, also not contacting the gypsum board, and with use of an approved mastic. Seating platforms and stages should then be installed over the new sub-floor.

C.2 NOISE CRITERION, BALANCED (NCB) CURVES

Figure C-1 depicts the approximate NCB curves ranging from NCB 65 (relatively high noise level) to NCB 10 (perceived silence). These curves account for the non-linear perception of human hearing, with reducing loudness perception as the frequency decreases.

Performance Levels for background noise objectives (see Section 8.5) include both *recommended* (lower number) and *maximum* (higher number) NCB ratings. These are represented on the chart as ranges for each Performance Level, respectively.
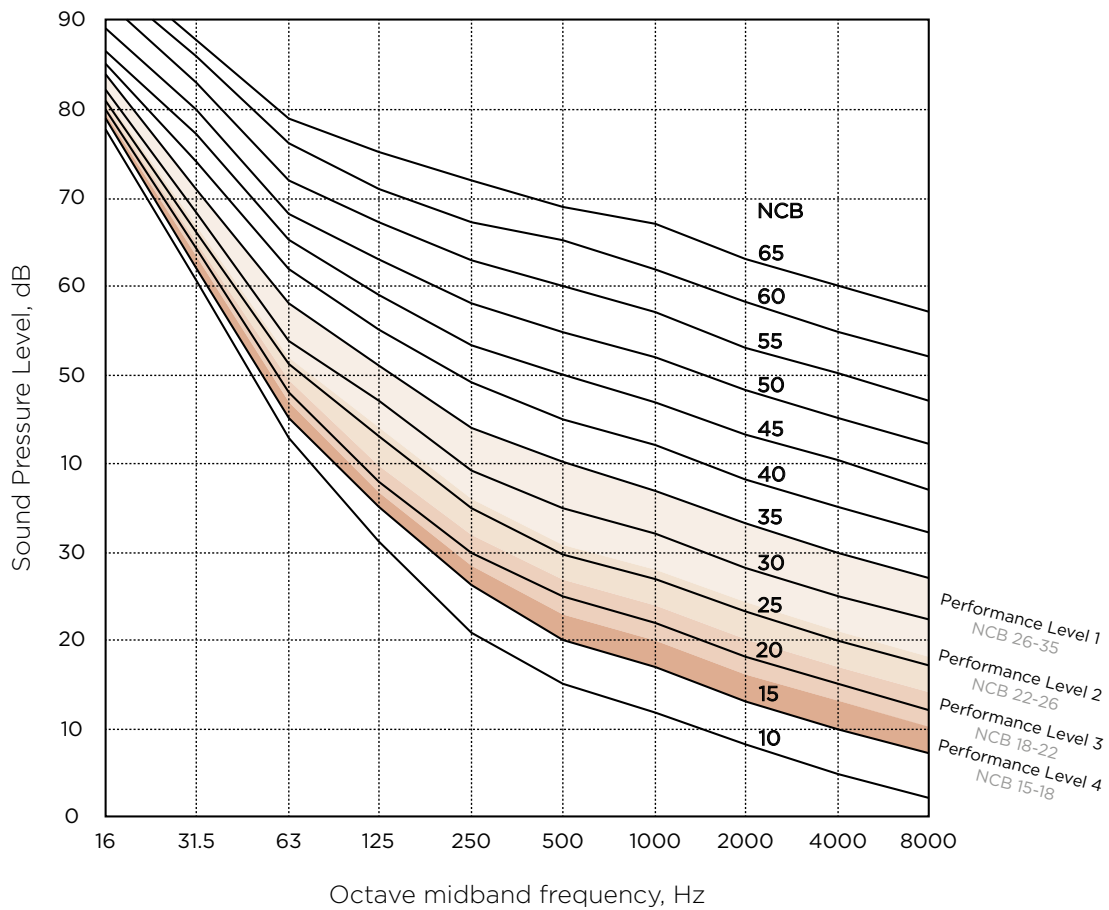
Figure C-1: NCB noise criterion curves showing Performance Level ranges (recommended to maximum)

For more detailed information regarding NCB and its rating curves, please refer to the 2019 ASHRAE Handbook — HVAC Applications, chapter 49 (pages 49.5-49.6).

APPENDIX

D

CALCULATING REVERBERATION TIME

D.1 CALCULATION USING CLASSIC SABINE EQUATION

The Sabine Equation is one of several approaches for calculating reflection decay time (expressed as RT60) in a space. It is most accurate for true reverberant spaces (large spaces). As such, Sabine is not necessarily the best method for small room acoustics where other methods (not referenced here) may result in more accurate predictions. However, due to its simplicity, it is a useful predictive tool to assist in approximating how much acoustical absorption is required.

The Sabine formulas for both metric and imperial measurements are as follows:

Metric:	**Imperial:**
RT60 = 0.161 V / A	RT60 = 0.049 V / A
RT60 is in secs	RT60 is in secs
V= Room volume in m^3	V= Room Volume in cubic feet
A = Absorption area in m^2	A = Absorption area in square feet
A = Sα	A = Sα
S = Surface area (m^2)	S = Surface area (ft^2)
α = Average Absorption Coefficient	α = Average Absorption Coefficient

"A" is calculated by adding the coverage area of sound absorbing materials (carpet, drapes, walls, etc.) on each boundary, multiplied by their individual absorption coefficients:

$$A = (S1α1 + S2α2 + S3α3 . . .)$$

Where S is the area in m^2 or ft^2, and α is the absorption coefficient for the material covering that area. Absorption coefficient is a measure of the proportion of sound that is absorbed by the material (the balance is reflected). It results in a number from 0 to 1, expressed in sabins; 0 means no sound is absorbed, while a coefficient of 1 means 100% is absorbed.

The sabine equation is frequency dependent, so a calculation must be made at each octave band 125 Hz to 4,000 Hz. This will provide a series of RT60 times per octave, which can be plotted and compared with the Performance Level criteria being targeted.

It is recommended to construct a spreadsheet or use a reliable app to make the calculations.

D.1.1   SABINE EQUATION EXAMPLE

Ideally the room should be measured empty to get an idea of the preexisting amount of acoustic absorption. Then the effect of the treatment & furnishings can be added. Otherwise the areas of untreated floor, walls, and ceiling must be included along with their absorption coefficients.

The following example starts without an absorption measurement.

Room size (LxWxH):	7m (23 ft) x 5m (16.4 ft) x 3m (9.8 ft)
Description of Room:	Dedicated Media Room, Performance Level 2
Construction:	Concrete floor, ceiling and walls lined with two layers of plasterboard on frame, 50 mm airspace with mineral wool
Floor:	Carpeted, with underlay
Seating:	9 (3 x 3 rows) leather-clad seats, each approximately 1 m (3.28 ft) wide by 1 m tall
Features:	Bass traps in the front corners
Acoustic treatments:	Sides have some diffusors and absorption panels (100 mm / 4 in.) Ceiling has some diffusion and absorption (50 mm / 2 in.) Back wall has some absorption panels (100 mm / 4 in.)

The table below includes the random incidence absorption coefficients of the materials, with data reproduced from http://www.acoustic.ua/st/web_absorption_data_eng.pdf. Branded absorption figures courtesy of RPG Europe and Artnovion.

Acoustic Treatment Product	Random Incidence Absorption Coefficient α, Hz					
	125	250	500	1000	2000	4000
2 x gypsum board on frame, 50 mm air space with mineral wool	0.15	0.1	0.06	0.04	0.04	0.05
9 mm pile carpet on felt underlay	0.08	0.08	0.3	0.6	0.75	0.8
Leather-clad seat (per m^2)	0.4	0.5	0.58	0.61	0.58	0.5
RPG Modex corner	0.54	0.36	0.21	0.26	0.32	0.46
Artnovion Lugano with diffuser	0.2	0.3	0.23	0.3	0.31	0.32
RPG absorber 100 mm	0.76	1	1	1	1	0.96
RPG absorber 50 mm	0.28	0.75	1	1	1	0.96

Summary of Room Dimensions	Measure
Length (**L**)	7 m
Width (**W**)	5 m
Height (**H**)	3 m
Volume	105 m³
Surface area **S-x**, side walls, (L x H x 2 walls)	42 m²
Surface area **S-y**, front and back walls, (W x H x 2 walls)	30 m²
Surface area **S-z**, floor + ceiling (L x W x 2)	70 m²
Total surface area	142 m²

Following is an example of the sabine calculations.

Products used	W mm	H mm	Qty	m²	125 Hz α	Sabine m²	250 Hz α	Sabine m²	500 Hz α	Sabine m²	1000 Hz α	Sabine m²	2000 Hz α	Sabine m²	4000 Hz α	Sabine m²
Absorption side walls (S-x)																
RPG 100mm absorber	800	1200	4	3.84	0.76	2.92	1	3.84	1	3.84	1	3.84	1	3.84	0.96	3.69
Artnovian Lugano with diffuser	600	600	12	4.32	0.2	0.86	0.3	1.30	0.23	0.99	0.3	1.30	0.31	1.34	0.32	1.38
RPG Modex corner	600	600	6	2.16	0.54	1.17	0.36	0.78	0.21	0.45	0.26	0.56	0.32	0.69	0.46	0.99
Seating	1000	1000	3	3.0	0.4	1.2	0.5	1.50	0.58	1.74	0.61	1.83	0.58	1.74	0.5	1.50
Total area of side walls				42												
Treatment coverage				13.32												
Untreated wall remaining				28.68	0.15	4.30	0.1	2.87	0.06	1.72	0.04	1.15	0.04	1.15	0.05	1.43

Products used	W mm	H mm	Qty	m²	125 Hz α	Sabine m²	250 Hz α	Sabine m²	500 Hz α	Sabine m²	1000 Hz α	Sabine m²	2000 Hz α	Sabine m²	4000 Hz α	Sabine m²
Absorption front and back walls (S-y)																
RPG 100mm absorber	800	1200	6	5.76	0.76	4.38	1	5.76	1	5.76	1	5.76	1	5.76	0.96	5.53
RPG Modex corner	600	600	6	2.16	0.54	1.17	0.36	0.78	0.21	0.45	0.26	0.56	0.32	0.69	0.46	0.99
Seating	1000	1000	3	3	0.4	1.2	0.5	1.50	0.58	1.74	0.61	1.83	0.58	1.74	0.5	1.50
Total area of front and back walls				30												
Treatment coverage				10.92												
Untreated wall remaining				19.08	0.15	2.86	0.1	1.91	0.06	1.14	0.04	0.76	0.04	0.76	0.05	0.95

Products used	W mm	H mm	Qty	m²	125 Hz α	Sabine m²	250 Hz α	Sabine m²	500 Hz α	Sabine m²	1000 Hz α	Sabine m²	2000 Hz α	Sabine m²	4000 Hz α	Sabine m²
Absorption ceiling (S-z)																
RPG 100mm absorber	800	1200	6	5.76	0.28	1.61	0.75	4.32	1	5.76	1	5.76	1	5.76	0.96	5.53
Artnovian Lugano with diffuser	600	600	6	2.16	0.2	0.43	0.3	0.65	0.23	0.50	0.3	0.65	0.31	0.67	0.32	0.69
Seating	1000	1000	9	9	0.4	3.60	0.5	4.50	0.58	5.22	0.61	5.49	0.58	5.22	0.5	4.50
Total area of side walls				35												
Treatment coverage				16.92												
Untreated ceiling remaining				18.08	0.15	2.71	0.1	1.81	0.06	1.08	0.04	0.72	0.04	0.72	0.05	0.90

Products used	W mm	H mm	Qty	m²	125 Hz α	Sabine m²	250 Hz α	Sabine m²	500 Hz α	Sabine m²	1000 Hz α	Sabine m²	2000 Hz α	Sabine m²	4000 Hz α	Sabine m²
Absorption floor (S-z)																
Seating	1000	1000	9	9	0.4	3.6	05	4.50	0.58	5.22	0.61	5.49	0.58	5.22	0.5	4.5
9mm pile carpet on felt underlay	*Floor less seating*			26	0.08	2.08	0.08	2.08	0.3	7.80	0.6	15.60	0.75	19.50	0.8	20.8
Total floor area				35												
Treatment coverage				35												
Untreated floor remaining				0												

Results	125 Hz		250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz	
Total sabines	34.09		38.08		43.43		51.30		54.80		54.90	
RT60	0.50		0.44		0.39		0.33		0.31		0.31	

Summary	Frequency, Hz					
	125	250	500	1000	2000	4000
RT60	0.50	0.44	0.39	0.33	0.31	0.31
Target Upper	0.5	0.5	0.4	0.4	0.4	0.4
Target Lower	0.2	0.2	0.2	0.2	0.2	0.2

In this example, the room will meet the criteria for recommended RT60 range (0.2 - 0.5 s).

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APPENDIX

E

UNIFIED SPEAKER LAYOUTS

E.1　SPEAKER LOCATION LABEL CORRELATION

Different industry standards and immersive audio formats not only employ some difference in speaker layouts approaches, as depicted in Section 5.2, but also in some specific speaker placement guidelines (especially elevation and azimuth angles of upper speakers) and corresponding labels.

Most speaker locations can be correlated and unified for use across the various formats. Table E-1 on the following page provides a cross-reference for discrete feed speaker location labels as detailed in this recommended practice against the equivalent labels as used by the immersive audio format developers, and approximate correlation to the ITU-R BS.2051-3 (05/2022) standard.

The descriptions in bold represent the most common locations that compose a 7.1.4 system. Surround speaker locations ending with a number (e.g., SL1/SR1, SL2/SR2, etc.) are secondary locations to the corresponding primary pair (SL/SR), the latter of which is relative to the reference seating position, as detailed in Section 5.3.

Table E-1: Cross-reference of discrete speaker feed location labels between formats

Description	RP22	Dolby Atmos	Auro-3D	DTS:X (≤ 7.1.4)	DTS:X Pro	SMPTE ST 377-42
Listener-level layer						
Front Left	**FL**	L	L	L	L	L
Front Center	**FC**	C	C	C	C	C
Front Right	**FR**	R	R	R	R	R
Front Center Left	FCL	Lc	-	-	Lc	Lc
Front Center Right	FCR	Rc	-	-	Rc	Rc
Front Wide Left	FWL	Lw	-	-	Lw	Lw
Front Wide Right	FWR	Rw	-	-	Rw	Rw
Surround Left 1	SL1	Ls1	Ls	Ls / Lss	Lss	Lss
Surround Left	**SL**	Ls				
Surround Left 2	SL2	Ls2			Ls	
Surround Right 1	SR1	Rs1	Rs	Rs / Rss	Rss1	Rss
Surround Right	**SR**	Rs			Rss	
Surround Right 2	SR2	Rs2			Rss2	
Surround Back Left 1	SBL1	Lrs1	Lb	Lsr	Lss1	Lrs
Surround Back Left	**SBL**	Lrs			Lss	
Surround Back Left 2	SBL2	Lrs2			Lss2	
Surround Back Right 1	SBR1	Rrs1	Rb	Rsr	Rs	Rrs
Surround Back Right	**SBR**	Rrs			Rsr	
Surround Back Right 2	SBR2	Rrs2				
Surround Center Left	SCL	Lcs	-	-	Lsr	-
Surround Center Right	SCR	Rcs	-	-	Rsr	-
Surround Center	SC	Cs	-	-	Cs	Cr
Upper layer						
Height Front Left	HFL	Lfh	HL	Lh / Ltf	Lh	Lh
Height Front Center	HFC	-	HC	-	Ch	Ch
Height Front Right	HFR	Rfh	HR	Rh / Rtf	Rh	Rh
Top Front Left	**TFL**	Rtf	-	Lh / Ltf	Ltf	Ltfs
Top Front Right	**TFR**	Rtf	-	Rh / Rtf	Rtf	Rtfs
Top Middle Left	TML	Ltm	-	-	Lhs / Ltm	Ltms
Top Middle Right	TMR	Rtm	-	-	Rhs / Rtm	Rtms
Top Back Left	**TML**	Ltr	-	Ltr / Lhr	Ltr	Ltrs
Top Back Right	**TMR**	Rtr	-	Rtr / Rhr	Rtr	Rtrs
Top Middle Center	TMC	-	T	-	OH	Ts
Height Back Left	HBL	Lrh	HLs	Ltr / Lhr	Lhr	Lrsh
Height Back Center	HBC	Rrh	HRs	Rtr / Rhr	Rhr	Crh
Height Back Right	HBR	-	-	-	Chr	Rrsh

E.2 RECOMMENDED SPEAKER LAYOUTS FOR IMMERSIVE SOUND OVER MULTIPLE SEATS

Performance Level parameter 2 stipulates the minimum required number of discrete speaker feeds from the processor/OAR, as follows:

Parameter (continued)	Unit	Target	Level 1	Level 2	Level 3	Level 4	Room/ Seat
2. Decoder/renderer capability and discretely rendered speaker configuration, excl. subwoofers	Number discrete speakers	Min.	**5**	**11**	**15/13***	**15/13***	Room
Includes all listener-level and upper discrete processor outputs, though there are multiple combinations of speaker locations possible therein, depending on the room design and characteristics. * Auro-3D specific room design requires 13 discrete feeds; for other formats the minimum should be 15 for Levels 3 and 4.							

In support of this, several speaker layout recommendations are depicted in the following pages. These range from 5 main speakers (Appendix E.2.1) as the entry point for both an immersive audio system and Performance Level 1, to more than 19 main speakers (Appendix E.2.9) to contribute to a high-end realization of a Performance Level 3 or 4 system. Note that these speaker counts are for listener-level and upper discrete speaker feeds and exclude LFE/subwoofers.

Other recommended speaker layouts composed of up to 38 main speakers are presented in other documents — see resources #4 and #5 in Appendix E.3. These include up to 5 screen speakers, up to 16 surround speakers, and up to 15 upper speakers, along with more subwoofer and quadri-amp screen speakers.

Where a speaker layout is described as "sub-optimal" for a given format, it refers to some available speakers not being required or used by the format, while other speakers are missing to reproduce the content at its highest performance.

For example, a speaker layout that includes front wide (FWL/FWR) but no height front center (HFC) or top middle center (TMC, "Voice of God") speakers will be sub-optimal for Auro-3D. Conversely, a speaker layout with height front center (HFC) and top middle center (TMC) speakers but no front wide left/right speakers (FWL/FWR) will be sub-optimal for Dolby Atmos. The presence of *all* of these speakers, as depicted in "19 Discrete Speakers" (Appendix E.2.8), will not only enable optimal reproduction of both Dolby Atmos and Auro-3D content, but also DTS:X Pro.

E.2.1 5 DISCRETE SPEAKERS

Systems comprising 5 main speakers can be in a variety of configurations for entry level immersive sound. These include traditional 5.1 without upper layer, 3.1.2 with reflected upper layer using upfiring/ elevation speakers instead of overhead speakers, or 3.1.2 configuration with overhead speakers. The latter is depicted below.

- Minimum for **Performance Level 1**
- A first step toward immersion for basic Dolby Atmos and DTS:X
- Suitable with seating against back wall

- No upper layer if 5.1, no surrounds if 3.1.2
- Large gaps in sound field
- Unstable localization and limited front-back steering
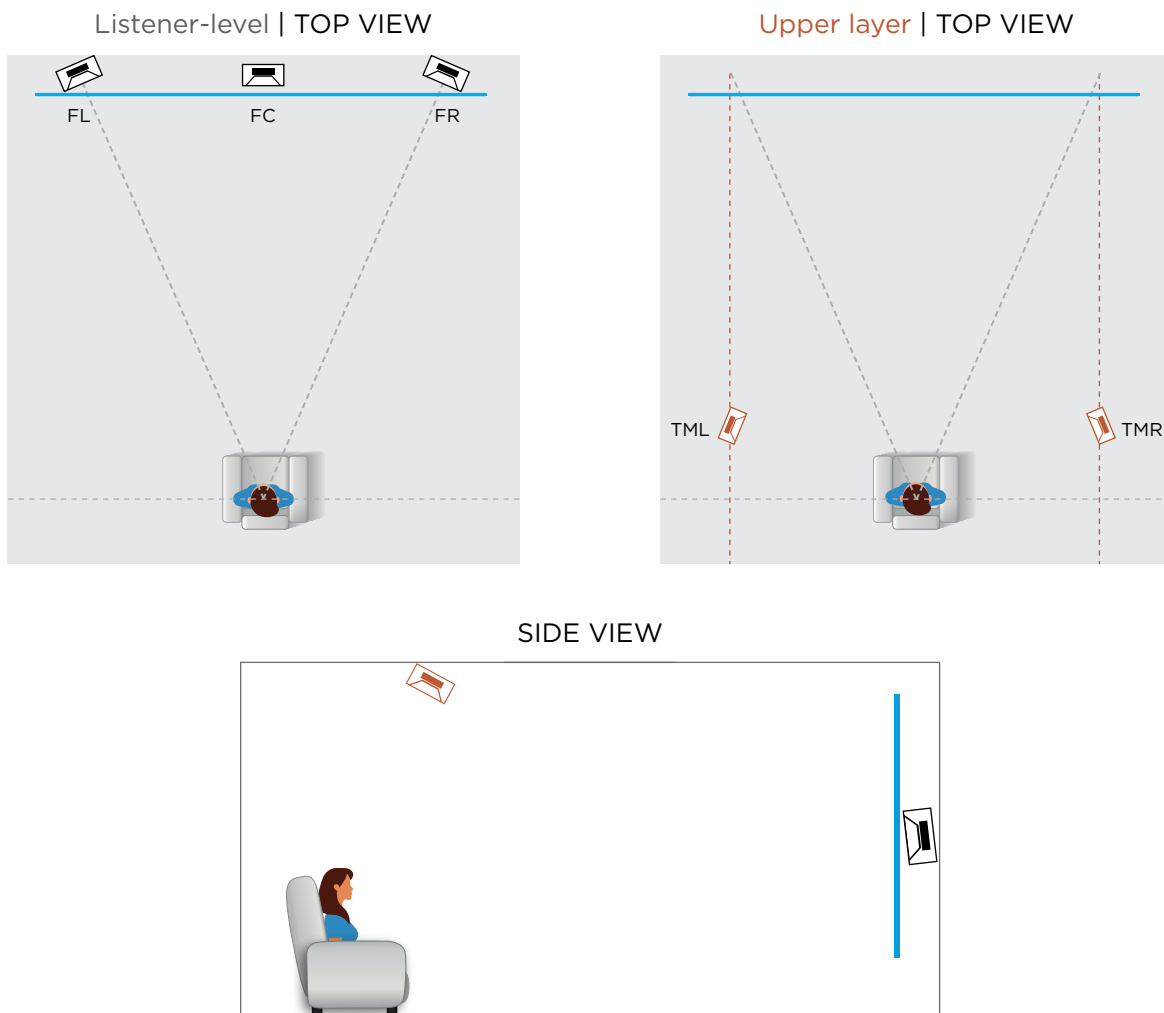- Correct spatial rendering for one seat only
- Unable to play Auro-3D

Listener-level | TOP VIEW

Upper layer | TOP VIEW

SIDE VIEW

Figure E-1: Layout with 5 main speakers with no listener-level surrounds and a single pair in the upper layer

E.2.2 7 DISCRETE SPEAKERS

Features 7 main speakers in a 5.1.2 configuration.

- Improved **Performance Level 1**
- A step toward immersion

- Gap between listener and upper layers
- Unstable localization and limited front-back steering above the head
- Correct spatial rendering for one seat only
- Unstable rear image
- Unable to play Auro-3D
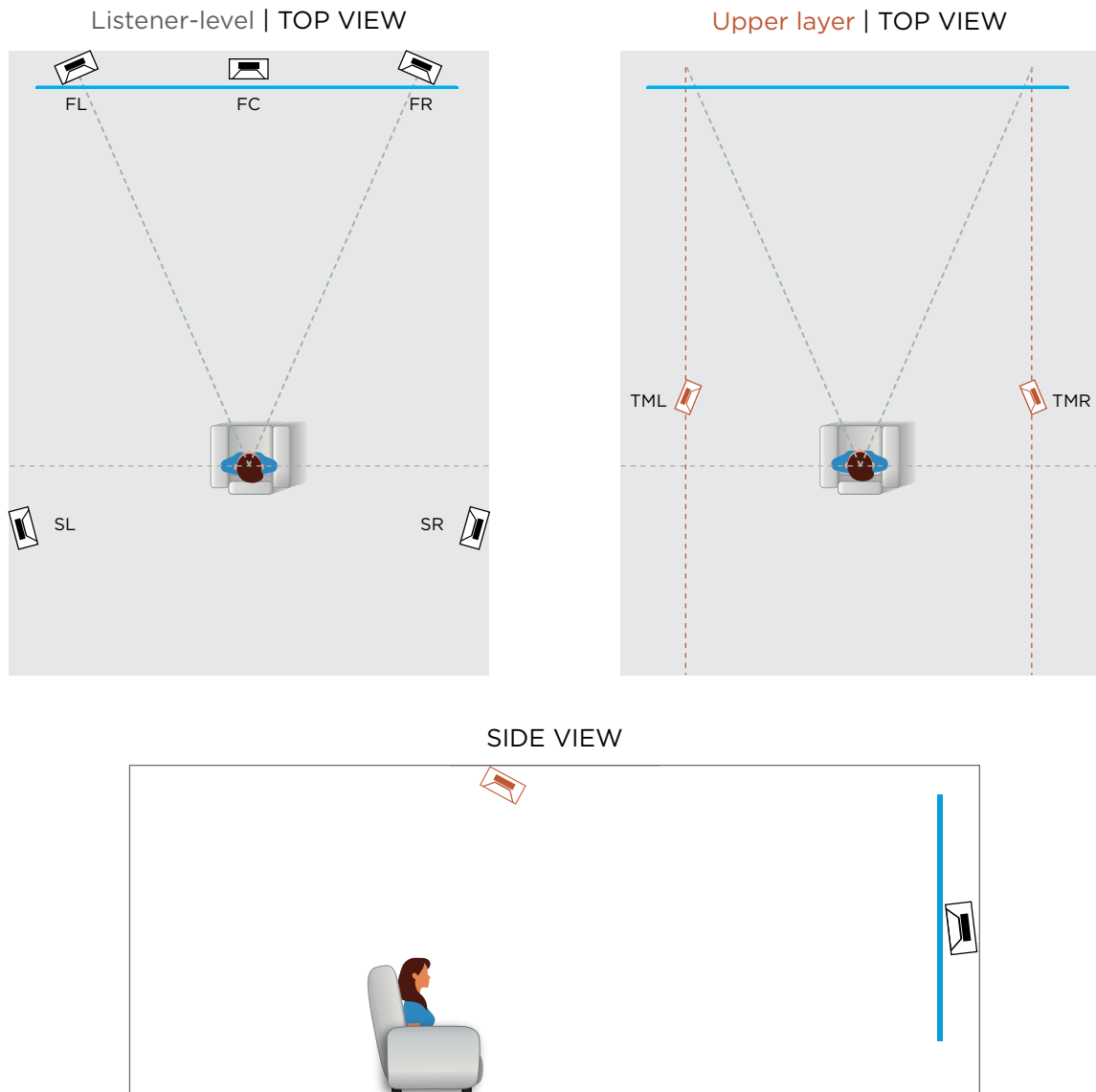- Gap between screen and surround

Listener-level | TOP VIEW

Upper layer | TOP VIEW

SIDE VIEW

Figure E-2: Layout with 7 main speakers with just a single pair in the upper layer

E.2.3   9 DISCRETE SPEAKERS

Features 9 main speakers in a 5.1.4 configuration.

- Recommended for **Performance Level 1**
- The minimum for effective immersive sound
- The minimum for Auro-3D (Auro 9.1)
- Possible seating against back wall (though not recommended)

- Correct spatial rendering for one seat only
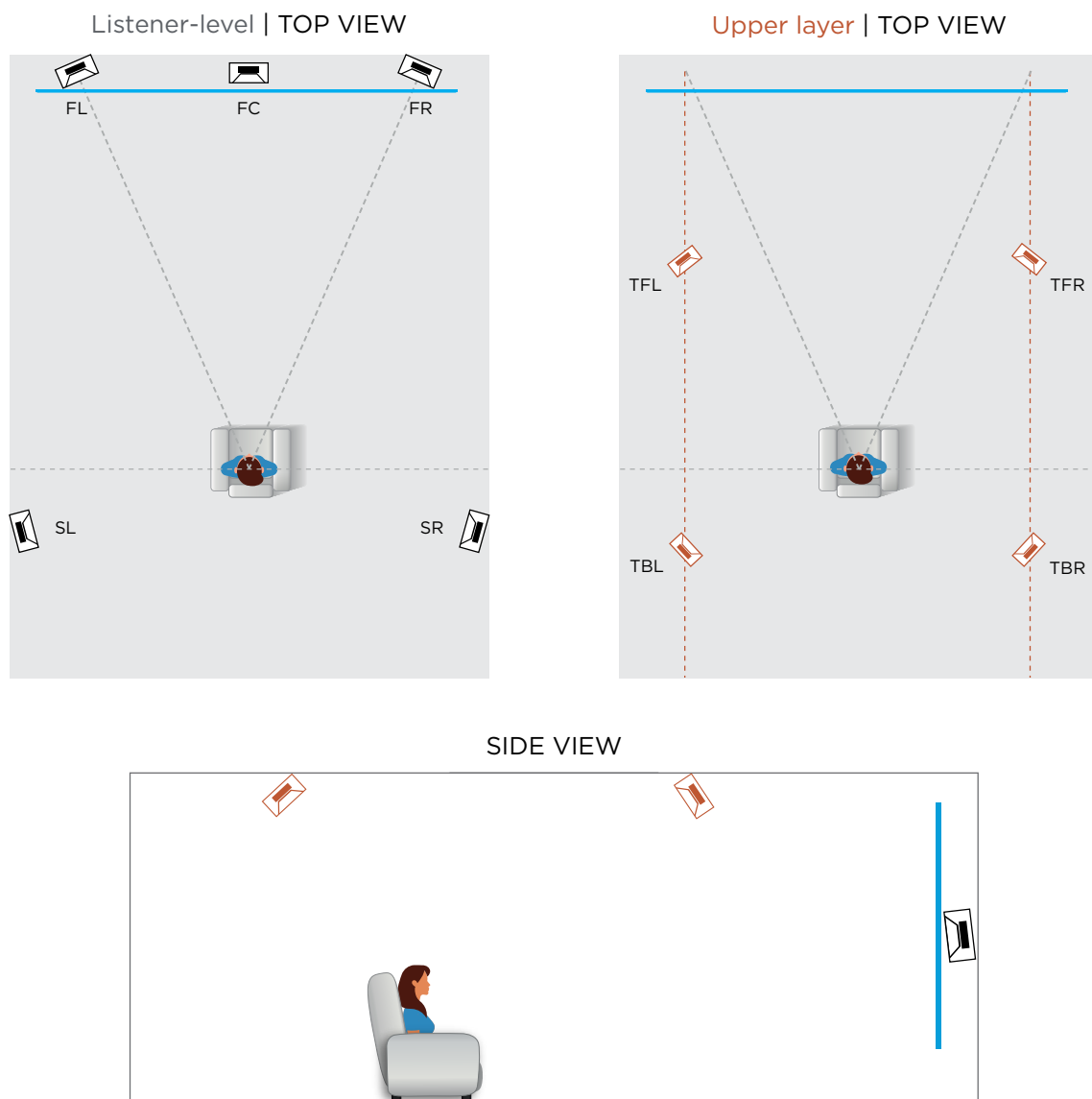- Unstable rear image
- Gap between screen and surrounds

Listener-level | TOP VIEW

Upper layer | TOP VIEW

SIDE VIEW

Figure E-3: Recommended layout with 9 main speakers for spatial rendering around a single seat

E.2.4   11 DISCRETE SPEAKERS

Features 11 main speakers in a 7.1.4 configuration.

| |
|---|
| • Minimum for **Performance Level 2**
 • Optimal locations for Atmos 7.1.4
 • Maximum support for DTS:X (not Pro)
 • Equates to Auro 11.1
 • Minimum configuration for full envelopment |
| • Gap between screen and surrounds
 • Sub-optimal height locations for Auro 11.1 (unified with Atmos and DTS:X)
 • Not suitable for situations where the seating (e.g., couch) is against the wall |

Listener-level | TOP VIEW

Upper layer | TOP VIEW

SIDE VIEW
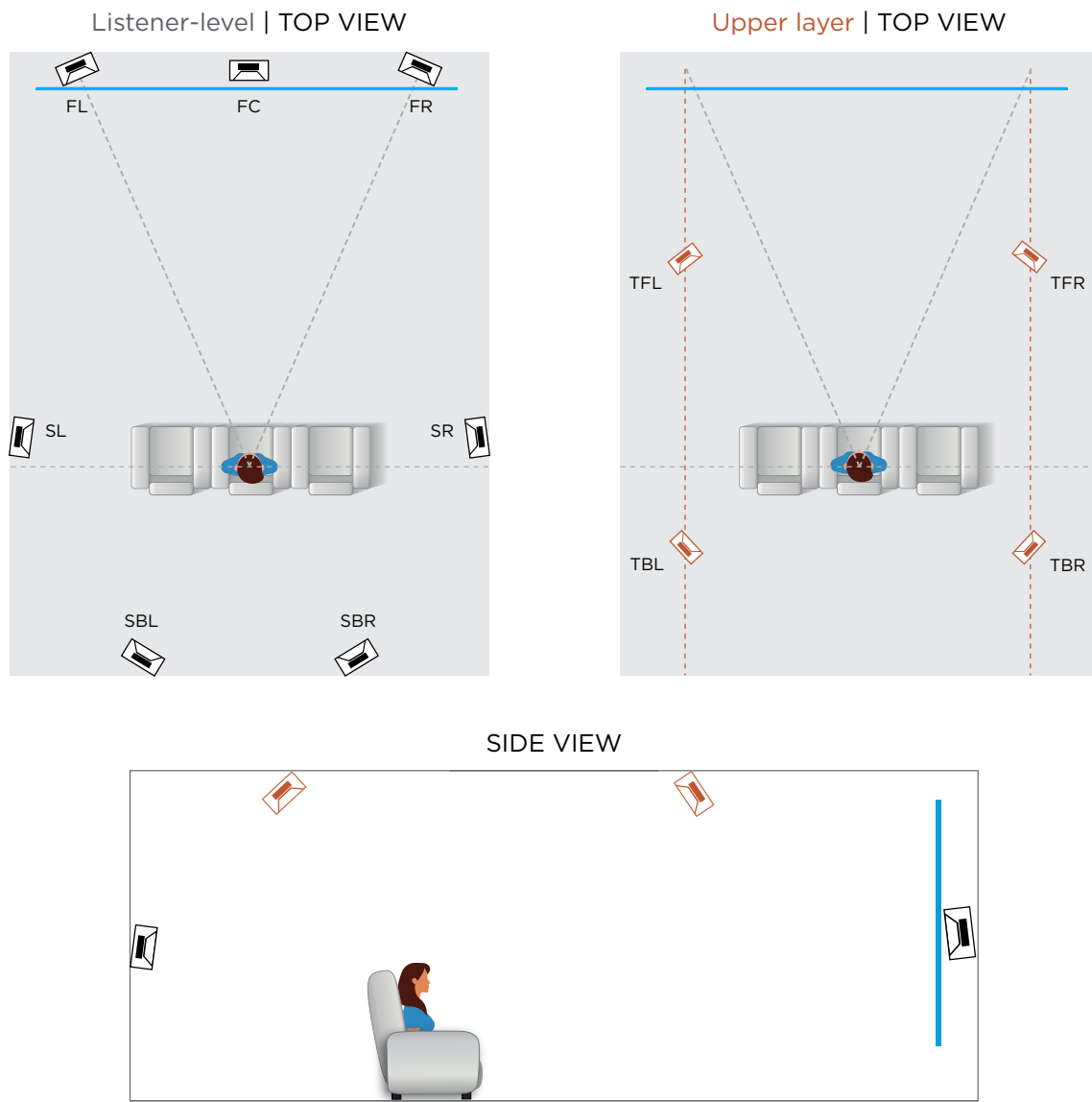
Figure E-4: Recommended layout with 11 main speakers configured around a single row of seating

E.2.5   13 DISCRETE SPEAKERS

Features 11 main speakers with additional 2 being a choice between front wide pair (FWL/FWR) for Atmos and DTS:X Pro, or height front center and top middle center (HFC + TMC) to optimize Auro-3D.

- Enhanced **Performance Level 2**
- Maximum Auro 13.1 supported if HFC/TMC are implemented, albeit with comprised height front/back positioning
- **Suitable for single row of seating**

- **Dolby Atmos limited to 7.1.4** if FWL/FWR not implemented
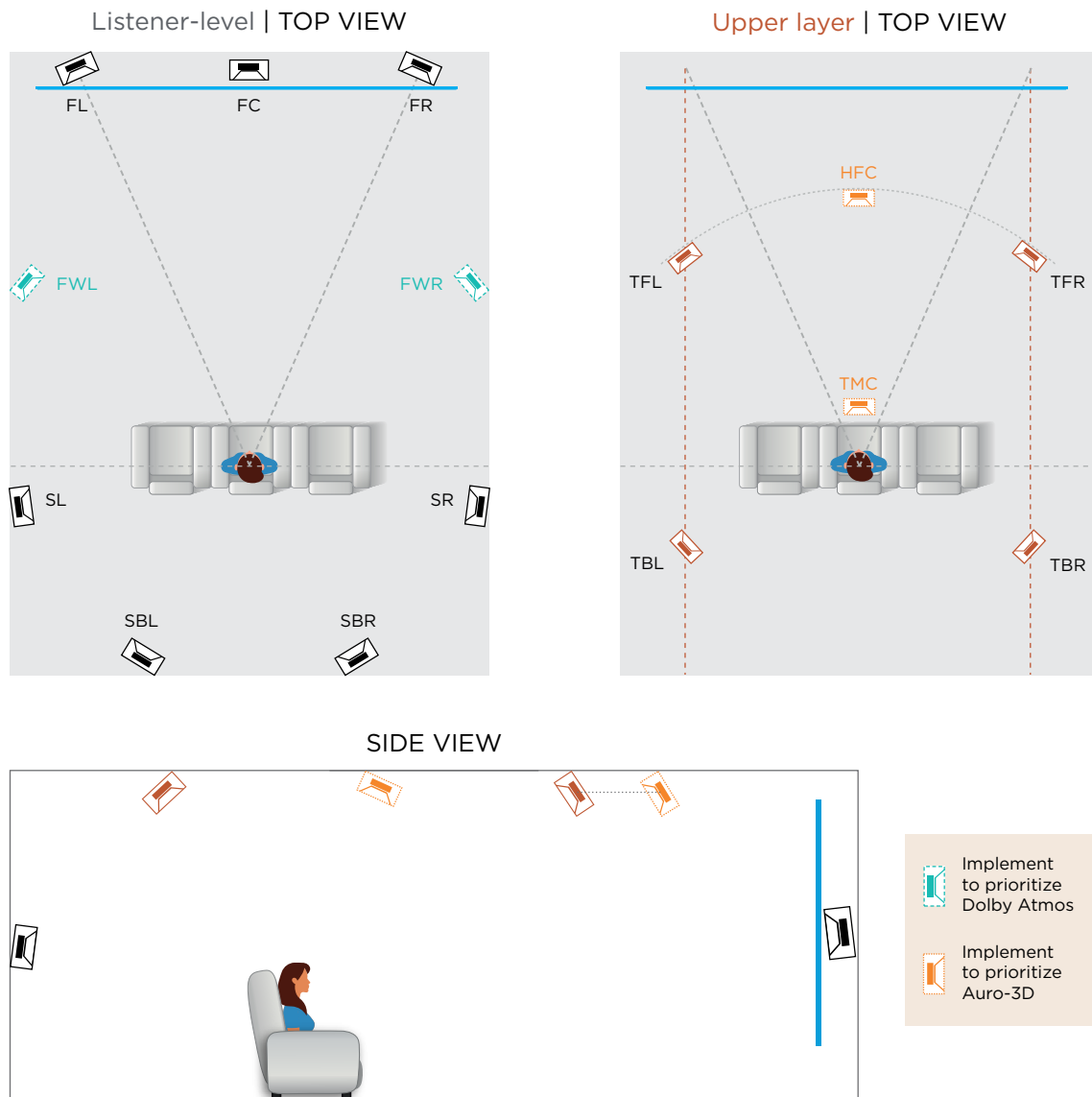- **Auro-3D limited to 11.1** if HFC/TMC not implemented

Listener-level | TOP VIEW

Upper layer | TOP VIEW

SIDE VIEW

Implement to prioritize Dolby Atmos

Implement to prioritize Auro-3D

Figure E-5: Recommended layout with 13 main speakers configured around a single row of seating

E.2.6 15 DISCRETE SPEAKERS

Features 13 main speakers with additional 2 being a choice between top middle pair (TML/TMR) for Dolby Atmos or height front center and top middle center (HFC + TMC) to optimize Auro-3D.

- Recommended for **Performance Level 2**
- Improved Atmos front-back steering if TML/TMR are implemented
- Auro 13.1 if HFC/TMC are implemented
- **Suitable for single row of seating**

- **Dolby Atmos limited to 9.1.4** if TML/TMR not implemented
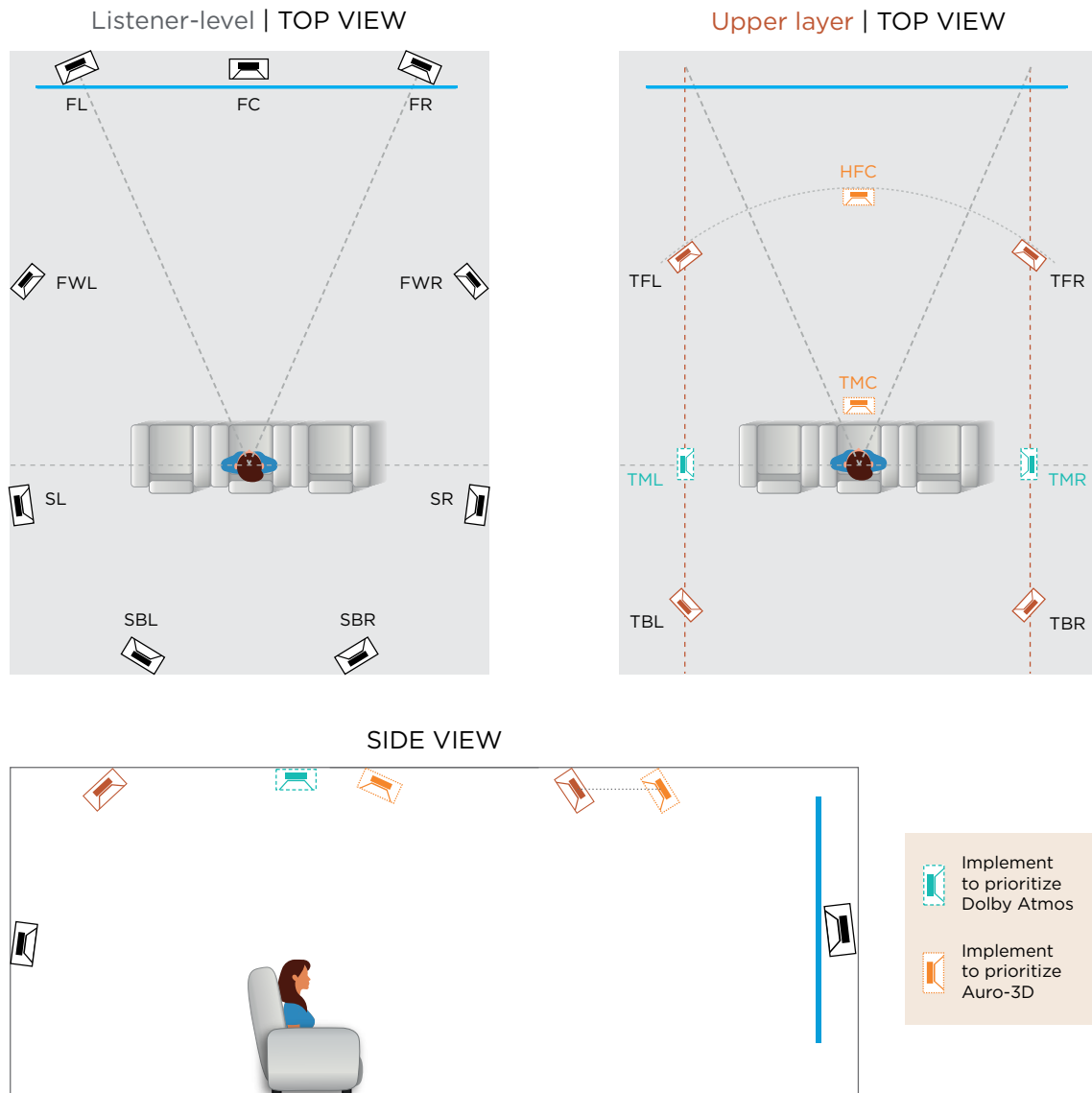- **Auro-3D limited to 11.1** if HFC/TMC not implemented

Listener-level | TOP VIEW

Upper layer | TOP VIEW

SIDE VIEW

Implement to prioritize Dolby Atmos

Implement to prioritize Auro-3D

Figure E-6: Recommended layout with 15 main speakers configured around a single row of seating

E.2.7   17 DISCRETE SPEAKERS

Features 15 main speakers with additional 2 being a choice between top middle pair (TML/TMR) for Dolby Atmos or height front center and top middle center (HFC + TMC) to optimize Auro-3D.

- Minimum for **Performance Levels 3 & 4**
- Improved Atmos front-back steering if TML/TMR are implemented
- Auro 13.1 if HFC/TMC are implemented
- **Recommended minimum for 2 rows**

- **Dolby Atmos limited to 11.1.4** if TML/TMR not implemented
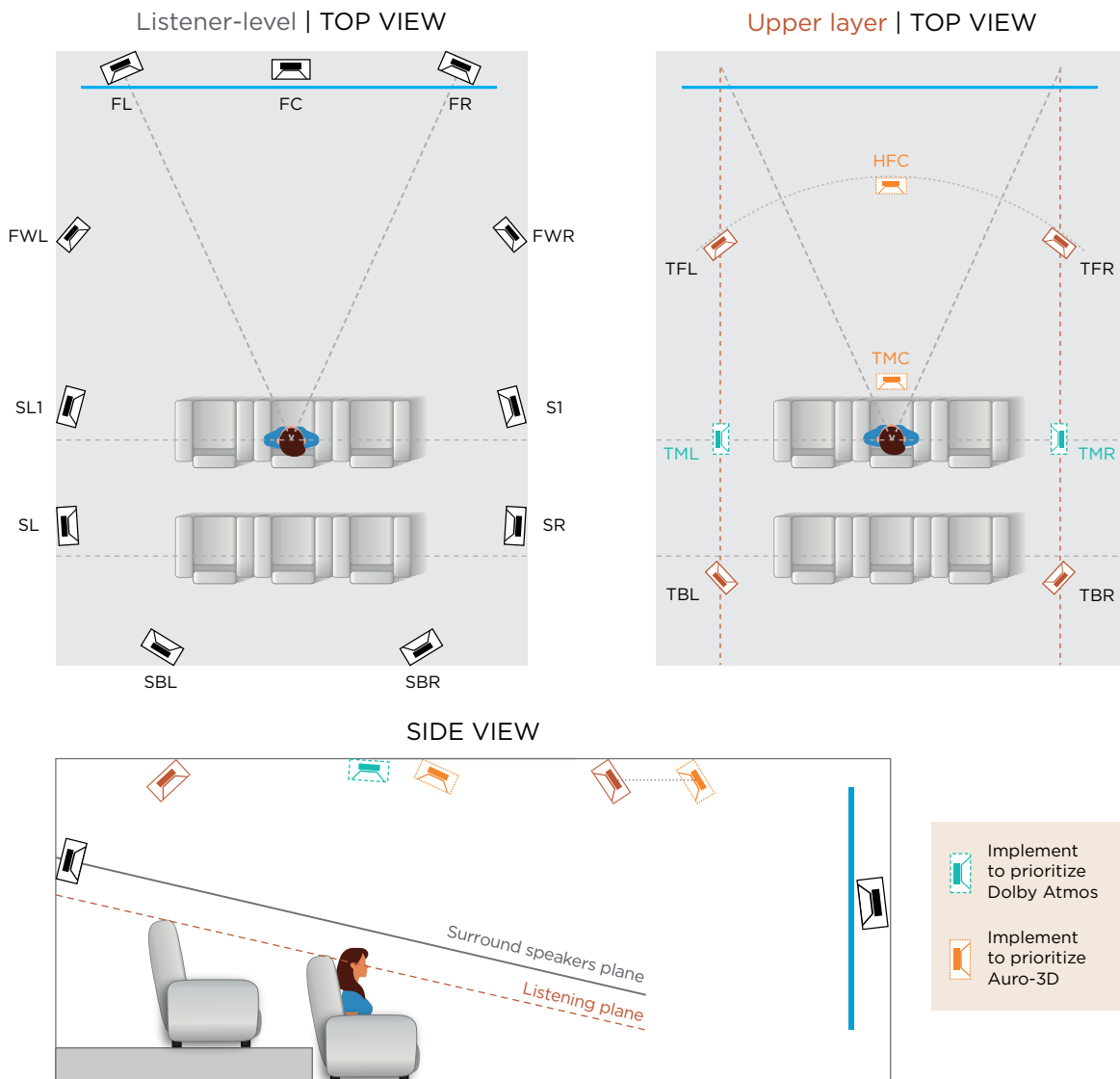- **Auro-3D limited to 11.1** if HFC/TMC not implemented

Figure E-7: Recommended layout with 17 main speakers, includes additional 2 surround speakers to accommodate 2nd row

E.2.8   19 DISCRETE SPEAKERS

Employs all speakers from the 17 speaker layout without having to choose between TML/TMR and HFC/TMC to optimize all formats.

- Enhanced **Performance Levels 3 & 4**
- Optimal reproduction of immersive formats including Auro 13.1
- Recommended minimum for 2 rows

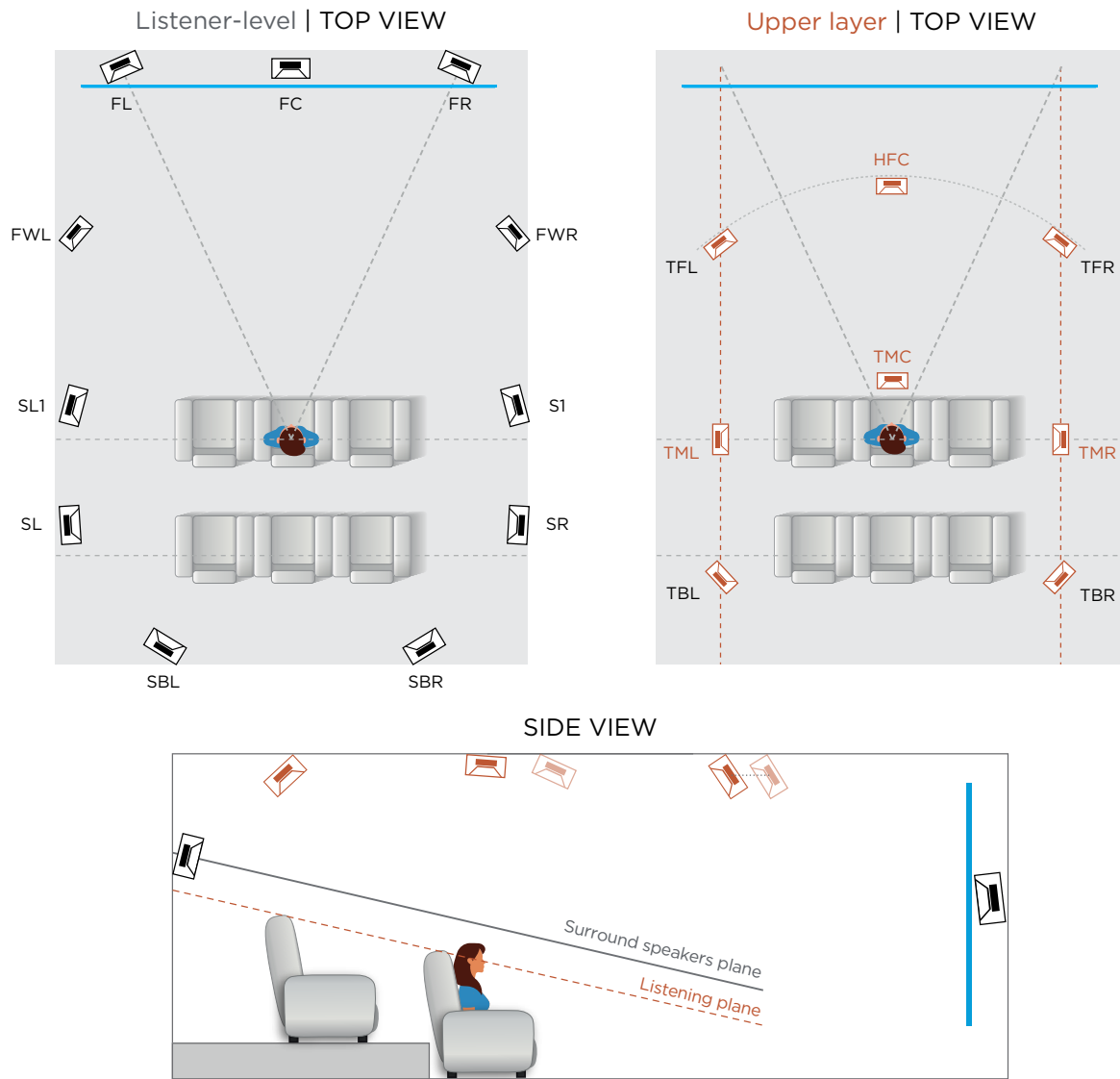- Dolby Atmos limited to 11.1.6, not maximum 11.1.8 or full complement of DTS:X Pro

Listener-level | TOP VIEW

Upper layer | TOP VIEW

SIDE VIEW

Figure E-8: Recommended layout with 19 main speakers to optimize all formats

E.2.9 MORE THAN 19 DISCRETE SPEAKERS

Figure E-9 illustrates an example of a layout composed of 29 main speakers for high spatial resolution over a larger seating area (3 rows).

- **Performance Levels 3 & 4**
- Very high spatial resolution
- Front height speakers (HFL/HFC/HFR) placed according to Auro-3D guidelines
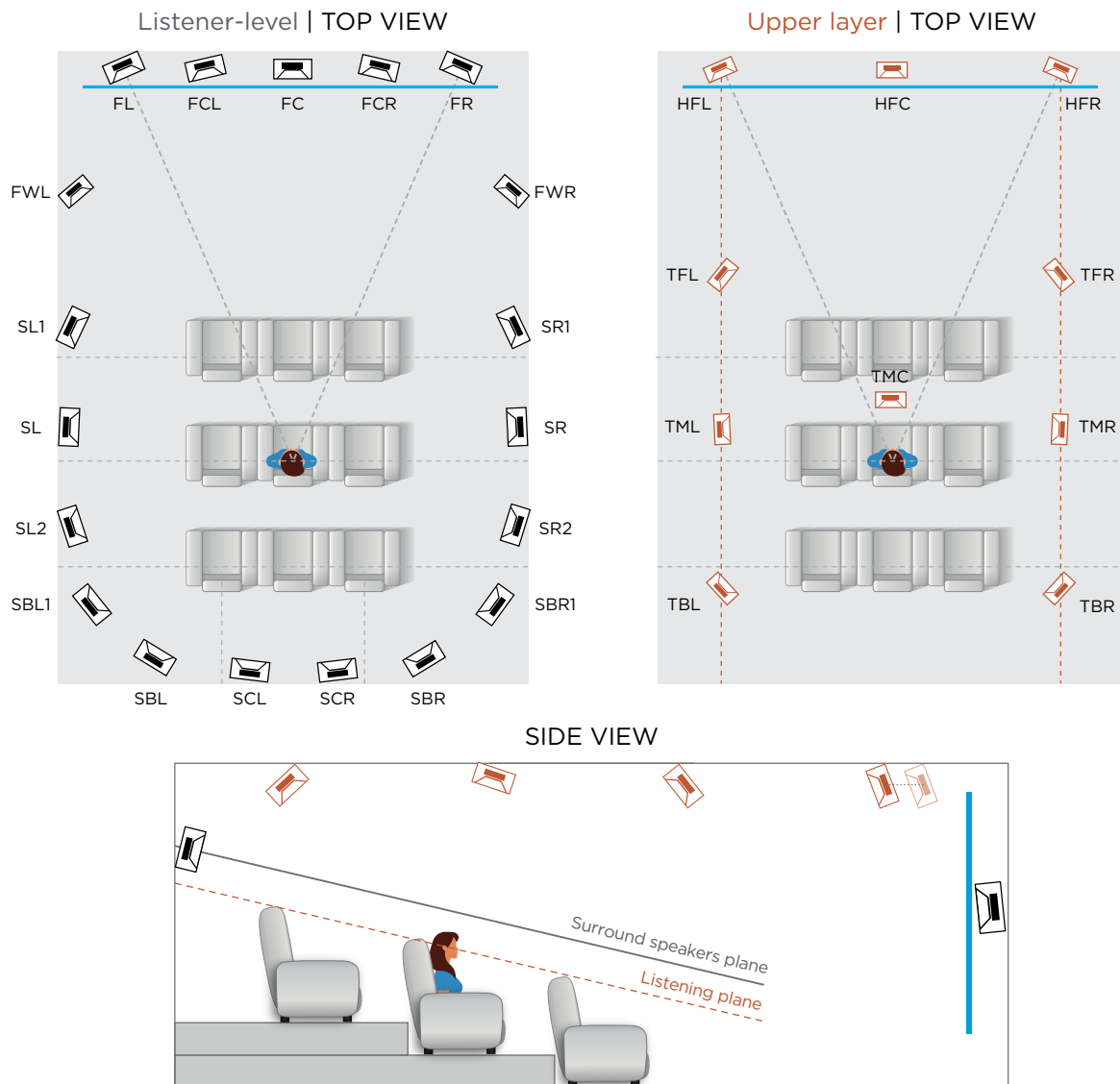- **Recommended for 3 rows or more**

Listener-level | TOP VIEW

FL FCL FC FCR FR

FWL FWR

SL1 SR1

SL SR

SL2 SR2

SBL1 SBR1

SBL SCL SCR SBR

Upper layer | TOP VIEW

HFL HFC HFR

TFL TFR

TML TMC TMR

TBL TBR

SIDE VIEW

Surround speakers plane

Listening plane

Figure E-9: Example of layout with 29 main speakers to optimize high spatial resolution in all formats

The higher channel count in this example can provide exceptional spatial resolution and seat-to-seat consistency over an enlarged listening area. A vast number of speaker layouts can be developed according to specific project needs. These should be based on industry recommended practices and standards.

E.3 ADDITIONAL RESOURCES

The following resources provide further information and setup guides:

1. Dolby Atmos speaker setup guides, Dolby Laboratories, Inc.
   https://www.dolby.com/about/support/guide/speaker-setup-guides/

2. Auro-3D website by NEWAURO BV, Belgium
   https://www.auro-3d.com

3. MPEG-H Audio website by Fraunhofer IIS, Germany
   https://mpegh.com/experience/#imm-sec

4. One Speaker Layout for all Immersive Audio Formats, article by Wilfried van Baelen
   Widescreen Review issue 256, July/August 2021
   https://widescreenreview.com

5. Trinnov Audio Speaker Layout Guide
   https://www.trinnov.com/en/blog/posts/trinnov-speaker-layout-guide/

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1. CTA 2034 (Spinorama) image source: Harman International
   https://speakerdata2034.blogspot.com/2019/02/spinorama-cea-2034-2015-ansi-data-format.html

   Section 6.1.1

2. Horizontal and vertical directivity heat map diagrams provided by Perlisten Audio, WI, USA

   Section 6.1.2

3. "Low-frequency Optimization Using Multiple Subwoofers,"
   T. Welti, A. Devantier, J. Audio Eng. Soc. J. Audio Eng. Soc.,
   Vol. 54, No. 5,pp. 347-364 (2006 May)

   Section 7.3.2.1   App B.3

4. Noise reduction R_w plots based on doorset product testing reports from Falcon Panel Products Ltd, U.K.

   Section 8.1.1

5. Flanking paths image source — "Acoustics in Buildings, "
   Acoustics Products Ltd., U.K.
   https://www.acoustic-products.co.uk/faq/acoustics-in-buildings/

   Section 8.3

6. "An Investigation Into the Acoustic Effect of Cinema Screens on Loudspeaker Performance"
   P. Newell, J. G. García, K. Holland for the University of Southampton. Published by the Institute of Acoustics, Proceedings Vol. 35 Pt. 2, 2013

   Section 9.4.3

7. "How many Subwoofers are Enough?"
   T. Welti, J. Audio Eng. Soc. (Abstract), presented at the 112th Convention of the Audio Engineering Society, Preprint 5602 (May 2002)

   Appendix B.2

8. "Subjective Comparison of Single Channel versus Two Channel Subwoofer Reproduction"
   T. Welti, Journal of Audio Engineering Society, presented at the 117th Convention of the Audio Engineering Society, Preprint 6322, (Oct 2004)

   Appendix B.2

9. "Immersive Audio and Using the x.y.z Syntax," CEDIA White Paper (2022)

   Appendix B.2

10. "Multiple Digital Filter Design for Inversion Problems in Sound Reproduction," O. Kirkeby, P. A. Nelson, J. Audio Eng. Soc.,
    Vol. 47, pp. 583-595 (1999 July/August)

    Appendix B.3

11. "Inverse Filtering of Room Acoustics," M. Miyoshi, Y. Kaneda, IEEE Transactions on Acoustics, Speech, and Signal Processing, Vol. 36, No. 2

    Appendix B.3

12. "Low Frequency Sound Field Enhancement System for Rectangular Rooms Using Multiple Low Frequency Loudspeakers,"
    A. Celestinos, S.B. Nielsen, J. Audio Eng. Soc. Presented at the 120th Convention of the Audio Engineering Society, reprint 6688, (2006 May)

    Appendix B.3