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Perception of Reverberation in Small Rooms: A Literature Study

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ABSTRACT

Reverberation is considered as one of the fundamental perceived properties of an acoustical space. Literature is available on the topic and currently a range of sciences have contributed in understanding the properties of reverberant sound fields and the relevant auditory processes. This paper summarises the current literature following a top-down approach. It identifies the perceptual aspects of reverberation and attempts to establish links to physical measures, focussing on small rooms. Results indicate that the current acoustical metrics often have limited correlation to the perceptual attributes of reverberation and conclusive measurement data is restricted, especially for small spaces. A proposal for perceptually-based experiments is presented, aiming to further understand the links between physical properties of rooms and their effects on perception.

1. INTRODUCTION

In enclosed spaces, the interaction between the sound source and the room's boundaries produce a distinctive sound field, which is commonly characterised as *reverberation*. Reverberation is normally used as a global umbrella to describe a set of physical, perceptual and affective features of certain sound fields. In the physical domain, a number of objective metrics describing the acoustic properties of reverberant sound fields have been established and standardised [1, 2, 3]. However, what describes reverberation in the perceptual and affective domains -that is the human perception- is yet, not fully understood [4, 5]. This paper examines and analyses the published scientific literature related to reverberation, in an attempt to identify the most important perceptual characteristics of reverberant sound fields (Section 2), and seeks their relations to the proposed physical metrics (Section 3). This approach will form the benchmark framework for further investigation on the properties of reverberation aiming towards the perceptual control of reverberant sound fields in typical-sized, domestic spaces (Section 4).

As the direct investigation of the perceptual aspects of reverberation is very limited for small rooms, it is worthwhile to evaluate the scientific literature in concert hall acoustics, spatial audio, psychoacoustics, and acoustic measurement in an attempt to merge findings, identify common paths, and seek the applicability of these relationships in every-day listening spaces. Here, the literature is examined and analysed based on the principles of the *Filter Model* [6, 7, 8]; the content of the paper will be categorised based on the two domains of the model, the physical and the perceptual. A brief introduction to the model is given below.

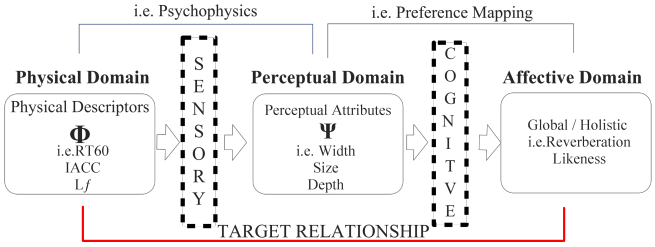


Fig. 1: The Filter Model, comprising three domains, physical, perceptual, and affective separated by a sensory and a cognitive filter respectively.

1.1. Filter Model

According to the filter model (Fig.1), a *physical stimulus* (e.g. sound event) is perceived after being filtered by our senses (e.g. hearing) resulting to a *perceptual entity* (e.g.

auditory event). The percept also passes through a *cognitive* filter, which represents the non-sensory factors such as mood, expectations, and memory. One advantage of the filter model is the ability to estimate the human *affective* response based on physical measurements, by using the perceptual domain as the bonding element. This approach effectively associates these domains by dividing it into two steps. The identification of: (1) links between the physical measurement and perceptual attributes - i.e. psychophysics and perceptual models, and (2) the links between perceptual attributes and the affective response for a given global percept - i.e. preference mapping.

1.2. Physical Domain - Reverberation

The physical basis of reverberation is briefly presented below, as several metrics reviewed in this manuscript are based on these principles. However, the physical description of a reverberant sound field is not the focus of this paper, and the interested reader is referred to [9, 10].

1.2.1. The Reverberant Sound Field

Reverberation was primarily thought to be a global acoustic behaviour of an environment: the distinct prolonging sound caused by reflective surfaces and slow speed of sound [9, 11, 12]; resembling what humans sense as *Reverberance*. Through years of research it was clear that the perceived sound field, as seen from the listener's position, consist of two distinct stages. Figure 2 shows a simplified example of a *Room Impulse Response* (RIR). Sound typically travels along the direct path - towards the receiver - and it arrives after a propagation delay *t*. Then, *early reflections* originating from nearby objects/boundaries (i.e. ceiling, floor, sidewalls) arrive at the receiver. As the reflections spread in a finite space and speed, they interact with each other, effectively increasing the echo density over time and decreasing their intensity. This interaction results to another typical pattern of an RIR, referred to as *late reflections*.

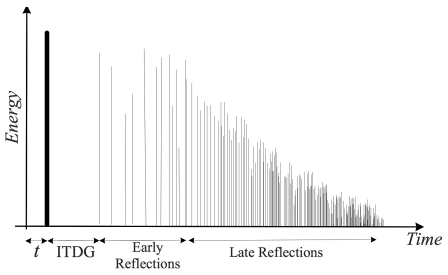


Fig. 2: A typical Impulse Response in a room.

It should be noted that in this paper 'reverberation' will be used as the global descriptor of the acoustic behaviour of the room, unless otherwise stated. The term 'Reverberance' will be used as a perceptual descriptor of sensing the late part of reverberation. In the following text, the current objective metrics used to characterise reverberant sound fields will be presented, followed by the perceptual attributes found in similar literature.

1.2.2. Reverberation's Objective Metrics

Research in acoustics, primarily in concert halls, initially focussed on the objective and physical characterisation of reverberation. Numerous physical aspects and mathematical explanations of reverberant fields have been investigated and their findings established common acoustic measurements such as *Reverberation Time* (RT), *Early Decay Time* (EDT), *Sound Strength* (G), *Early Energy Fraction* (J_{LF}), *Late Lateral Sound Level* (J_j), *Interaural Cross-Correlation* (IACC), *Clarity Index* ($C_{50/80}$) and others [1, 3, 13]. These metrics target the quantification of the average physical properties of the reverberant sound field in concert halls, 'providing a single number, which is relevant to at least some aspect of the acoustical quality' [14], p189. Recent studies [5, 15, 16, 17, 18] however, challenge the perceptual relevance of the established metrics while others identify uncertainties, imprecision, inadequate frequency range, and errors in acquiring and computing these parameters [5, 19, 20, 21, 22, 23, 24, 25, 26].

It seems therefore central to revisit these relationships and attempt to define the major perceptual attributes of reverberation *per se.* By establishing the perceptual attributes of reverberation, the direct investigation on the perceptual relevance of the current and/or novel metrics could be performed following a top-down approach, keeping the human perception as the core element of this analysis. A stronger link between physical metrics and perceptual attributes will enable a direct association between the physical properties of a space, objective metrics, and the final piece of the audio chain, the human listener. In the next section, the perceptual relevance of reverberation is examined, and the most frequently elicited perceptual attributes found in the literature will be discussed.

1.3. Perceptual Domain - Auditory Perception

In search of capturing the essence of reverberation, fundamental work in concert hall acoustics [27] revealed the importance of the time required for the sound pressure level to decrease by 60dB from its initial level, the RT_{60}.

RT_{60} was related to the global perceptual attribute of Reverberance, a key indicator of acoustical quality. This led to an 'optimum value' of RT [28]. Nevertheless, over the last decades acousticians recognised that achieving perceptually "good acoustics" was more than reaching an optimum RT. Lothar Cremer [29] illustrated that reflections' properties hold high importance in reverberant fields, such as their series of arrival, density, and their global decay characteristics. Similarly, many studies supported this notion [30, 31] relating the early part of reverberation to spatial characteristics of the field [32, 33], and more recently [34] to even enhanced dynamic range of an orchestra. Following these findings, acoustic research focussed on understanding the perceptual mechanisms of reverberation and its parameters, before addressing their physical characteristics (see [5, 35, 36]). In these investigations several methods have been applied to evaluate the perceptual aspects of reverberation and their properties. The major studies have conducted *in-situ* evaluations of concert halls using questionnaires [37, 38, 39, 40, 41, 42], laboratory-based studies intending to reproduce hall acoustics [43, 44, 45, 46, 47, 48, 49], while others focussed on the recording and reproduction techniques for reverberant and spatial fields [50, 51, 52, 53, 54, 55, 56].

Within the current literature there is a general agreement that reverberation is not a one-dimensional phenomenon, but it is rather related to a set of perceptual attributes all of which contribute to the acoustical identity of a space (see [3, 37, 57, 58]). It is therefore understood that the perception of the global acoustic behaviour of a room, namely its reverberation, is influenced by certain perceptual attributes such as: the source's apparent dimensions *Depth, Distance, Width, Size*, as well as *Timbre* [59], *Loudness* [60], *Distance* [60, 61, 62], *Perceived Room Size* [63], *Clarity, Localisation-Diffuseness, Transparency*, as well as semi-abstract 'immersive' percepts [52], such as *Warmth, Intimacy-Presence, Fullness, Spaciousness, Envelopment, Reverberance* and many others.

2. PERCEPTUAL ATTRIBUTES OF REVERBERATION

This decomposition of the holistic experience of reverberation into several attributes (i.e. Size, Timbre), can be thought as the process of visual face recognition [58]. A face can be perceived as a holistic entity i.e. a person's face, while it can be decomposed into individual attributes i.e. his/her eye colour. The advantage of looking into individual attributes (i.e. eyes color) rather than the global image (i.e. face) is that the perceptual aspects of the global and complex phenomenon can be justified objectively even when a small sample of human subjects is questioned. In this section, a non-exhaustive but representative summary of the most salient features of reverberation is presented (see Figure 3) based on the frequency of occurence that they appear in the literature reviewed. Following our research questions, the practical limitations, and the scope of application for domestic spaces, attributes related to general quality (i.e. Naturalness), attributes that are multidimensional by nature (i.e Timbre) as well as technical-related attributes (i.e. Distortion) that are depicted in Figure 3, will not be discussed further. The attributes of interest will be presented below following a cohesive order to aid the ease of reading, starting from high level space-related attributes to lower level source-related attributes (see [52]), rather than their frequency of occurence.

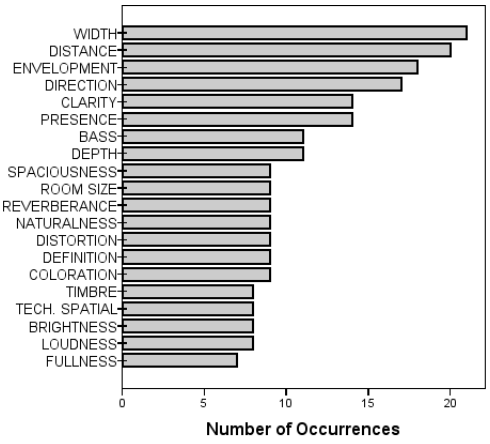


Fig. 3: Histogram depicting the rank-order of 328 perceptual attributes found in elicitation studies which were categorised in 74 unique terms.

2.1. Room Size

The apparent Room Size is fundamental in identifying the space we are in; a psychological process known as *space perception* [64, 65]. The perceived room size is believed to modulate our perception, cognition [66] and set our mental state, even without us being aware i.e. when sensory input matches expectations [13]. Room Size has been identified as a significant attribute in spatial acoustics and standardised as a perceptual rating in the multidimensional evaluation of spatial reproduction [67]. Recently [42] it was also found to be a mutual attribute in describing acoustic spaces by both acousti-

cians and musicians. The direct relationship between perceived Room Size and Reverberance is well deceptive in the literature (see [63]). This link is also supported by theoretical acoustics [9, 27], measurements [27, 68], and perceptual studies [15]. Rumsey [52] noted that the perception of Room Size does not require strong sense of Presence. In addition, Lokki *et al.* [4] suggested that Envelopment and Room Size are elicited independently, explicitly disassociating the 'sense of being enveloped' in a sound field and the perception of Room Size. Similarly subjects were able to distinguish between the perception of Room Size and Room Width and judge them individually [51].

Moreover, the *Direct-to-Reverb ratio* (D/R) is claimed to provide Distance cues, though individual differences are clearly apparent when using this cue. This variability is attributed to listener's mistake of using loudness as the main cue, while it is not a salient cue for Room Size [63, 69]. The majority of the studies reviewed above, credit RT as the main cue for apparent room size. Yet, the relationship between RT and increased physical size is not linear as it has been demonstrated that the auditory perceived Room Size differs from the physical, volumetric size [64, 70, 71, 72]. For example it is common to perceive an empty room bigger than what it really is.

Following the literature, it can be argued that the physical size of the room [71], the Acoustic Support (ST) originating by early reflections [61, 68] and the related decay of the reverberant field (RT) have the most influence on the apparent room size. However, the relationship is not linear [71], thus RT should not be taken as the *Lethe* to perceived size. In fact, RT changes in small rooms revealed no perceptual effect [68], indicating a possible influence of earlier reflections. Further, it could be seen that the auditory system evaluates the size of a room using different psychoacoustics mechanisms for different rooms [68]; an equivalent to perceived *distance parallax* (see [73]). It is therefore argued that room perception is not simple and linear as the cross-modal interaction plays a vital role in this process, by even violating classical acoustic theories.

2.2. Room Presence-Intimacy

Presence has been recognised as the perceptual sense of being inside an enclosed space and feeling its boundaries [52] - a hearing-equivalent of 'seeing' the walls of a room [37]. 'Presence', used mainly by recording/broadcasting engineers, is thought to be equivalent to 'Intimacy' used in concert hall acoustics [37, 52, 74]. In this paper only the term Presence will be used.

Since the early investigations on listener's preferences in concert halls [37, 38], Presence has been credited 40% of the overall quality in halls; compared to 15% attributed on Reverberance [13, 35]. In fact, Letowski [75] includes Presence as a major component of sound quality assessment. Following the definitions given in each study reviewed here, it is clear that perceptual attributes such as *sense of space* [56, 76], *feeling of space* [77], *feeling of Presence* [53], *Immersion* [35], and *Proximity* [41] all relate to the perceptual experience used to describe Presence. Sotiropoulou *et al.* attempted to link Proximity to Nearness and Envelopment in a single rating. However, it has been recently shown that that Proximity and Envelopment form separate factors when assessing concert halls [17]; similar findings were shown for Envelopment and Presence in sound reproduction assessment [52]. Presence has also been used to describe the *Naturalness* of a sound field [53, 68], an attribute that was later found to be strongly correlated with Presence [51]. In fact, in the domain of virtual environments, Presence and Immersion were sometimes treated as equal. However, it has been argued that Immersion requires a self-representation in a virtual environment, whereas Presence is a state of consciousness, a more high-level psychological sense of being somewhere [78, 79].

The main contributor towards the perception of Presence is thought to be the time period between the direct sound and the first reflection (see Figure 2), which is reffered to as *Initial Time Delay Gap* (ITDG). The optimal ITDG towards intimate environment is believed to be around 25ms in concert halls [37], or 20ms in operas [80]. An alternative measurement known as Time-Delay Spectrometry [81] was also used to investigate effects of ITDG in smaller rooms (recording studios). These studies [82, 83] related ITDG with comb-filtering effects due to early reflections summing.

Overall, Presence seems to be an important attribute contributing to the 'sense of space' as a natural habitat, in virtual environments, as well as being a pre-requisite of Envelopment in an acoustic space [52]. Still, the robustness of the current metrics (e.g. ITDG) is not well established, and standardised methods are not available. The authors would therefore like to motivate investigations towards a more sophisticated and robust method in calculating ITDG. For example, techniques used in signal processing for radar and sonar applications such as *Time-Delay Estimation* [84] (see also [85]), could be employed. This may enable a direct evaluation of

ITDG thresholds and perceived attributes, such as Presence/Intimacy, based on objective metrics.

2.3. Spaciousness

In this paper, 'Spaciousness' is defined as the perceptual sense of feeling immersed in an acoustic space, and the experience of being enveloped by its reverberant sound field [58, 75, 86, 87, 88, 89]. This sensation has been also expressed as equal to or a part of *Spatial Impression* [53, 45, 47, 90, 91, 92], and *Spatial Responsiveness* [31, 93], which were all found to relate to the listeners' preference of concert halls and their perceived qualities [13, 37, 44, 56, 89, 91, 94, 95, 96, 97, 98, 99], as well as quality of sound *per se* [75, 100]. These immersive attributes are usually used as global, cover-it-all terms, and they cannot form a one-dimensional, well-defined perceptual attribute that is needed in practice [52]. Still, if the linguistic and cultural ambiguities are omitted, it could be argued that most of these investigations aimed to describe two perceptual experiences: (a) a modification of the perceived dimensions (Width/Size) of the sound source, and (b) the sense of being enveloped and surrounded by the reverberant sound field. In fact, Morimoto and Maekawa [90] demonstrated that Spaciousness (Spatial Impression in their words) comprises of two major components. These components were later identified as separable percepts attributed to the *Apparent Source Width* (ASW) and *Listener Envelopment* (LEV) [47], and standardised [1] as components of Spaciousness (see [101]).

There is a common understanding in the literature that Spaciousness is primarily related to lateral reflections, hence, influenced by reflection's properties such as time, level, angle of incidence, spectrum, as well as the total sound level of both reflections and direct sound (see [91, 93, 102]). Consequently, it is argued that Spaciousness is influenced by fluctuations of *Interaural Time Difference* (ITD) and *Interaural Level Difference* (ILD) over time [87, 92, 103, 104, 105, 106, 107], see also [18]. In addition *Binaural Quality Index* (BQI) [37, 108], a physical metric based on IACC, was found to relate linearly to Spaciousness [109, 110]. Okano, Beranek and Hidaka [101] demonstrated that specific frequency bands make different contributions to aural Spaciousness.

Nevertheless, the reviewed literature contends that Spaciousness should be abbreviated as the global percept of feeling immersed, comprising of: a surrounding impression (LEV) and a broadness effect (ASW) [52, 111]. Thus, equating Spaciousness to a single aspect i.e. Width/Broadness of a source [112, 113] should be avoided (see [87]). The specific properties of LEV and ASW will be discussed below.

2.4. Listener's Envelopment - LEV

Listener's Envelopment (LEV) has been outlined in the literature as the perceptual sense of feeling in the centre of- [51] and surrounded by- [101] a reverberant sound field; as the 'analogous of swimming underwater than being sprayed by a water hose' [58]. LEV has been associated with the *Degree of Fullness* [99], *Room Impression*, the *extent of Immersion* [114], and *Immersion* (see [115]). Based on literature, one could identify a question that reappears in various papers: 'is envelopment a by-product of a very wide ASW?'. Similarly, Rumsey proposed [52] that envelopment should be classified as (1) *Environmental Envelopment* following LEVs definition, and (2) *Source-related Envelopment* describing the envelopment effect created by anechoic sound sources as found in sound reproduction studies (see [52]). Nevertheless, LEV seems to follow a combination of perceptual mechanisms, all of which contribute to a more global percept of feeling enveloped and surrounded within the acoustic space; an experience that is likely to increase immersion and preference in reverberant enviroments. The physical properties of reverberation that influence these percepts seem to be the spatial distribution of reflections [99], including front-back [116] and vertical directions [117], as well as the level of direct sound [63] and the overall sound level at the receiver position [47].

2.5. Apparent Source Width - ASW

One of the fundamental perceptual characteristics of a sound source in a room is its apparent *Width*. Width, or more commonly referred to as Apparent Source Width (ASW) [1], and Auditory Source Width [118] describes the perceived horizontal size of a sound source, and it has been defined as the spatially- and temporally- fused *auditory image* of the original sound and early reflections [101, 119]. The perceived Width has been identified as a major component of acoustical quality in several perceptual studies [17, 51, 61, 95, 120, 121] and it is also included in acoustical quality standards [67, 122] under its most common label of ASW. In fact, the rank-order analysis performed in this paper, depicts Width as the most commonly elicited attribute in reverberant and spatial sound fields. ASW has been associated to the sensations of *Broadness* [32], *Diffusion*, *Blurriness* [96] and ambiguity in source angular *Localization* [51] (see also [114]). Rumsey [52] argued that the signal

properties elicit different perceptual experiences, which may explain the confusion in the literature i.e. the arbitrary definition of a 'source'. He then proposed a *scene-based* paradigm where he distinctly categorised width for (1) a single source - the *Individual Source Width* (ISW) - (2) for a group of cognitively similar sources - the *Ensemble Width*, and the (3) *Environmental Width*, which the author linked to Spatial Impression (BSI), as defined by [87, 111], and the human ability to isolate the reverberant sound fields originating from the recording room and reproduction room, as individual entities; initially hypothesised by [123]. The physical parameters of the ASW have been primarily linked to early reflections' level, direction, frequency content, and their structure (see [32, 52]), total Sound Pressure Level [31, 108, 109, 124] as well as the source-receiver Distance [125]. Hidaka *et al.* [126] estimated the greatest effect on enhancing perceived ASW from reflections at angles of $\pm 60^{\circ}$, while no effect was found due to the reflections originating from behind [116] or above the listener in both concert halls [117], and domestic listening rooms [127]. Similar to Spaciousness, the proposed ASW metrics primarily follow the binaural properties of the human auditory system in both temporal and frequency domains [18, 87, 92, 103, 106, 107, 111, 128, 129]. The most prominent metrics include IACC [1, 130, 131] and simile i.e. *Degree of Interaural Cross Correlation* (DICC) [132], BQI [24], and *Interaural Coherence* (ICC) [20, 103, 104]. Links were also established with newer metrics such as J_{LF} [1, 91, 108], G, combined J_{LF} and G known as *Degree of Source Broadening (DSB)* [13]. Moreover, ITD [133, 134] and loudness measures [135, 136] were also related to the perception of ASW. Still, the standardised estimations of the perceived ASW include several imperfections, resulting disengagement to the perceptual experience. These imperfections might be linked to the claimed frequency dependency of ASW [32, 91, 92, 137], as well as its influence by Distance which are not considered by these calculations [22, 125]. In fact it is argued that there is no reliable relationship between 1-$IACC_E$ or J_{LF} with perceived ASW [5, 22, 125] in its current form.

Overall, it is evident that although ASW is a well-defined perceptual attribute describing the perceived dimensions of an auditory event, the current physical metrics encompass high level of uncertainties [22, 125], which challenge their perceptual relevance *per se*. The inclusion of human auditory processess in the estimations i.e. binaural processing (i.e. ITD, ILD [138]), frequency dependent Interaural Correlation ([139]), and the Precedence Effect may enable better estimation of the perceived ASW.

2.5.1. ASW Vs LEV

Although ASW and LEV have been identified as separate attributes, they both contribute in a more global percept, Spaciousness. Thus, it is argued [111] that it is unlikely to perceive a room as spacious (i.e. 'large' and 'open') if only one of the two attributes is elicited. Further, the arbitrary boundary point 80ms [1]-100ms [3] between early and late energy in halls, as well as practical issues with standardised methods (see [20]), point towards the need of more research in the area, especially when different sized rooms are considered. Perhaps, measures such as *Echo Density* [59] and *Centre Time (Ts)* [1] may indicate a more perceptually relevant temporal boundary between LEV and ASW.

2.6. Source Depth

Depth is a perspective-sense, which is identified mainly, but it is not limited to, reproduced sound [52]. Although, it has been considered as an elusive concept, as some listeners may have difficulties to perceive it, several studies suggest that during elicitation test, subjects described [53] and drew [140] sources as being curved and flat. Depth can be thought as a source's dimension, but concurrently the apparent Depth of the room may also elicit this sense. In fact, Rumsey [52] proposed an attribute known as Environmental Depth and attempted to relate Depth to Spaciousness -as defined by Griesinger [111]. The perception of Depth for a sound event has been attributed to frequency de-correlation [53, 140] and lateral reflections produced by components lower than 3KHz are responsible for the perception of Depth [103]. It has been also been noted that the directivity of a sound source influence the Depth of a sound even in a sound reproduction system, where directivities close to dipole have the biggest positive influence on perceived Depth [141].

2.7. Source Distance

Distance, is considered as an aspect of source localisation mechanism [142] a natural practice of our auditory system. In the literature attributes such as *Nearness* [77], *Presence* [52], *Closeness* [143], seem to have been used as linguistic alternatives of perceived Distance. It is noted that although reverberation normally degrades localisation abilities, the distance perception is believed to be enhanced [144]. In fact, room reflectivity [145, 146], and especially the early reflections play

a major role in Distance perception [147], whilst the number of reflections [73], as well as the angle of incidence [124] influence this relationship. Auditory Distance perception has been also linked with D/R [62, 148] (when RT is high enough [149]), Spectrum (for familiar sounds [150, 151]), and binaural cues [152]. Moreover, it is argued [147] that loudness is not a major cue of Distance in typical rooms, as one would expect; this was also demonstrated in concert halls [153, 154], even under blindfold scenarios. This disconnection between perceived distance and the actual physical distance [147] could be linked to a loudness memory that humans seem to posses. This memory produces a crude estimation of the Distance if required [155, 156], even following only a visual mental reference [70] and other non-audio cues (i.e. vision, familiarity, expectation). It is therefore evident that humans use several cues [156] in Distance estimation, the weighting of each is highly adaptive (see [148]) and the related perceptual constructs seem multidimensional.

3. DISCUSSION

The perceptual relevance of reverberation is highly apparent in the acoustics literature, and the current research focus has been shifted towards understanding perceptual aspects of reverberant sound fields rather than purely physical metrics. These studies highlight the importance of attributes related to early reflections, and more specifically the reflection pattern they exhibit [37, 61]. Still, perceptual characteristics of sound are diffiuclt to epistomise and the lack of common vocabulary make it difficult to merge studies' results. Nevertheless, following the descriptions given in each study, this investigation revealed the most commonly elicited attributes in revebrant sound fields and several links to objective measurements have been presented (Section 2). A graphical summary is provided in Figure 4, depicting the perceptual attributes discussed in this manuscript and their relationships found in the literature. In the next paragraphs, the central topics are addressed, and the identified issues within this stream of acoustic research are discussed. The applicability of these findings in small rooms is reviewed (Section 3.1) and a proposal for perceptual-based experiments for reverberation in such rooms is presented (Sections 4-5), including considerations and points of attention.

3.1. Small Vs Large Rooms - Applicability

The physical differences between large rooms (i.e. auditorium) and small rooms (i.e. living room) will be discussed, as a tool to identify common paths and differences to our findings. These differences can be categorised by their three main causes: (1) the physical parameters of the propagation medium (i.e. the room), (2) the characteristics of the sound source used to excite the room, and (3) the psychological and psychophysical properties of the receiver, the human listener.

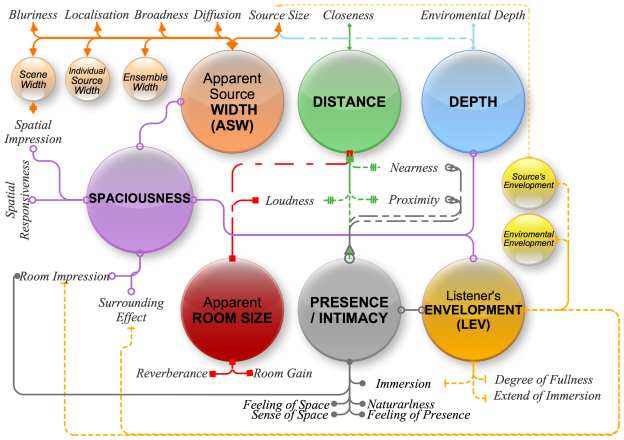


Fig. 4: Paper overview based on the perceptual attributes presented. Large circles denote the fundamental attributes, while the small circles indicate their possible subcategories. Lines indicate the links between attributes as found in the literature.

3.1.1. The Medium - The Room

Due to lower volumetric dimensions, the typical RT in domestic spaces is much lower than a typical hall. These differences also influence the echo density of the reverberant soundfield in small rooms, exhibiting frequency irregularities and modal behaviour especially at Low Frequencies [10, 123]. The shorter lengths between boundaries in domestic rooms, impact the temporal distribution of reflections, introducing shorter ITDG, as well as stronger and distinct early reflections. Moreover, the first reflections typically originate from the floor and ceiling, rather than lateral directions as in concert halls (see [157]). Based on the reviewed perceptual attributes (Section 2) these characteristics are likely to influence the perception of Distance, ASW, Presence and apparent Room Size in smaller spaces. Moreover, it is expected that some objective metrics used in concert halls may not be suitable for smaller spaces. The temporal discrimination between early and late reflections at 50/80ms is not ideal, considering that most of the reflective energy in small rooms occurs within the first 50ms [111]. Thus, common measures that follow this strategy such as *Early*

Interaural Cross-Correlation ($IACC_E$), BQI, and $C_{50/80}$ may not indicate the appropriate measure of their related subjective impressions. The Centre Time (T_s) [1], a measure of the energy distribution over time, may serve as good measure for the physical boundary for early/late reflections.

3.1.2. The Source - Loudspeakers or Orchestra

In both halls and listening rooms, the scope is to experience music. However, a major difference between domestic rooms and concert halls is the sound source. In a hall the source is typically an orchestra based at a specified and acoustically designed area. In small rooms a reproduction system is involved, and the room's design requirements often discard acoustical performance. Consequently, an additional set of parameters is added which modify the perceived acoustical experience (for review see [127, 123]). Imperfections of the transducers, their placement, directivity, and performance of the system also influence the perceived experience (see[157]). Moreover, the perceived sound includes at least two distinct reverberant fields, that of the recording room, and also the reproduction one. Still, listeners are able to dinstinquish between the two independently [52, 123]. In conclusion, techniques used in concert halls, for example the use of a single omnidirectional loudspeaker to simulate the sound source, may not reveal perceptually relevant results.

3.1.3. The Receiver - The Human Listener

The surrounding environment is found to alter humans' cognitive processing (i.e. emotional state, alertness). Moreover, humans have certain expectations of the acoustics of the room [69] and have already memorised schemata to aid faster processing of complex scenarios; even for typical reproduction setups, such as 2ch. stereo [158]. This preconception may create inattentional blindness to auditory cues [159], as well as information suppression due to the already established space characteristics from other inputs such as vision [160, 161]. It seems therefore important to remove these biases in subjective evaluations of small room acoustics, for example by conducting the experiments in ecologically valid rooms, in matched visual and auditory environments, unfamiliar rooms, and/or blind setups.

3.2. Dealing with Perception

In order to tackle the issues related to reverberation, one needs to deal with physical acoustics as well as perceptual acoustics. The existence of a non-linear and highly adaptive processor within our auditory system, the brain, makes the establishment of direct relationships between numbers and perception somewhat impossible. Hence, human responses are fundamental in understanding the perceptual relevance of physical parameters, and in consequence reverberation properties *per se*. Having human subjects as the measuring instruments introduce interpersonal differences, based on taste, beliefs, experience, value, and need [162]. In addition, there is no common vocabulary for acoustic stimuli, and we mostly borrow words from other senses (i.e. warmth, clear, muddy) [163]. Even the most cited terminology of perceptual attributes in acoustics [37], has been described by the author as a 'non-accurate depiction'. This ambivalent interpretation of data is very limiting [19] and generalisations are problematic even when identical contextual factors are used. Fortunately these limitations have been known in other industries (e.g. food, wine) and tools like *Sensory Evaluation* [164] make it possible to extract objective information often hidden behind people's global judgments (i.e. preference).

3.2.1. Summary of Experimental Techniques in the Perceptual Domain

The majority of published studies in the perceptual domain aim to provide a model, where subjects make judgements about the acoustics of certain rooms. Over the last decades several techniques have been employed, which can be roughly categorised in three major groups: (1) *in-situ* evaluation (2) Auralisation / Laboratory settings (3) Combination Multichannel recording/reproduction techniques. Conducting *in-situ* evaluations of live performances in concert halls seems the most ecologically valid scenario, as its purpose and provided settings match the reality. However, it includes many uncontrolled parameters, as halls differ in a myriad of ways (i.e. shape, structure, materials), orchestra performances are rarely repeatable (i.e. dynamics, tempo), and the required test-to-test period expands to days, introducing cognitive issues (i.e. memory, mood, expectation) [165] making it difficult to pinpoint direct influences. Moreover, the standardised objective metrics, which are effectively the independent variables of such evaluation cannot provide the whole picture but averages for certain parameters of the sound field. Conducting laboratory-based evaluations overcomes numerous shortcomings of *in-situ* evaluations, as it includes standardised source, signals, listening environment, and direct comparison of different halls. However, these methods often miss realism due to lack of visual input

and imperfect reproduction while subjects have certain demand characteristics (see [52]), i.e. an orchestra in a room should sound like subjects are expecting it to. It is apparent that perceptual attributes elicited in these studies relate to technical inadequacies, i.e. noise, distortion, spatial distribution. A new hybrid concept of a 'loudspeaker orchestra' presented in a series of papers by Tapio Lokki and his group (see [166]), seems to overcome several shortcomings of both techniques while sourcing the merits of both in-situ and controlled laboratory settings. This approach could be applied in a scalable system for smaller rooms.

4. FURTHER WORK

The aim of the study was to formulate our initial investigation on the perceptual attributes of reverberation, by using existing relationships as a key framework and benchmark, towards further experiments in the perceptual control of reverberant sound fields. It is apparent that perception is highly important in understanding reverberation, but dealing with perception includes various biases, as well as a trade-off between controlled settings, and ecological validity.

Sensory Analysis methodologies found in food and wine industry [164, 167] have been sucessfully applied to acoustical research over the last decade [4, 7, 17, 34, 168, 169, 170, 167, 171, 172, 173] and they seem to provide more accurate information about perception of acoustical features, avoiding linguistic, subjective, and biased responses as discussed above, in a well-structured and scientific framework (see [7, 170]). The advantage of these techniques in investigating such complex phenomena lies in their ability to extract information normally hidden behind hedonic and affective judgments. It seems therefore a well-suited set of techniques for investigating human's responses to different reverberant fields in small rooms. Considerations in further work should include the standardisation of the sound source (i.e. a typical directional speaker), lifelike, dynamic and time-varying signals, systematic alteration of certain room parameters, as well as to provide as realistic scenarios as possible (i.e. providing visual input, including head-tracking). Moreover, the existence of two categories of listeners' preference in reverberant settings [4, 39, 44, 45] should also be considered; individual vocabulary techniques maybe used [76, 174]. Last but not least, the requirement of Sensory Analysis of simultaneous comparison of ' tasting samples' – i.e. this paper's rooms with different reverberant fields – suggests that these settings must be recorded and reproduced in the laboratory. *In-situ* evaluation will not reveal reliable results due to limited auditory memory, and other reasons already discussed above. Following these findings, a systematic experiment will be further performed aiming to verify perceptual attributes of reverberation and their thresholds, based on realistic, yet controlled settings.

5. CONCLUSIONS - GENERAL REMARKS

This paper summarises the published literature on reverberation following a top-down approach, from high level conceptual attributes to lower level metrics, physical description of reverberant fields. This investigation included a representative set of relevant works in concert hall acoustics, in-situ and in laboratory settings, as well as psychoacoustics, acoustic measurement and spatial audio research. As the published literature is plentiful, we examined and analysed the most important results that fall in the perceptual domain of the filter model. Here we presented a summary of the most salient perceptual attributes already identified in the literature as well as any possible direct relationships to physical, and affective domains. The identified perceptual aspects presented, aim to provide not necessarily an exhaustive list, but a characteristic ranked sample of perceptual attributes and senses related to reverberation, as an attempt to provide a key framework for further research. In the interest of this study it has been apparent that several major perceptual attributes seem to relate highly to properties of the auditory system such as Precedence Effect, masking, spectral and temporal binaural processing, as well as other cues (i.e. vision, expectation, episodic memory). Such mechanisms should be considered by objective metrics, and thresholds (JNDs) should be identified for the major perceptual and objective aspects of reverberation, towards efficient and robust characterisation of reverberant sound fields.

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