
The Language of Rooms: From Perception to Cognition to Aesthetic Judgment

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Summary. Rooms are not perceptual objects themselves; they can only be perceived through their effect on the presented signal, the sound source, and the human receiver. We will give an overview of different approaches to identify the qualities and the dimensions of ‘room acoustical impression’ and to develop psychological measuring instruments for room acoustical evaluation from the audience perspective. We will outline how the psychoacoustic aspects of room acoustical perception are embedded in a socio-cultural practice that leads to an aesthetic judgment on the quality of performance venues for music and speech.

1 Language and Perception

The aim of this contribution is to highlight the relationship between the characteristics of performance venues for music and speech and the language which is used to describe them. On the one hand, we want to give an overview of different approaches to use language as a “measuring instrument” for the qualities of these spaces. On the other hand, we are interested in what conclusions can be drawn from the language used with respect to the characteristics of these spaces, the listeners using this language, and the perceptual and cognitive processes involved.

We will look at these relationships through the lens of a theoretical frame describing the relationship between cultural artifacts (performance spaces), their perception, and their linguistic encoding. This frame model, combining elements of perceptual psychology and cognitive linguistics, assumes a perceptual front end, where an external acoustical signal is transformed into neural activity by our sensory organs. For hearing, this process takes place in the inner ear, where sound pressure transmitted by the outer and middle ear is transduced into neural signals. In a perceptual back end, these signals are integrated above different sensory modalities and activate *concepts*, i.e., mental representations corresponding to abstract classes of objects, which “tie our past experiences to our present interactions with the world” (Murphy, 2004, p. 1) and allow us, for example, to classify an audiovisual experience in a

certain social setting as a “concert” and a spatial environment of a certain size, design, and acoustical properties as a “concert hall”. The result of this comparison of sensory information with preconfigured categories (concepts) is called *percept*.

The size and the structure of the concept repertoire as well as the matching process with the sensory input depends on many personal and situational factors, including the knowledge, the experience, the expectations, the motivation, and the attention of the listener. Accordingly, the percept, such as “a successful concert in an acoustically appropriate environment”, depends as much on these situational factors and the conceptual repertoire of the individual listener as it depends on the sensory input at this specific moment.

The relevance of language in this process has two important aspects. First, language is – not the only, but the most important – “metrological” access to human perception. From paired comparisons, similarity judgments, sorting tasks, multidimensional scaling, semantic scales, to vocabulary profiling and related qualitative and quantitative analyses: most studies of the auditory properties of performance venues and of sound description in general (Susini *et al.*, 2011) have relied on language-related tasks borrowed from the repertoire of methods of experimental psychology and quantitative and qualitative social research. Second, the language used can itself provide information about the speaker’s conceptual representation of the world ((Murphy, 2004, p. 389); (Evans and Green, 2007, p. 5)), including the spatial environments where he or she perceives music or speech. The taxonomic organization and the privileged level of categorization which we use in our everyday language about spatial concepts is the result of preceding experiences and it also shapes the lens through which we observe new experiences. The preferred vocabulary about performance venues can not only reflect the knowledge and the professional experience, e.g., of expert vs. lay listeners; it is also assumed to have a direct impact on their instantaneous perception and the respective mental models (on mental models Johnson-Laird (1983); on frame-theory see Minsky (1977)). This kind of “linguistic relativism”, which has been evidenced for the languages of different ethnic groups by many empirical observations in cognitive linguistics (Dabrowska and Divjak; Dancygier, 2017; Everett, 2013; Levinson; Thiering, 2018), also happens on a small scale in lay vs. expert language linguistics, or when we compare the languages of groups with different kinds of expertise, such as music listeners vs. musicians.

2 Linguistic Inventories as a Basis for Psychological Measuring Instruments in Room Acoustics

Throughout the first half of the 20th century, the investigation of room acoustical environments was mainly focused on the effects of reverberation, with its dependence on frequency, and with its control through volume and absorption according to Sabine’s formula (Sabine, 1900). Psychological experiments



Fig. 1. Musical events as a cultural, social, visual and acoustic experience. The language to describe performance venues for music and speech reflects each of these domains. The image shows the concept for a new concert hall, to be opened in Munich in 2021.

were conducted already by Sabine himself, who invited a number of musical experts in 1902 in the recently built New England Conservatory of Music to judge the acoustic quality of piano instruction rooms while seat cushions were successively added to the rooms in order to reduce their reverberation time. Sabine observed that the listeners judged all rooms to be acoustically optimal if the reverberation time was within a quite narrow range of tolerance, from which he concluded a common taste of “surprising accuracy” for the acoustical conditions of musical performance venues (Sabine, 1906). This unexpected consensus on the appropriate acoustical conditions for classical concert venues, which would hardly have been observed 100 years earlier (Weinzierl, 2002), can only be interpreted as the result of a cultural process which accompanied the emergence of public concert life, and which was largely completed around 1900 (Tkaczyk and Weinzierl, 2019).

While Sabine asked his subjects only whether the duration of reverberation was appropriate, the British architect and acoustician Hope Bagenal carried out similar experiments with musicians as test subjects, who were asked to assess the effect of room acoustic conditions on different sound qualities including reverberation (too long/too short), tone (full/bright/rich/soft), tone (hard/thin/dead/dull), loudness (sense of power, body of tone), reinforcement of notes (even/uneven) and “conditions”, by which he asked his subjects to name specific halls which resemble the conditions reached (Bagenal, 1925). Even if this scheme “was not rigidly adhered to” by his subjects, it can be considered as the first attempt to have the acoustics of concert halls evaluated

by a semantic differential, covering the room acoustical effect on spatial, dynamic and timbral dimensions, and considering the effect of “typicality” with respect to prototypical reference halls. The first standard with guidelines for auditorium acoustics, issued in 1926 by the American Bureau of Standards, however, was mainly focused on specifying an optimal range of reverberation times for halls of different sizes, along with recommendations how to reach these values (Bureau of Standards, 1926).

After 1950, an increasing awareness can be observed, that an optimal reverberation time alone is no guarantee for a successful room acoustical design, and that “reverberance” should not form the only criterion for the perceptual assessment of halls. The British Broadcasting Corporation (BBC) and the Acoustics Group of the Physical Society sponsored a number of experiments, where an identical repertoire (*Don Juan* by R. Strauss) was performed and recorded in four different British concert halls. Subjects listening to the different recordings were then asked to produce a ranking of these halls with respect to tonal quality, definition and overall preference. Consistent rankings, however, could not be observed for lay listeners, and practising musicians exhibited preferences which were different from other skilled listeners (Somerville, 1953).

In a further study, a glossary of 14 acoustic terms was collected, which were, according to the authors, “commonly used” to describe the qualities of concert halls and recording studios (table 1, Somerville and Gilford (1957)). A similar list of 18 attributes was proposed by Beranek (1914–2016) in his landmark book on *Music, Acoustics and Architecture*, along with relations between these perceptual qualities and physical properties of the hall, which was based on his own intuition and experience (Beranek, 1962).

The two lists of attributes, along with a third, originally German list described below, demonstrate the grown awareness for the multi-dimensional impact of room acoustical conditions on the perceived sound qualities in these halls. At the same time, the studies reflect an awareness for the need to separate the physical and the perceptual domain more clearly. Somerville and Gilford emphasized that the “subject under investigation is purely aesthetic and therefore must begin and end with human aesthetic judgments” (Somerville and Gilford, 1957, p. 171). Nevertheless, their list is a mix of perceptual and physical items, including aspects such as ‘scattering’ or ‘standing wave system’ without an obvious equivalent in the perceptual domain. Beranek’s features, on the other hand, are psychological throughout, at least if aspects such as ‘ensemble’ and ‘dynamic range’, which can be interpreted both ways, are understood as ‘perceived ensemble’ and ‘perceived dynamic range’.

The way to analyze the results of questionnaire studies constructed on the basis of these terms was paved by the psychological fundamentals of the use of semantic differentials (Osgood *et al.*, 1957) and the statistical techniques of multidimensional scaling (MDS, Torgerson (1952)) and factor analysis (Spearman and Jones, 1950) all of which were laid during the 1950s. One of the first applications of these new tools was made in a study by Hawkes and Douglas

Table 1. Attributes addressed in early investigations on the differential qualities of room acoustical environments. The translation of the originally German attributes by Wilkens (1977) was adopted from Kahle (1995).

	Somerville and Gilford (1957)	Beranek (1962)	Wilkens (1977)
1	Balance	Intimacy	small/large
2	Bass masking	Liveness	pleasant/unpleasant
3	Coloration	Warmth	unclear/clear
4	Deadness	Loudness of the direct sound	soft/hard
5	Definition	Loudness of the reverberant sound	brilliant/dull
6	Diffusion	Definition/Clarity	rounded/pointed
7	Echoes	Brilliance	vigorous/muted
8	Flutter echoes	Diffusion	appealing/unappealing
9	Liveness	Balance	blunt/sharp
10	Pitch changes	Blend	diffuse/concentrated
11	Scattering	Ensemble	overbearing/reticent
12	Singing tone	Immediacy of response	light/dark
13	Slap back	Texture	muddy/clear
14	Standing-wave system	Freedom from echo	dry/reverberant
15		Freedom from noise	weak/strong
16		Dynamic range	emphasized treble/treble not emphasized
17		Tonal quality	emphasized bass/bass not emphasized
18		Uniformity throughout the hall	beautiful/ugly
19			soft/loud

(1971). 16 attributes inspired by Beranek’s list (table 1) were used for a questionnaire applied in four different British Concert Halls (with different musical programs and performers), in the Royal Festival Hall, London, with the newly installed Assisted Resonance system in different technical settings, and in the Royal Festival Hall at 23 different positions. With an interest in identifying the “different dimensions of acoustic experience” (Hawkes and Douglas, 1971, p. 249), the authors applied both MDS and factor analyses, arriving at 4–6 orthogonal factors. The authors were, however, also confronted with the challenges of such analyses, since the solutions they obtained were different both for the different stimulus settings and for the different types of analyses, i.e., both the number of factors and the relation of factors and items were different for each of the sub-studies. We will return to this problem in section 3.

While Hawkes and Douglas collected data in the field, i.e., by interviewing concert goers, Lehmann and Wilkens (1980) used an experimental approach by presenting dummy head recordings of the Berlin Philharmonic Orchestra in six different halls and capturing the assessment of subjects on a semantic differential with 19 different (German) attributes (table 1). These were selected from a list of originally 27 items by eliminating those with a too large inter-rater variance, indicating an inconsistent interpretation between

subjects. The factor analysis of the ratings delivered three orthogonal factors, explaining 89% of the total variance. Considering the loadings of the original attributes on these variables, these were interpreted as *strength and extension of the sound source, definition and timbre of the overall sound* (Wilkins, 1977). In an attempt to overcome the limitations of the experimental approach lacking “the complexity of live concert situations”, Sotiropoulou *et al.* (1995) used a questionnaire to be rated at three concerts in two different concert halls in London. Similar to Lehmann and Wilkins (1980), they started with a larger vocabulary of about 100 labels, which was reduced to 54 bipolar attributes based on a “relevance” rating collected in pretests. Analysing the ratings of ca. 80 participants by factor analysis, the authors obtained four factors explaining ca. 66% of the total variance, which they interpreted as *body, clarity, tonal quality*, and *proximity*. Hence, both groups were aware that linguistic descriptors are not necessarily suitable as measuring instruments, if their meaning is inconsistently interpreted by different raters or if their immediate relationship to the perceptual object under consideration is not assured.

The numerous investigations dedicated to find suitable *technical* parameters to predict certain perceptual categories are not the subject of this contribution. Only some of them are also interesting here, because they highlighted the importance of specific perceptual aspects which did not appear in earlier studies (cf. table 1). Most importantly, a group of studies emphasized the importance of spatial aspects of room acoustics, in particular of an increased perceived ‘source width’ and the perceived acoustic ‘envelopment’ of the auditorium (Barron, 1971; Barron and Marshall, 1981; Bradley and Soulodre, 1995). All of these studies, however, employed synthetic sound fields created by loudspeakers in the anechoic chamber, and asked participants to evaluate these qualities as isolated items. Since they were not evaluated as part of a multi-dimensional measuring instrument, it is not obvious to what extent they form *independent* aspects of the room acoustical impression, or whether they are physically or perceptually correlated to other aspects.

In this context, it is important to bear in mind that the ratings of two objects can be correlated because two labels refer to similar perceptual impressions (such as ‘loudness’ and ‘strength’ of sound), or because different perceptual qualities co-vary in the physical objects of the stimulus pool. For example, rooms providing more ‘reverberance’ could – for physical reasons – always provide more ‘envelopment’, although the qualities are clearly different on a psychological level.

After 2000, the study of the perceptual space of room acoustic conditions as a whole attracted a renewed interest directed to the *individual* vocabularies used to describe room acoustic conditions. Several studies, first aiming at the evaluation of spatial audio reproduction systems (Berg and Rumsey, 2006) and then also on the perception of natural acoustical environments, included a qualitative part for the verbal elicitation of the terminology and a quantitative part for the statistical analysis of the generated terms, allowing to identify clusters of attributes with a similar meaning. An initial of

two studies conducted at Aalto University, Helsinki, produced room acoustical stimuli by impulse response measurements of a loudspeaker orchestra in three different concert halls, encoded in Ambisonics B-Format, processed with directional audio coding (DirAC, Pulkki (2007)) and reproduced by a 16-channel loudspeaker system; a second study used impulse responses of eight different concert halls, encoded in Ambisonics B-Format, processed with the spatial impulse response rendering algorithm (SIRR, Merimaa and Pulkki (2005)) and reproduced by a 14-channel loudspeaker system. Analysing the large set of about 100 individual attributes generated and rated by 20 resp. 23 participants in the two studies, two resp. three main components could be extracted explaining 66 resp. 67% of the total variance. These were interpreted as *loudness/distance* and *reverberance* in the first study (Lokki *et al.*, 2011), and *loudness*, *envelopment* and *reverberance*, *bassiness* and *proximity* and *definition* and *clarity* in the second study (Lokki *et al.*, 2012).

As a summary of their own and other work, authors of the same group suggested a “wheel of concert hall acoustics”, including eight main categories and 33 items to visualize the main perceptual aspects of concert halls with un-amplified musical instrument sounds (Kuusinen and Lokki, 2017). The wheel format, which has a longer tradition in the domain of food quality and sensory evaluation (cf. Noble *et al.* (1987)) is a structured and hierarchical form to present a lexicon of different sensory characteristics. Pedersen and Zacharov (2015) used the wheel to present such a lexicon for reproduced sound, with the selection of the items and the structure of the wheel based on hierarchical cluster analysis and measures for discrimination, reliability, and inter-rater agreement of the individual items – an empirical basis which was not provided in Kuusinen and Lokki’s wheel for concert halls (Fig. 2).

3 Psychometrics and Scale Development in Room Acoustics

The studies summarized above have, in different ways, confirmed the multidimensional character of room acoustical conditions as a mediator for the sound qualities of music and speech, and provided different lists of attributes to describe these qualities. As underlying dimensions of the room acoustical impression, the *loudness* or *strength* and the *reverberance* of rooms were consistently extracted from the ratings of these attributes, as well as a factor for the *timbre* of the room. None of these studies, however, attempted to construct a standardized measuring instrument that can be used with different groups of listeners to describe the whole width of the room acoustic perception space. From today’s point of view, this was impossible due to shortcomings in terms of the experimental stimuli, the participating subjects and the statistical analysis techniques employed in these works. According to modern standards in social research, any psychological measurement instrument has to meet established quality criteria in terms of *reliability*, *validity*, and *invariance* with

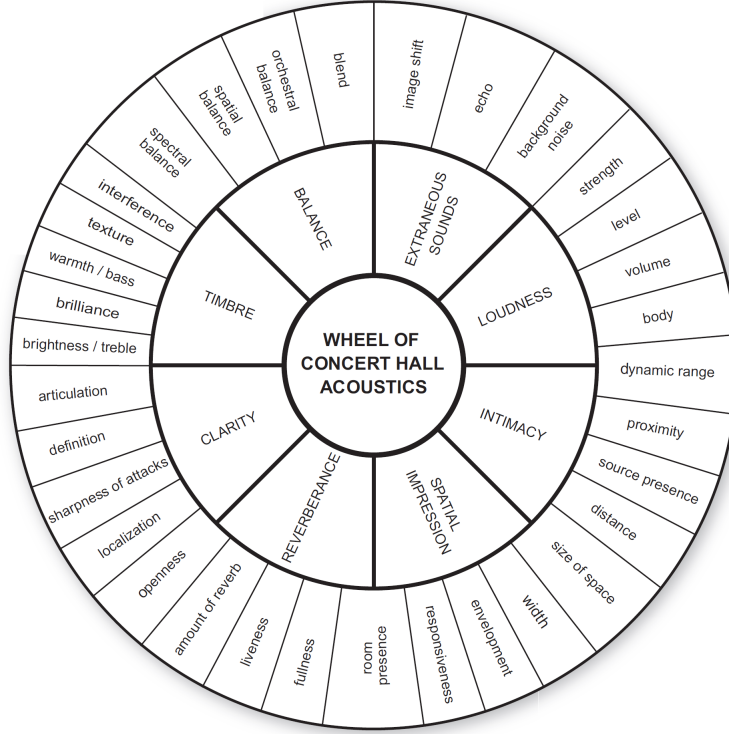


Fig. 2. Wheel of concert hall acoustics (Kuusinen and Lokki, 2017).

respect to a typical sample of users and stimuli. To establish perceptual dimensions, the investigation has to take care of *representativeness* and *breadth* of stimuli, possible hidden *confounders* and a proper *sample selection* in order to prevent bias concerning the generalizability of results.

A first problem that pertains to most of the early studies in acoustical room impression measurement is the lack of experimental control concerning the stimuli presented. Studies that collected ratings in physically existing rooms always risked the influence of hidden confounders such as the audio content, the visual impression, or the musical performance, all of which co-vary with the auditory impression of the room. Presenting the whole breadth of possible room acoustical conditions while keeping these confounding variables constant seems only possible with state-of-the-art technologies for auralization. It is, of course, true that such an experimental approach can not account for all visual, architectural and social aspects that constitute the multi-modal impression of a concert venue. To determine the acoustical properties of a room, however, these influences act as confounders increasing the measurement error of the test.

One may ask to what extent full control of all non-acoustic factors makes sense, since, for example, an interaction between the room acoustic conditions and the playing style of musical performers is also present in the real situation and thus not an experimental artefact in the narrower sense. However, incorporating such interaction into the experimental design might, on the one hand, conceal characteristics of space if, for example, musicians were tempted to compensate for the effect of space by adjusting their timbre and volume in the opposite direction. On the other hand, the effect of space on the performer's playing has proven to be quite individual. Different musicians react in very different ways to room acoustic conditions (Schärer Kalkandjiev and Weinzierl, 2013, 2015). The consideration of the interaction of space and performance would therefore face the problem of which reaction pattern should be used as a basis here. Nevertheless, at the latest in an overall aesthetic judgment of space ("is the room suitable for a musical content") it must be taken into account that this question cannot be conclusively evaluated in the laboratory.

A second challenge lies in the sample of rooms presented in terms of representativeness. The identification of latent dimensions of room acoustical perception, i.e., a stable factor analytic solution of the measured data, which is valid beyond the specific sample of rooms used in the test, cannot be expected for a too small set of stimuli. In order to identify five largely independent perceptual dimensions, a set of at least $2^5 = 32$ stimuli would be required so that all perceptual qualities are able to vary systematically and independently from each other and hence can be properly identified by a factor analysis. Furthermore, only with a sufficiently large sample of rooms, the results can be considered representative for the targeted population of room acoustical conditions. Comparing these requirements with the sample sizes used in the above mentioned studies, with typically less than ten rooms, it becomes obvious that neither the dimension of the perceptual space, i.e., the number of latent variables, nor the structure and interpretation of the adopted factor solution could be reliably determined.

A third challenge is the size of the sample of listeners. In order to reliably assess the dimensionality of perceptual constructs represented by questionnaire item batteries by factor analyses, it is recommended to use sample sizes of at least 100–200 subjects or at least a sample of three times the number of employed items, even in the favorable case of a good fit of attributes and factors (high communality). If this requirement is not met – and it never was in the above cited studies, stable solutions can be expected only for the most important factors, i.e., those carrying most of the variance, while all other factors, representing the more subtle aspects of room acoustic impression, are affected by a large sampling error (MacCallum *et al.*, 1999).

Finally, any psychological measuring instrument requires an analysis of the psychometric qualities of the perceptual constructs and questionnaires based on them in terms of validity, reliability, and measurement invariance. Techniques and criteria for this purpose have been developed extensively in

the social sciences (Vooris and Clavio, 2017). Typical requirements for psychological questionnaire instruments comprise the use of *latent measurement models*, the demonstration of *convergent and discriminant validity* (do the scale’s subdimensions actually measure what they are supposed to measure and are sub-dimensions sufficiently different from each other?), as well as demonstrations of sufficient *construct reliability* (how precise does the scale measure?) and *measurement invariance* (Millsap, 2011) across time, stimuli, and populations of interest (are the scale’s measurements independent of the experimental factors employed?).

In order to achieve and demonstrate an acceptable degree of validity, reliability, and measurement invariance, and to deal with different sources of measurement error (Schmidt and Hunter, 1999), psychological scale development today typically relies on latent variable models (Loehlin, 2004). In this approach, it is assumed that every manifest measurement of a questionnaire item is in fact the expression of underlying latent psychological constructs. When at least three items are measured for any construct exclusively (“simple structure”), it is possible to not only estimate the degree of item measurement error, construct loading and resulting construct reliability, but also to calculate error-free construct scores and work with these in later analyses. The latent variable approach also allows to check for reliability across time (re-test reliability), which is considered the most important indicator of reliability for scales since Cronbach (1947), and invariance across experimental conditions. Since past studies on room acoustics predominantly drew on principal component analyses (PCA) and clustering techniques, where none of these tests is possible (Fabrigar *et al.*, 1999), only a minority of reliability-, validity-, and invariance-related questions could be systematically addressed.

4 The Room Acoustical Quality Inventory (RAQI)

To develop a language-based measuring instrument for the different qualities of room acoustical environments for music and speech addressing the methodological gaps described above, a multi-stage investigation was conducted by the Audio Communication Group at TU Berlin (Weinzierl *et al.*, 2018). In a first step, expert knowledge from different professional domains in room acoustics was acquired by help of a focus group in order to provide a comprehensive terminology covering all aspects of the room acoustical impact on music and speech performances. In a second step, listening experiments with acoustical experts and laymen using 35 rooms of different architectural types, different size and different average absorption were conducted with different audio content (solo music, orchestral music, and dramatic speech) in order to address the most important acoustic performance types and their specifics). The goals of the subsequent statistical analyses were to

- find an exhaustive list of verbal attributes that describes all relevant room acoustical properties,

- identify the best suited items of this list to form a standardized measurement instrument,
- analyze the underlying dimensions of room acoustical impressions,
- construct a measurement instrument based on these dimensions and corresponding items,
- demonstrate reliability of the new instrument across and within raters,
- demonstrate measurement invariance of the new instrument across experimental conditions such as audio content type and subject samples, and
- demonstrate sufficient discriminant validity of its subdimensions.

In order to realize this in an experimental setting that permitted controlling for any possible confounders, the study drew on room acoustical simulation and auralization by dynamic binaural synthesis. The consensus vocabulary generated by the expert focus group consisted of 50 perceptual qualities related to the timbre, geometry, reverberation, temporal behavior, and dynamic behavior of room acoustical environments, as well as overall, holistic qualities. While some attributes reflect lower order qualities closely related to temporal or spectral properties of the audio signal ('loudness', 'treble/mid/bass range tone color', perceived 'size', and 'width' of sound sources), other attributes reflect higher-order psychological constructs, supra-modal, affective, cognitive, aesthetic, or attitudinal aspects such as 'clarity', 'intimacy', 'liveliness', 'speech intelligibility', 'spatial transparency', or 'ease of listening'. For the listening experiment, binaural room impulse (BRIR) datasets were simulated for 35 rooms at 2 listening positions for solo music and speech. For the orchestral piece, 25 rooms at 2 listening positions were selected, leaving off 10 rooms where the stage area would not be large enough for an orchestra. Thus, in total, 190 room acoustical conditions (rooms x listening positions x source characteristics) were simulated for the listening experiment. 14 of these 190 different possible stimulus combinations were rated by each of the 190 participants in a balanced incomplete block design, using 46 items selected from the focus group terminology.

To estimate the number of independent latent dimensions contained in the full item data matrix, an exploratory factor analysis (EFA) based on the common factor approach was conducted, using the scree- and Kaiser-criterion as a starting point for constructing a multidimensional measurement model. For each of the possible solutions, a series of confirmatory factor analyses (CFA) was conducted to consecutively remove single items from the measurement models up to a point where an implied removal would have led to less than three items per factor, or otherwise, the overall fit of the measurement model was already good. The latter was read from root mean square errors of approximation (RMSEA), comparative fit indices (CFIs), and standardized root mean square residual (SRMR) coefficients, as well as congeneric construct reliability (CR), indicating the internal consistency of a factor construct, and average variance extracted (AVE) indicating how well a factor explains the scores of its underlying items (Fornell and Larcker, 1981).

		Factors	Items	Poles	W	I
9-factor RAQI	6-factor RAQI	Quality	Liking	I like it – I don't like it	1.0	2
			Room acoustic suitability	suitable – not suitable	1.0	56
			Ease of listening	difficult – effortless	0.9	10
			Global balance	balanced – unbalanced	0.8	4
		Strength	Size	small – large	1.0	57
			Loudness	soft – loud	0.7	64
			Width	small – large	0.8	57
		Reverberance	Duration of reverberation	short – long	1.0	47
			Reverberance	dry – reverberant	1.0	54
			Strength of reverberation	weak – strong	1.0	51
			Envelopment by reverberation	weak – strong	0.7	48
		Brilliance	Brilliance	not brilliant – very brilliant	1.0	48
			Tone Color bright/dark	bright – dark	-0.8	-7
			Treble range characteristic	attenuated – emphasized	0.7	3
		Irregular decay	Flutter Echo	none – very strong	1.0	26
			Echo	none – very strong	0.7	40
			Irregularity in sound decay	none – very strong	0.9	32
		Coloration	Boominess	not boomy – very boomy	1.0	37
			Roughness	not rough – very rough	0.7	31
			Comb filter coloration	none – very strong	0.8	34
	4-factor RAQI	Clarity	Temporal clarity	clear – blurred	1.0	10
			Spatial transparency	blurred – transparent	1.0	1
			Precision of localization	precise – diffuse	-0.8	-6
		Liveliness	Liveliness	dead – lively	1.0	11
			Spatial presence	low – high	1.0	63
			Dynamic range	small – large	0.9	50
		Intimacy	Intimacy	remote – intimate	1.0	-3
			Distance	close – distant	-0.8	51
			Warmth	cool – warm	0.5	3
	Single items		Metallic tone color	not metallic – very metallic		
			Openness	open – constricted		
			Attack	soft – crisp		
			Richness of sound	low – high		

Fig. 3. The Room Acoustical Quality Inventory (RAQI). Four, six, and nine factors as possible sub-dimensions of room acoustical impression can be measured with questionnaires containing 14, 20, and 29 items, which are given with corresponding poles. Weights (W) and intercepts (I) should be used to measure factors and for structural equation analysis. Four additional single items with high re-test reliability, which could not be assigned to one of the factors, are given below.

The factor analysis suggests possible solutions with 4, 6 or 9 factors. These can be interpreted as a general room acoustical *quality* factor, *strength*, *reverberance*, *brilliance* (4-factor solution), *irregular decay* and *coloration* (6-factor solution), *clarity*, *liveliness* and *intimacy* (9-factor solution). The corresponding item batteries consist of 14, 20 and 29 attributes (Fig. 3). From a statistical point of view, the 6-factor RAQI scale with 20 items is the best compromise between a comprehensive assessment of the full complexity of room acoustical impressions while at the same time ensuring sufficient statistical independence of the different factors.

With *strength* and *reverberance*, two of the sub-dimensions are omnipresent in the room acoustical literature. Also *clarity* and *intimacy* as additional factors have been frequently highlighted by previous studies (Hawkes and Douglas, 1971; Lokki *et al.*, 2012). With *brilliance*, *coloration* and *intimacy* appearing as largely independent factors, it seems that timbre-related qualities play a greater role with more dimensions than previously assumed. The importance of perceived *irregularities in decay* and of *liveliness* as an independent construct has, however, hardly been considered so far.

In terms of psychometric quality, the factors of the 6-factor RAQI exhibit good across-rater consistency and within-rater stability. With regards to measurement invariance, scalar measurement invariance across measurement occasions could be demonstrated for a rather long distance of approximately 42 days. Scores from all RAQI sub-dimensions can thus be directly compared across studies as long as experimental conditions and test subject sample are identical. Similar results pertain to changes in experimental listening position: Scores taken from different listening positions in the same room did not differ systematically. Although the acoustical transfer functions might be quite different, as was demonstrated even for minor changes of the listening position (de Vries *et al.*, 2001), listeners are obviously able to identify the room and its acoustical properties as a consistent cognitive object.

5 Low Re-test Reliabilities of Experts vs. Laymen: A Problem of Language or a Problem of Perception?

As part of the RAQI development study, the listening test with 88 subjects of 190 in total was repeated six weeks later with identical stimuli. Based on these data, test-retest reliabilities could be determined, calculated as the correlation of measurements within individuals across time, as a measure of the precision, with which certain room acoustical features could be evaluated. For a majority of the 46 items rated by all participants, the reliabilities turned out to be rather low. Only three items related to reverberation ('reverberance', 'strength' and 'duration of reverberation') exceeded values of $r = 0.7$, which is usually considered as a criterion of *good* reliability. Many other items, including popular ones in room acoustics such as 'sharpness' or 'transparency', turned out to be based on rather unreliable judgements ($r = 0.37 / 0.43$), using the variation over time within subjects as an indicator.

The low stability of most single item scores indicates that room acoustical impressions appear to be strongly influenced by time-varying situational factors, such as variations in attention, mental efficiency and distraction (*random response errors*) and variations in mood, feeling and mindset (*transient errors*, Schmidt and Hunter (1999)). The extent of these psychological measurement errors, however, also depends on the expertise of the listeners. Since the above mentioned subject sample consisted of 60 music-interested laymen and 28 individuals with professional education in room acoustics, the relevance of this

personal trait could be determined, showing a mean retest reliability of 0.50 across all items for laymen vs. 0.59 for acoustical experts. Since there is no evidence for differences in the sensory performance between the two groups, the reasons for this difference have to be sought in the perceptual back-end, to pick up on a term in section 1.

Laymen could assess properties, which are clearly room-related and accessible to everyday experience such as the 'size' of the room ($r = 0.59$ vs. 0.58 for experts vs. laymen), the occurrence of 'echoes' (0.67 vs. 0.68) and even the degree of 'liking' (0.59 vs. 0.62) with the same, sometimes even better reliability than experts. Whenever, however, the influence of the acoustical source and the influence of the room on the same auditory qualities had to be separated, such as when rating the 'brightness' (0.65 vs. 0.49) and the 'bass range characteristic' (0.64 vs. 0.17), or the impact of the room on 'temporal clarity' (0.72 vs. 0.49) and 'speech intelligibility' (0.70 vs. 0.58), experts were clearly in the advantage. In these cases, the ability to judge this reliably depends on the extent to which "the performance" and "the room" are clearly separated cognitive objects attracting differentiated attention. In addition, experts then also cultivate a special vocabulary, including attributes such as the 'comb filter coloration' (0.56 vs. 0.44) or the 'spatial transparency' (0.56 vs. 0.38), which are hardly required to describe everyday experiences with music and speech.

Hence, the question whether the higher precision of experts in evaluating the acoustic properties of rooms is due to a better trained perception or a more sophisticated vocabulary points to the same interwoven phenomenon: The cognitive performance in the separation of source and space requires a more sophisticated vocabulary, but the sophisticated vocabulary in turn can lead to a more differentiated perception.

6 The Perceived Quality of Performance Spaces

Most studies dedicated to room acoustic qualities have, in one way or another, also examined what makes up the overall quality of performance spaces. To avoid terminological confusion between the two concepts, Blauert has suggested distinguishing between the "aural quality" of a room and a set of "quality features" making up the "aural character" of the room (Blauert, 2013). In the following we will stick to the distinction between "qualities" and "quality", because "qualities" is an established term in the psychological literature.

Quality, in the sense of liking or preference, was already an issue in early investigations aiming at preferred values for the reverberation time of concert halls (Sabine, 1906; Watson, 1923; Bagenal, 1925; Sabine, 1928; Knudsen, 1931). Multi-dimensional approaches have often tried to find correlations between the rating of individual attributes or factors and the overall 'pleasantness' (Wilkins, 1977), the degree of 'enjoyment' (Hawkes and Douglas, 1971) or the 'preference' (Soullodre and Bradley, 1995; Lokki *et al.*, 2012) of

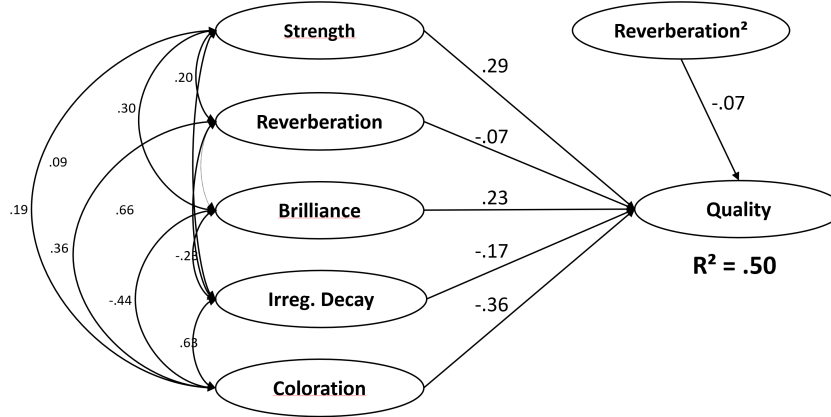
the room acoustical impression. The relation between the rating of individual qualities and overall quality judgements, however, turned out to be dependent on many factors beyond the room acoustical properties, such as the musical repertoire, the musical performance, and the taste of individual listeners. Some of the studies could even identify different preference groups, one of which preferred more reverberance while the other preferred more clarity and definition (Lehmann and Wilkens, 1980; Lokki *et al.*, 2012).

The proportion of the variance in overall quality judgments which can be explained only by acoustic qualities of the rooms themselves, was estimated by the authors of this contribution, based on the ratings of 190 participants, collected in the development of the Room Acoustical Quality Inventory (Weinzierl *et al.*, 2018). Since an unspecific quality factor turned out to be one dimension in each factor solution, the relationship of this general factor to the other dimensions could be estimated. For this purpose, the measurement model of the RAQI was turned into an equivalent structural equation model that regressed the scores of the quality factor on the other factors to estimate their respective determining influences and the overall explained variance for the quality factor. Not only linear, but also quadratic influences were tested, since psychoacoustic influences on cognitive percepts often show a u-formed (or inverse u-formed) relationship, for example between preference and reverberation, where an optimal range and a decrease in quality on both sides is the most plausible relation. To account for this, the LMS approach for non-linear effects in structural equation models was used (Harring *et al.*, 2012).

In the 6-factor version of the RAQI (Fig. 3), the model was able to explain about half of the variance in *quality* (Fig. 4). While *strength* and *brilliance* scores exhibit the largest positive influence on *quality* judgements, a decrease in quality arises with higher *coloration* and higher *irregular decay* values. *Reverberance* had both a linear and an inverted-u relationship to *quality*.

One should be aware that the influence of the individual factors (indicated by the beta weights) as well as the explanatory power of this *quality* model (indicated by the measure of determination, R^2) depends significantly on the properties of the stimulus pool from which it is derived. The less the rooms and the content presented there, such as music and speech, correspond acoustically to the expectations of the listeners, the higher the proportion of the overall quality will be that can be explained solely by acoustic properties. Also, the sign and the value of the linear beta weights initially only indicate in which direction and to what extent, for example, the reverberance of the rooms was on average distant from the perceived optimum from the listener's point of view. In order to obtain values for these relationships that correspond to a certain cultural practice, it is therefore important to work with a stimulus pool that is a representative representation of this practice.

The 50% of the variance in *quality*, explained by perceptual attributes of the room in the presented model, can be considered as the context-independent part of the overall preference judgements, not accounting for the musical repertoire, the musical performance, and the individual taste of the



MLR-Estimation (subject cluster); $\chi^2=715.712$; $df=154$; $p<0.01$; RMSEA=.037; CFI=.956; SRMR=.045

Fig. 4. Structural Equation Model estimating the influence of five dimensions in the 6-factor-RAQI on the overall *quality* factor. Path coefficients are beta-weights/correlations. The parameters indicating the fit of the model are explained in section 4.

listeners. To explain the preference of music listeners for specific concert halls in a specific situation, a significantly extended model would thus be required. Although various potential influencing factors related to the cultural context of such an overall judgement have been proposed, for example, by Blauert (2013), who pointed out the importance of the typicality of concert halls as a result of two hundred years of Western concert culture, a comprehensive model for the overall aesthetic impression of performance venues, validated by empirical data, has not yet been proposed.

A promising candidate for such a model could emerge when taking into account that judgments about concert halls are always embedded in musico-cultural practices in which the music piece, its performance, the performance space and the predisposition of listeners are intricately interwoven, and in their entirety shape the aesthetic judgment of a musical event. Thus, when music psychology examines the factors that influence the aesthetic judgment of a concert performance, the spatial and social context under which that judgment is made will always form a part of that judgment. Listeners can try to consider individual aspects and, for example, try to analytically separate the contributions of the sound source and the performance space to the perceived sound event (Traer and McDermott, 2016). However, this separation will be always incomplete. Hence a reasonable approach will possibly lie in applying models that have already been proven empirically to explain the aesthetic judgment of music and music performances also to the evaluation of the *venues* in which music is performed.

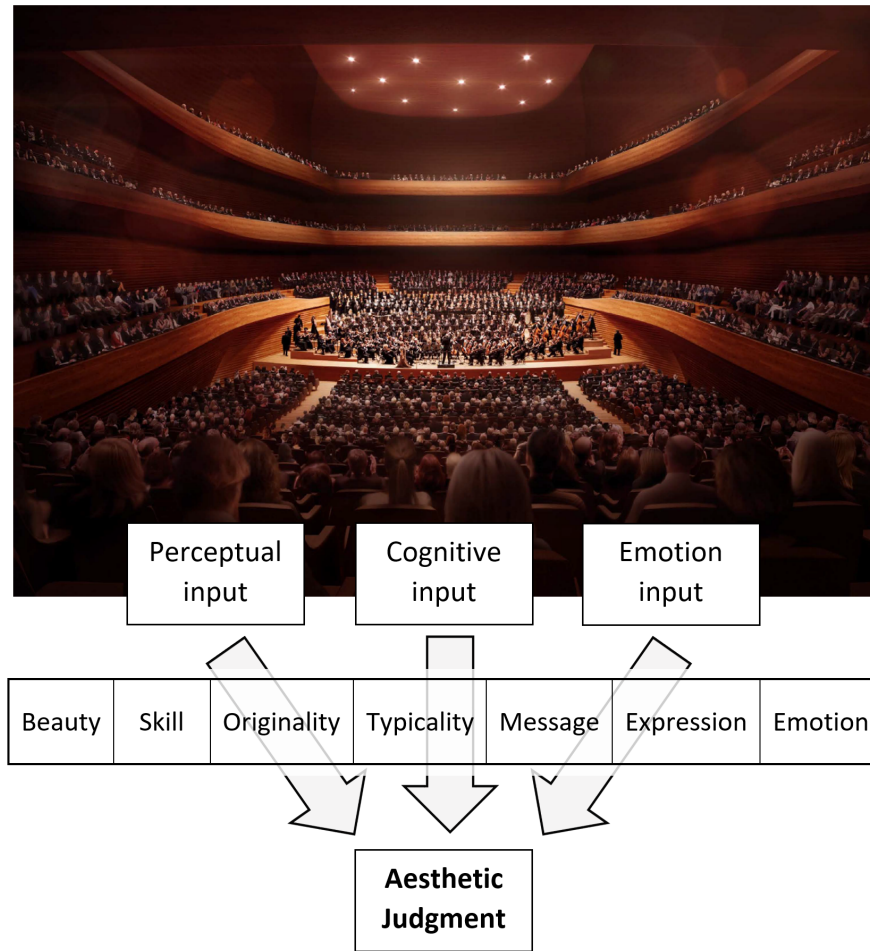


Fig. 5. A model for the formation of aesthetic judgments about music, according to Juslin *et al.* (2016). The analysis of a musical event is channelled through the perception, cognition, and emotion of the listener. Whether these inputs will have an effect on the resulting aesthetic judgment depends on the listener's criteria, which act as filters for the processed information.

Such an approach is exemplified by the model of Juslin *et al.* (2016), shown schematically in Fig. 5. It assumes that listeners make aesthetic judgments in particular situations in which they adopt what the authors call an “aesthetic attitude”. It is, not least, the concert ritual and the concert hall itself that encourages listeners to adopt this attitude. Once this condition is met, aesthetic processing may be influenced by several factors in the artwork, the perceiver, and the situation. These influences are mediated through the perception, cog-

nitition, and emotion of the listener. For one thing, a clear separation of these processes is difficult to draw, and the same musical cues can be processed perceptually (i.e., as sensory impressions), cognitively (i.e., depending on conceptual knowledge) and emotionally (i.e., aroused by other psycho-physiological mechanisms). But even more important is the observation that different listeners use different criteria that determine which of these information and which of those channels have an impact on the resulting aesthetic judgment.

These criteria can be related to varying degrees both to the musical work, to a performance and to a performance space. One of these criteria is *beauty*. In relation to the performance space, beauty can be understood as the sum of the room acoustical qualities, for which a multi-dimensional measuring instrument has been developed with the RAQI (Fig. 3). Although there is a certain temptation to identify beauty with aesthetic value in general, it can be observed that other criteria such as the degree of originality of a musical event, the skill in its realization, the typicality with respect to performance traditions, the degree of expression and emotional contagion, and the message related to the socio-cultural connotations of the musical event, can play a major role for many listeners. In the study of Juslin *et al.* (2016), most listeners appeared to use a small number of three to five criteria in their judgments, and there were significant individual differences among the listeners, both in how many criteria were used and which criteria were used.

It is tempting to assume that it is the individual choice of criteria which may account not only for the different aesthetic judgments about music as an integrated experience, but also for the different judgments about musical performance venues. An empirical verification of this assumption could be an important contribution to a problem that might have been considered for too long only from a psychoacoustic perspective.

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