BINAURAL MODELLING OF PERCEPTUAL QUALITIES IN ROOM ACOUSTICS

Frans A. Bilsen
Applied Physics Dept., Delft University of Technology,
P.O. Box 5046, 2600 GA Delft, The Netherlands

1. Introduction

Early in the 20th century, Wallace Clement Sabine performed his famous room acoustic experiments and developed his well-known reverberation time formula (see Sabine, 1964). Since then, research on the perceptual aspects of room acoustics was primarily aimed at finding "rules" describing the relation between the physics of a concert hall and the subjective experience in that very hall. It was common practice to find such rules heuristically by performing large series of listening tests using more or less sophisticated psychophysical methods. In this manner different measures of acoustic quality like, for example: "definition" ("Deutlichkeit"), "Klarheitsmass", "Zeitliche

Diffusitat", were introduced (see e.g. Beranek, 1962; Kuttruff, 1979). Essentially, these measures are extractable from the hall's impulse response between the source and a single omni-directional microphone. Accordingly, they are representative for monaural listening only.

Independently from this room acoustic research, much progress was made in psychological and physiological acoustics in understanding the functioning of our hearing organ, a.o. in binaural hearing. At the same time, in room acoustics and sound reproduction one became aware of the large differences between monaural and binaural listening (e.g. Koenig, 1950). This is particularly evident with respect to localization of sound sources and the existence of binaurally-determined room acoustic qualities like "spaciousness" .

For an understanding of the differences between monaural and binaural hearing for the different relevant subjective parameters involved, and for the development of proper binaural room acoustic criteria, it seems necessary to do comparison measurements based on the "binaural impulse response" and to apply or to develop binaural models to interpret or to predict these measurements.

In the present contribution a review of research results on spaciousness and coloration, obtained in our group at Delft specifically, will be presented. Measurements performed in the laboratory situation as well as in several concert halls in the Netherlands will be summarized. Also use has been made of an Acoustic Control System providing a variable acoustic environment in the great auditorium of the Delft University (Berkhout, 1988). The results will be interpreted and modelled with the Central Spectrum concept of binaural hearing (Bilsen, 1977). In the long run we hope to find more refined quantities applicable in room acoustical practice, or at least to provide a psychoacoustical basis to existing quantities.

As the majority of experiments has been performed with headphone listening after recording with artificial head systems in real acoustic situations, we will first summarize the similarities and differences between localization and lateralization, in section 2. Then, in section 3, the Central Spectrum model will be shortly explained. The explanation of dichotic pitch phenomena will be dealt with in section 4. Application of the CS-model to predict coloration and understand binaural decoloration will be reported in section 5. Application to spaciousness in room acoustics will be dealt with in section 6.

2. Localization versus lateralization

Normally, we are able to localize sound sources in our environment with reasonable precision: the "localization blur" is in the order of 1 degree of arc for the horizontal plane, and 10 degrees for the vertical plane (see Blauert, 1983, for a detailed review). Physical parameters involved are the *interaural intensity difference* (IID), *the interaural time difference* (ITD) and *head-related transfer functions* (HRTF) (see Fig. la and g). Although errors are sometimes made, the perceived sound source (the "auditory event") is located in space at about the same position as the sound source (the "physical event"). Under daily-life conditions, IIDs, ITDs and HRTFs are coupled parameters.

In laboratory conditions, though, we are able to uncouple these parameters. If we present signals by headphones, the listener will generally locate the auditory event inside-the-head (IHL) instead of outside-the-head. Fig.1b sketches a traditional experimental set-up to study the effect of IID and ITD separately. Generally, the listener reports that, with a change in ITD (range: -1 to +1 ms) or a change in IID (range: -10 dB to +10 dB), the auditory event moves in the head along a line that connects the left and right ear; this is called *lateralization*. Just noticeable differences (JND) or lateralization blur are in the order of 0.01 ms and 1 dB respectively. The phenomenon that an ITD can be compensated for by an IID is called *trading*.

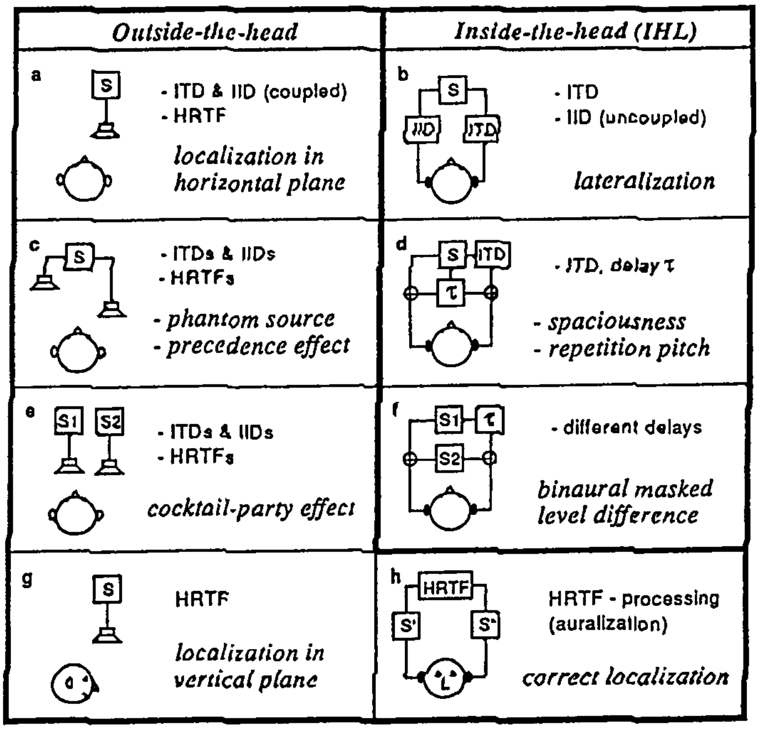

Figure 1. Perception of signals from external sources (left column), and signals reproduced by headphones (right column); S = signal, ITD = interaural time difference, IID = interaural intensity difference, HRTF = head-related transfer function. For further explanation see text.

Generally, the time-fine-structure of a signal is effective in conveying ITD-information for frequencies below 1500 Hz, with a dominant region around 500 to 600 Hz (Bilsen & Raatgever, 1973). For higher frequencies, the signal envelope is important, if the modulation frequency is lower than about 300 Hz. All (critical band filtered) signal parts play a role in IID processing.

If a signal is presented by more than one loudspeaker (e.g. conventional stereo-set-up as given in Fig. 1c) one normally perceives the auditory event between the loudspeakers, as if there were a *phantom source* (This is called summing localization by Blauert, 1983). For time delays larger than about 1 ms between the signals, the *precedence effect* comes into play, i.e. the sound S is heard as coming from the direction of the loudspeaker of which the sound arrives first at the listener' ears. The delays involved can be as large as 50 ms for speech, but only 5 ms for sound clicks. In the laboratory situation (Fig.1d) the perception is different. Image broadening *(spaciousness)* coupled with decreased accuracy in lateralization, and coloration *(repetition pitch)* are perceived (Bilsen, 1977; Salomons et al., 1991; Potter, 1993).

If direction-dependent HRTFs are taken into account, it is possible to obtain correct outside-the-head localization with headphone presentation (see Fig. 1h). The results are optimal if the subject's own HRTFs are used in the calculation (simulation) of the sound field (e.g. Wightman & Kistler, 1992) and if head movements are appropriately incorporated in the simulation.

If more than one sound signal arrive at the ears of a listener at the same time, it will be more difficult for him to perceive the wanted sound. In Fig. 1e, for example, S1 may be a wanted source, e.g. a person talking to the listener, whereas S2 may be noise from another direction in the same room. Our ability to more easily detect the wanted sound using both ears instead of one ear, is called the *cocktail-party effect*. Apparently, the binaural system uses both ITDs and IIDs as well as spectral information (HRTFs) to separate the two signals and facilitate detection.

In the laboratory situation (Fig. 1f) the corresponding release of masking has been studied extensively. If the interaural time (or phase) relations are different for signal (S1) and masker (S2) *a binaural masked level difference* (BMLD) is measured with respect to the situation where both signal and masker have the same interaural phase. The BMLD can amount to 15 dB for sine tones in noise. The effect is maximum for frequencies around 500 Hz, the dominant frequency region. Durlach developed the Equalization and Cancellation theory to account for BMLDs in a quantitative way (see Colburn & Durlach, 1978, for a review, also of other detection theories). A theory that specifically deals with the detection of wide-band (sub) signals in noise is the central spectrum theory.

3. Central spectrum model

The Central Spectrum concept was originally developed to explain dichotic pitch effects (Bilsen, 1977). The structure of the theory, however, is such that lateralization and binaural signal detection are adequately described also (Raatgever and Bilsen, 1986). Jeffress'(1948) basic idea is adopted that neural activity in one frequency channel from one ear is delayed like it is in the same channel from the contralateral ear and that a delay-dependent coincidence takes place in coincidence cells, thus performing a kind of discrete cross-correlation for that particular frequency channel (see also Blauert, 1983, for a review of similar but not identical models).

In the CS-model the analogue (cochlear) filter outputs are considered to be the inputs for the binaural system. The delaying elements, in reality most probably of neural origin, are assumed to be analogue delay lines running from corresponding filters of both ears and leading towards each other and across each other. The undelayed signal from the one ear is added to the signal from the contralateral ear at regularly spaced tabs along the delay line, and vice versa. After squaring of the added signals a continuum arises of power versus frequency and internal delay, mimicing neural activity, the *Central Activity Pattern,* abbreviated: CAP. Further, for the time being, only stationary signals will be considered and it is assumed that the binaural system performs an integration with a time window sufficiently large to allow us to neglect a leaky function within the integration. The power in the CAP is then given by:

$$P(f_c,\tau_i) = \int_{-\infty}^{+\infty} \left|H(f,f_c)\right|^2 \left\{ \left|F_l(f)\right|^2 + \left|F_r(f)\right|^2 + 2\,\mathrm{Re}\left[S_{rl}(f)\exp(2\pi f\tau_i)\right] \right\} df$$

(1)

with $H(f,f_c)$ the transfer function of the cochlear filter with center frequency f_c, $F_l(f)$ and $F_r(f)$ the fourier transforms of the signal at the **left and right ear** respectively, and $S_{rl}(f)$ the cross-power spectrum (Raatgever and Bilsen, 1986).

Finally, the theory supposes a scanning mechanism operating on the CAP in such a way that internal-delay-dependent *Central Spectra* $P(f_c)_{\tau i}$ will be distinguished and passed

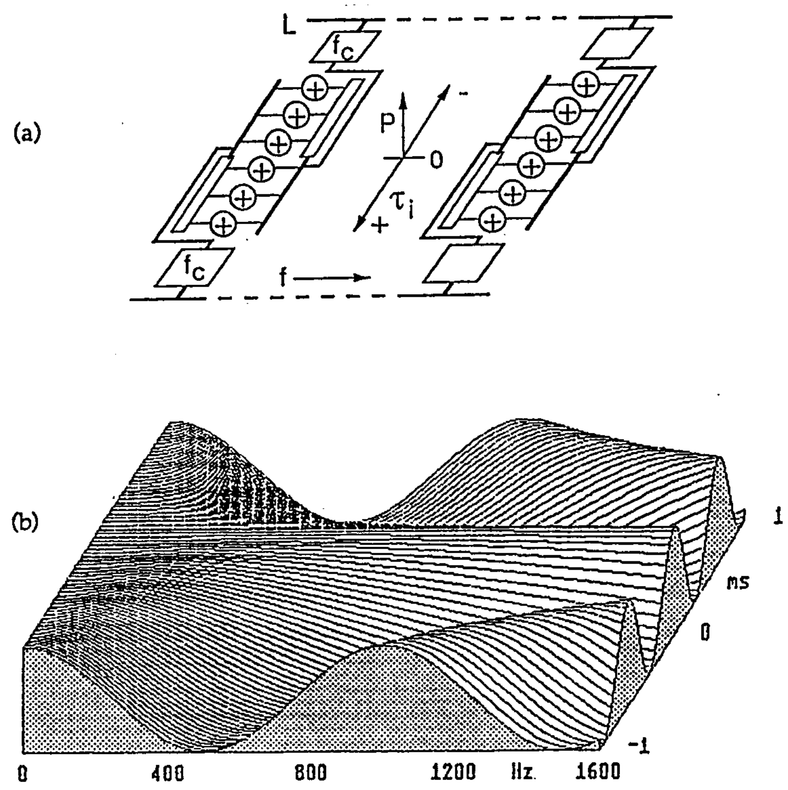

Figure 2. Schematics of the Central Spectrum Model (a); f_c represents the center frequency of the cochlear filters, τ_c is the internal (neural) delay, P represents the output power mimicing neural activity (CAP). Central Activity Pattern (CAP) of diotic white noise (b).

to a selection mechanism. This mechanism recognizes relevant spectral information by making use of clues like harmonicity *(e.g.* in the case of dichotic pitch) or a priori knowledge of the spectral features (e.g. relevant for lateralization). The spectral information at a particular internal delay is attributed a directional sensation coupled with the delay. Thus, lateralization as well as dichotic pitch is based on a scanning and spectral pattern recognition process. The CAP of diotic noise (i.e. identical noise signals at both ears) is given in figure 2, as an example.

As it involves basic anatomical and neurophysiological facts like sharp peripheral filtering, followed by neural delay and synaptic addition along sets of delay lines from corresponding cochlear filters, it can be considered as a linearized analogy to the actual physiology. In its quantitative dealing with the results of listening tests the CS-theory is merely a psycho-physical theory.

4. Dichotic pitch

The operation of the CS-theory will now be illustrated for dichotic pitch phenomena. Let us first consider the Huggins Pitch (Cramer and Huggins, 1958). In the original concept this pitch arises when noise (having a flat power spectrum) is led to one ear

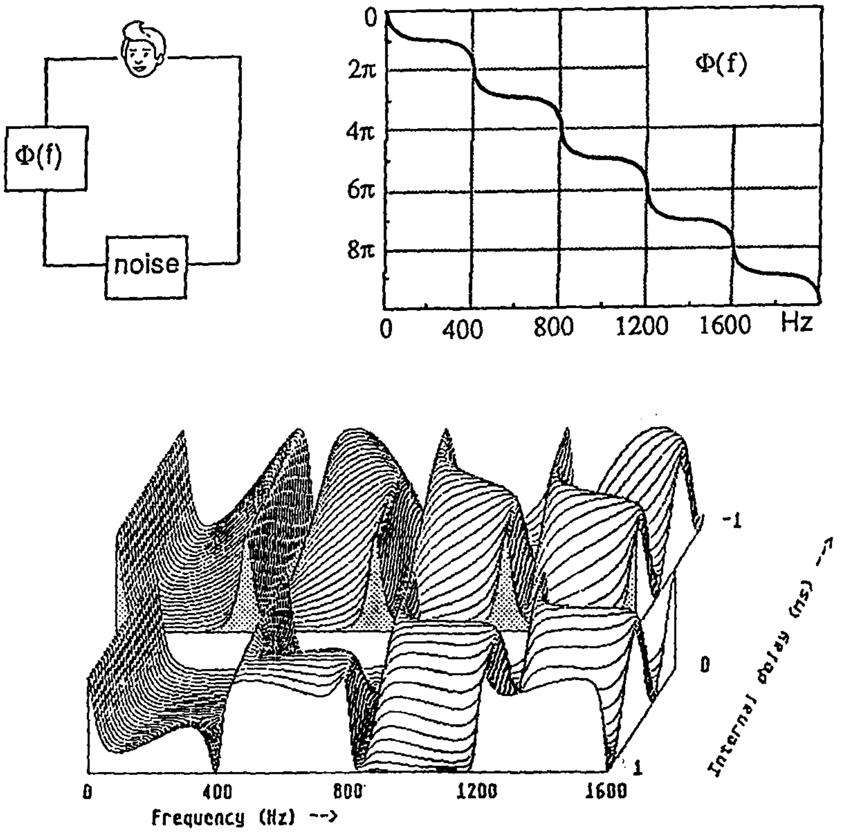

Figure 3. MPS (dichotic) noise configuration and its CAP for 400 Hz fundamental

directly and presented to the other ear through an all-pass network introducing a phase shift of 2° over a narrow frequency band around a frequency f_0. According to the literature on this phenomenon, somewhere in the head a pitch sensation is elicited that corresponds to the center frequency f_0 and that, for small relative bandwidths, has the character of a fluctuating pure tone.

As Bilsen (1976) pointed out this dichotic pitch sensation can be reinforced a great deal by applying 2π-phase shifts not only at frequency f_0 but also at the harmonic frequencies nf_0 ($n=1,2,3,..$). These so-called Multiple-Phase-Shifted signals (MPS) can be realized in an elegant way by using a phase shifting network that consists of a delay with feedback and negative bypass. The computed CAP of MPS is given in Figure 3 for f_0=400 Hz. This figure reveals that in the center ($\tau_i = 0$) a well-modulated spectrum is recognized with sharp peaks at f_0 and its harmonics up to about 1500 Hz (for easy view, a cross section has been made). This spectrum gives rise to the perception of a periodicity pitch (or: residue pitch, low pitch, virtual pitch) corresponding to 400 Hz, that is localized centrally. The irregular spectra at other places do not provide periodicity pitch information.

Since binaural percepts like dichotic pitch are supposed to be the results of the binaural time-processing system exclusively, they are not expected to show substantial time-intensity trading. Interaural intensity differences cause a decreased modulation in the CAP as can be seen from Eq. (1), thus weakening the perceived phenomena coupled herewith. Consequently, the lateralization of dichotic pitch images is expected to behave typically as found for "time-images" in general (compare Hafter and Jeffress, 1968). Trading experiments performed by Bilsen et al. (1978) and Raatgever (1980) have confirmed this point. The trading ratios found in this case are significantly below the upper limit of 40 μs/dB specified by Blauert (1983) for low-frequency signals which are dominated by time-images.

Although the CS-theory in its present form is not aimed at a quantitative description of BMLD's in general, the resemblance of calculated and measured values for HP- and MPS-stimuli is remarkably good, in spite of the simplifications in the calculations (Raatgever and Bilsen, 1986). For results of BMLD experiments with dichotically delayed white noise we refer to Raatgever (1980). These results, like those of comparable measurements by Langford and Jeffress (1964) are consistent with the theory.

5. Modelling of binaural decoloration

It is well-known that sufficiently strong reflections cause a coloration of the original sound. For delay times smaller than about 30 ms, this coloration is accompanied by the perception of repetition pitch (e.g. Bilsen, 1966). This pitch is extracted from the (periodic) comb-filtered power spectra characteristic for a signal added to its delayed replica (Bilsen, 1977). For larger delays, rattle perception prevails (flutter echo). Coloration may sometimes be very manifest in artificial reverberation systems (e.g. Schroeder, 1961). But also in good concert halls, where the reflections are more or less randomly distributed in time, the total sound impression differs from "white" (Kuttruff, 1979).

Experiments were performed in our lab. by Salomons et al (1991) with stimuli consisting of a series of reflections distributed randomly in time and derived from the same white noise. As a measure for the perceptibility of coloration for such a signal, the amount of (uncorrelated) white noise (the masking signal) is determined for which the total signal is indiscriminable from white noise. The results show that, especially for small delays (order of magnitude: 1 ms on the average), quite a large number of irregular reflections is needed to avoid coloration. Adding up to sixteen reflections produces hardly any decoloration. Decoloration is more pronounced for larger delays; for an average delay of 33 ms, it is reached already by adding only three reflections. Note, however, that for such large delays there is a clear perceptible effect (in the time domain) with short-duration stimuli instead of white noise as a basic stimulus.

Coloration due to interfering reflections in halls is perceived as less disturbing in the case of binaural instead of monaural listening (Zurek, 1979; Salomons et al., 1991). In terms of the CS-model, this might be explained by the fact that different comb-filtered signals presented to the left and right input of the CS-model simultaneously, will give rise to a CAP in which the periodic structure of the combs is blurred. For example, in the case of complementary combs (figure 4), $P(f_c)_o$, i.e. the central spectrum in the middle of the head, will be "white". This is confirmed by the results of psychophysical experiments.

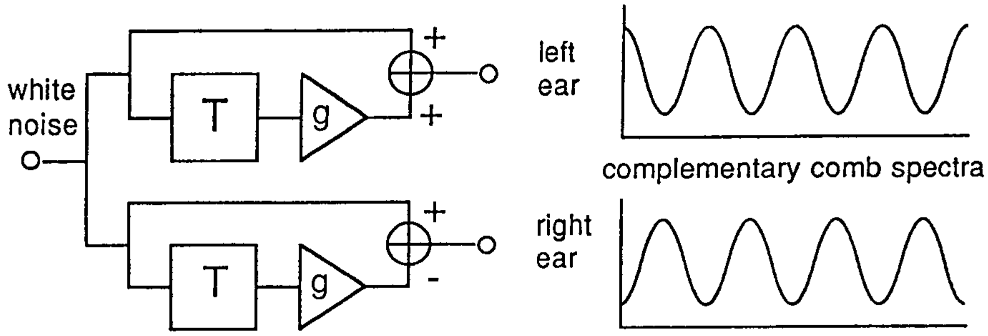

Figure 4. Experimental setup to obtain optimal binaural de-coloration for a white noise stimulus with its repetition (echo) after T ms delayed. The ears are presented with complementary comb spectra.

6. Modelling of spaciousness

When listening to a sound field in a space that is partly or completely enveloped by reflecting surfaces, the listener instantaneously experiences a notion of the type and size of that space (auditory spatial impression). Reverberance, impression of size and *spaciousness* are the primary components of the auditory spatial impression. Reverberance is the characteristic temporal slurring of auditory events that results from late reflections and reverberation. Size impression is the notion of the type and size of a space, that a listener experiences in a space, and which results from reflections coming from side walls, floor and ceiling. Spaciousness denotes a characteristic spatial spreading of the auditory events (e.g. Reichardt and Lehmann, 1978), and is defined as "the subjective broadening of sound sources, in the sense that they seem to fill a larger amount of space than is defined by the visual contours of the sound source, e.g. an orchestra" (Kuhl, 1977). In this paper, the term spaciousness will be used for the subjective broadening of the sound source.

Investigations attempting to identify the auditory components determining the listeners' appreciation of the acoustic quality of concert halls show that spaciousness is strongly correlated with the positive judgments of concert halls. This has been confirmed in many studies, e.g. Schroeder et al. (1974), Plenge et al. (1975), Lehmann and Wilkins (1980), Barron and Marshall (19~1), Ando (1985) and Blauert and Lindemann (1986). Spaciousness is therefore, an important parameter determining the subjective preference of concert halls.

In normal concert halls spaciousness emerges from a decrease in correlation of the left- and right-ear signal resulting mainly from early lateral reflections. Reflections that arrive at the listener no later that 80 ms after the direct sound are generally considered to be early reflections (e.g. Blauert and Lindemann, 1986).

Marshall (1967) already suggested the possible importance of early lateral reflections in creating spaciousness. Since then, a substantial body of evidence from many other authors has accumulated to support this claim. Barron (1971), who made the first systematic subjective observations in this field, shows that it is not necessary to have numerous early reflections to create a spacious sound field. Under specific conditions, spaciousness can be produced, by adding just one lateral reflection to the direct sound. Ando (1985) shows that the spaciousness of a synthetic sound field converges rapidly to the final value after only four reflections have been taken into account.

The role of reverberation in creating spaciousness is usually considered to be limited due to the relatively low energy content compared to the early reflections. Studies by Bilsen and Brinkman (1983), Blauert and Lindemann (1986) and Morimoto and Posselt (1989) confirm this finding. It remains however doubtful whether it is adequate to compensate a lack of early reflections by low-frequency reverberation.

Several authors report on the dependence of spaciousness on the total sound pressure level, e.g. Marshall (1967), Bilsen (1980), Cremer and Müller (1982) and Cremer (1989). The spaciousness increases as the overall level of the sound field is increased. It is reasonable to conclude that level dependence of spaciousness is a consequence of the non-linear behavior of the perceptual system and not a hall characteristic as such. Implication for the design of concert halls is that one should at least have a sufficient sound level in the hall to attain spaciousness.

Image broadening is characteristic for spaciousness in room acoustics. In the psycho-acoustical literature, also, research indicating image broadening can be encountered. In that case, it concerns experiments using dichotic stimuli with variable cross-correlation coefficients presented through headphones. In psycho-acoustic research, laboratory-generated signals presented over headphones are often used as stimuli in experiments studying the effect on the perception of the change of one separate parameter of a stimulus, whereas in room acoustics parameters are notoriously hard to control, and generally more than one observable perceptual effect is present in possible experiments.

Chernyak and Dubrovsky (1968) performed psycho-acoustical experiments, in which the subjects had to indicate the position and the extent of a stimulus. Their results show, that the perceived width of a stimulus increases for a decreasing cross-correlation coefficient of the stimulus. The spatial mapping of dichotic noise stimuli for various cross-correlation coefficients was revisited by Blauert and Lindemann (1986), who found similar results.

Knowledge of the frequency dependence of spaciousness is essential when deriving a broad-band physical measure for spaciousness. Spectral regions that contribute most to spaciousness can be given more weight, while spectral regions that do not contribute to spaciousness can be excluded from the calculations. Psychophysical experiments by Bilsen (1980) generally indicate that low frequencies are important in creating image broadening for dichotic noise stimuli.

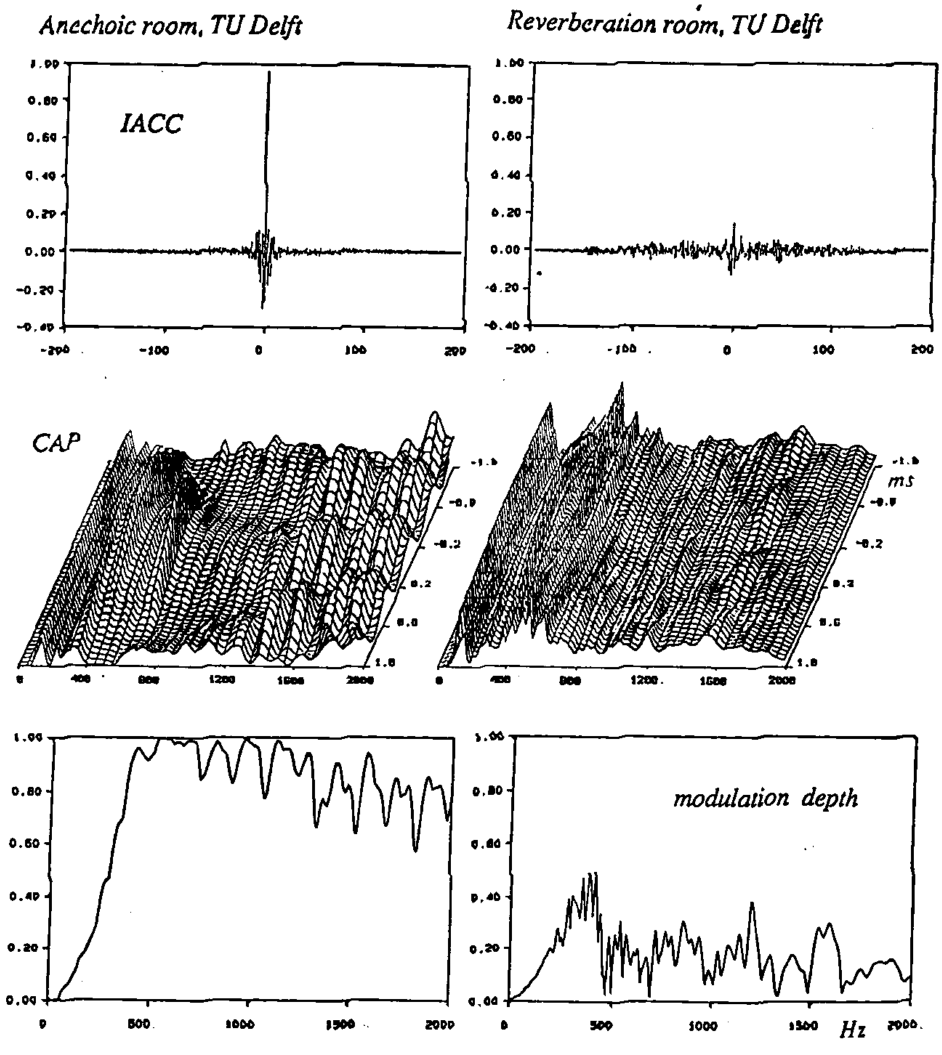

Figure 5. IACC and CAP's for an anechoic room (left) and a reverberation room (right) stimulated with white noise.

Since it is widely agreed by acousticians that spaciousness arises from a decrease in correlation of the left- and right-ear signal, caused by (early) lateral reflections, it is obvious that most room acoustical measures for spaciousness are either based on the interaural degree of coherence, e.g. the *Inter Aural Cross-Correlation Coefficient* IACC (Ando, 1985), or on the ratio of lateral sound energy to frontal or total energy arriving at the listener, e.g. *Lateral Energy Fraction* L_f (Barron, 1974, Barron and Marshall, 1981). In the acoustical literature, a number of other measures for the early lateral energy can be found, i.e.: Raumeindrucksmaβ R (Reichard and Lehmann, 1978), Lateral Efficiency LE (Jordan, 1981).

Only the IACC (Ando, 1985) is used for comparison in this contribution. It is defined as the maximum absolute value of the normalized interaural cross-correlation function, in the delay range $| \tau | < 1$ ms, in formula:

$$\mathrm{IACC} = \max_\tau |p_{rl}(\tau)| \quad \text{with } | \tau | \leq 1 \text{ ms} \tag{2}$$

The crucial step in the derivation of a measure based on the CS- model is the transformation of information in the three-dimensional central activity patterns (CAP) into one single meaningful criterion (number) for spaciousness. In order to know how spaciousness information can be extracted from the central activity patterns, it is essential to gain insight in the way the CAPs react to variations in the spaciousness. Since a decrease in interaural correlation is known to create spaciousness, it is helpful to study the effect of the interaural correlation on the CAP. This effect can be observed in figure 5.

It evidently shows that the modulation in the CAP decreases for decreasing interaural correlation. This effect can be observed from eq.(1) defining the power in the CAP. For decreasing interaural correlation, the interaction term S_{rl} decreases, thus lowering the modulation in the CAP. For interaural correlation equal to zero, this term becomes zero too, and only the monaural power at each ear remains. A preliminary predictor for spaciousness was therefore based on the modulation depth in the CAP $m(f_c)$ (Bilsen, Raatgever and Potter, 1990):

$$m(f_c) = \frac{max\{P(f_c, \tau_i)\} - min\{P(f_c, \tau_i)\}}{max\{P(f_c, \tau_i)\} + min\{P(f_c, \tau_i)\}} \tag{3}$$

The modulation depth $m(f_c)$ is a measure that provides insight in the lateralizability and hence the spaciousness of the different frequency components in the spectrum. Conversion of the modulation depth $m(f_c)$ into one single criterion for spaciousness requires additional processing. This could be achieved by applying a weighting function, giving greater weight to frequency regions that contribute most to spaciousness, and by integration over the thus weighted modulation depth $m(f_c)$.

The modulation depth $m(f_c)$ provides accurate predictions of the spaciousness in many practical situations. Still, for some extreme conditions like noise in anti-phase, predictions are unsatisfactory. Therefore, a new spaciousness predictor had to be found that would produce correct predictions for both normal and extreme acoustical conditions. Potter, Raatgever and Bilsen (1991) showed an inverse psychophysical relationship between spaciousness and the lateralizability of sound sources. This relationship triggered the conceptualization of a new measure for spaciousness, based on the Central Spectrum theory. This measure is known as the Central Modulation Coefficient (CMC) (Potter and Raatgever, 1990, and Potter, Raatgever and Bilsen, 1991). The derivation of this measure consists of a two-step process. First, the lateralization function $F_{lat}(\tau_c;)$ is calculated by integrating the weighted CAP over frequency, and by normalizing:

$$F_{lat}(\tau_i) = \frac{\int w(f)P(f,\tau_i)df}{\int w(f)df} \qquad (4)$$

Here, w(f) is a weighting function giving greater emphasis to the frequency components that contribute most to spaciousness. The same function is chosen representing the dominance weighting based on lateralization data by Raatgever (1980). From preliminary experiments, involving diotic white noise and dichotic white noise in anti-phase, this frequency weighting function proved to be the most successful in the calculations predicting spaciousness. Its shape mimics the frequency dependence of spaciousness found in the experiments found by Bilsen (1980). The range of the interaural delay (τ_i) is chosen between -3 ms and +3 ms (compare Raatgever, 1980).

The mean modulation depth in the lateralization function is the *Central Modulation Coefficient* (CMC):

$$CMC = \frac{max\{F_{lat}(\tau_i)\} - <min> \{F_{lat}(\tau_i)\}}{C_n} \qquad (5)$$

where <min> denotes the mean of the minima on both sides of the maximum in the lateralization function $F_{lat}(\tau_i)$; C_n is a normalization constant.

The value the CMC takes is, like the IACC, reversely related to spaciousness. Possible values for the CMC range from 0 for very spacious signals, to 2.0 for extremely non-spacious, narrow-band signals. For broad band dichotic noise stimuli, calculations show a linear relation between the CMC and positive values of the cross-correlation coefficient. The performance of the CMC for extreme conditions, e.g. stimuli in anti-phase is interestingly good. Other measures like IACC and modulation depth $m(f_c)$ fail to predict the spaciousness correctly for this rather artificial stimulus. In table 1, the values for IACC, CMC and the spaciousness S (Potter, 1993) are compared for three stimuli, diotic noise ($\rho_{rl} = 1.0$), dichotic noise, anti-phase ($\rho_{rl} = -1.0$) and dichotic noise ($\rho_{rl} = 0\ 5$).

Table 1. IACC, CMC, and perceived spaciousness S, for some dichotic white noise stimuli used in the psychophysical experiments.

Stimulus		IACC	CMC	S
Diotic noise	$\rho_{rl} = 1.0$	1.0	1.49	0.16
Anti-phase noise	$\rho_{rl} = -1.0$	1.0	0.81	0.59
Dichotic noise with	$\rho_{rl} = 0\ 5$	0.5	0.85	0.62

In another experiment, the spaciousness of a number of dichotic white noise stimuli recorded in the main Auditorium of the Delft University of Technology has been determined and predicted by both CMC and IACC. In the Auditorium an acoustical control system (ACS, Berkhout, 1988) is installed, providing variable acoustics through the electro-acoustical generation of reflections. The reverberation time and the amount of lateral energy can be varied using this system. Different settings of the ACS-system thus provide different -virtual- concert halls. Measurements were taken for three different setting of the ACS-system and two different positions in the hall. The settings consisted of: a) the hall itself, without ACS, RT=1.2s, b) a virtual chamber music hall (only early lateral energy is being generated by the system, RT=1.5s and c) a virtual concert hall (both early lateral energy and reverberation is generated by the system, RT=2.3s.

A paired-comparison method was used to determine the spaciousness of the stimuli. The results show clearly that both CMC and IACC are good predictors for spaciousness. The correlation coefficient (R) for the goodness of fit obtained from linear curve fits of IACC, respectively CMC against the perceived spaciousness, are R=0.995 for the IACC and R=0.998 for the CMC.

Further, in eight concert halls in the Netherlands acoustical measurements have been conducted, aimed at gathering reference and test material for the evaluation of both measures for spaciousness. The sizes of the halls in this study varied from a chamber music hall (604 seats) to a large concert hall (2230 seats). All measurements were carried out in unoccupied halls. The results of IACC and CMC measurements will be compared to the perception of spaciousness, determined in psycho-physical experiments.

The spaciousness of the stationary noise signals recorded in the concert halls was judged in paired-comparison experiments . Eleven stimuli have been evaluated, leading to a total of 121 comparisons per session. White noise stimuli recorded in the reverberation room and in the anechoic room of our institute have been included in this comparison. They have been used to scale the scores of the spaciousness for the concert halls. The scaling procedure sets the spaciousness of the reverberation room to a value of 1.0 and the spaciousness of the anechoic room to a value of 0.0. The scores of the concert halls under survey were well within these extreme situations.

In a first experiment, the noise signals recorded in the first receiver position (in the back of the hall, well off the center axis), and the center-front source position were used. The results of this experiment are presented in figure 6(a). In these figures, the spaciousness according to 1- IACC (calculated from the to 250-2,000 Hz band-limited and equalized recorded white noise signals) and 1- CMC is given as well. One can expect the sound field to be mainly diffuse for this position in the back of the hall. Therefore the spaciousness is high in most concert halls and only small differences in the spaciousness for the different halls are observed. One exception is the Auditorium of the TU Delft, where for both settings of the ACS (AU0, AU4), the spaciousness is generally lower. The ACS system however enlarges the spaciousness in this hall significantly (ACS 0 vs. ACS 4). In this hall (AU0), a big difference between the perceived spaciousness and the two predictions can be observed. No obvious reason for this discrepancy can be given.

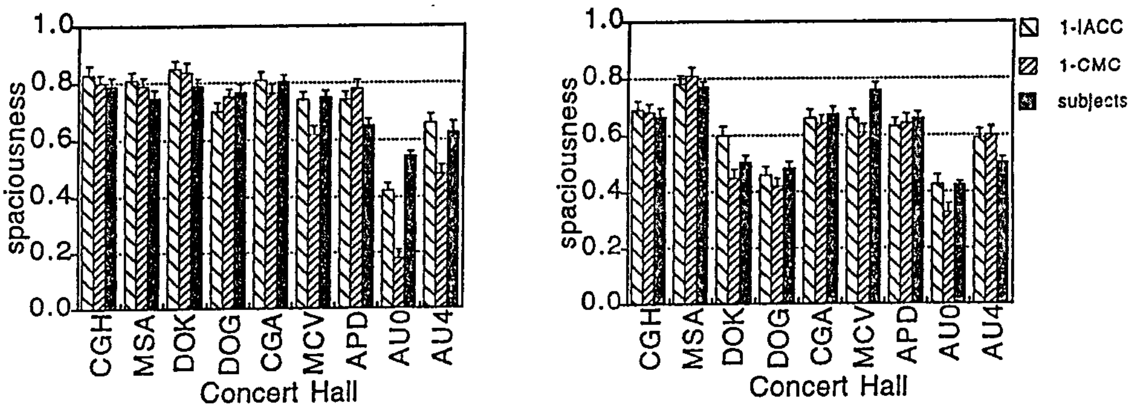

Figure 6. (1 - IACC), (1 - CMC), and perceived spaciousness (subjects), for 7 concert halls and the Delft Auditorium (two ACS-settings); back position (left) and front position (right)

In a second experiment, the noise signals recorded for the second receiver position (in the front of the hall, slightly off the center-axis) and the center-front source position, were used in the comparison experiment. The results for this experiment are presented in figure 6~b), together with 1 - IACC and 1- CMC values. The similarity between the two physical measures and the perceived spaciousness is remarkable. Considerable differences between the spaciousness of the different halls can be found, as could be expected from the receiver position in the front of the hall.

From both experiments we see that in most of the concert halls the spaciousness is high. Since spaciousness is strongly related with subjective preference of concert halls, these halls perform well on this point. The exceptions are the Auditorium of the TU Delft without the ACS system (ACS 0) and both halls of De Doelen (DOK and DOG) for the front receiver position. The Auditorium of the TU Delft is a wide, amphitheater-like lecture hall with only a small area of lateral reflecting surfaces. The sound is directed to the listeners mainly via the reflective ceiling. Frontal reflections, however, do not contribute to spaciousness. The concert hall of De Doelen (DOG) is a large and wide hall. The relatively low spaciousness in the front part of this hall probably stems from a lack of lateral energy due to the large distance from the side walls to the receiver position. The relatively low spaciousness for the front receiver position in the chamber music hall of De Doelen (DOK) is due to the receiver position chosen close to the stage (row 4, in the direct field) in this small hall, in order to keep the relative distances equal to the other (larger) halls.

In fact, both the IACC and the CMC provide assessments of the spaciousness that seem to correlate remarkably well to the perceived spaciousness. So, both measures are effective indicators for the spaciousness experienced in concert halls. For artificial signals (see table 1), the CMC is superior to IACC.

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