WHAT IS SO SPECIAL ABOUT SHOEBOX HALLS? ENVELOPMENT, ENVELOPMENT, ENVELOPMENT

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In spite of many attempts to surpass the sound quality obtained from shoebox shaped concert halls, this traditional design continues to lead the pack in sound quality ratings. In Leo Beranek's careful surveys of concert halls and opera houses (1962, 1996, and 2004), four of the five highest ranked halls in the world have a rectangular shape. A deeper understanding of what differentiates them from surround halls, fan shaped halls, or many other configurations will enable designers and architects to achieve a higher level of acoustical excellence in modern concert halls.

"The prominent feature of the most successful halls is their rectangular shape."

Highly-rated halls

Based on surveys of musicians, conductors, and knowledgeable listeners Beranek (1996, 2004) ranks the five best halls as: Grosser Musikvereinssaal (Vienna), Symphony Hall (Boston), Teatro Colon (Buenos Aires), Konzerthaus (Berlin), and Concertgebouw (Amsterdam). Figures 1-5 from Long (2006) show sketches of these halls based on Beranek's work. Most were constructed in the late nineteenth and early twentieth centuries. Konzerthaus was originally built in 1821 and rebuilt in 1993 after having been destroyed in World War II. While there are other fine halls, most have similar features. In fact four of the next five top rated halls are also rectangular.

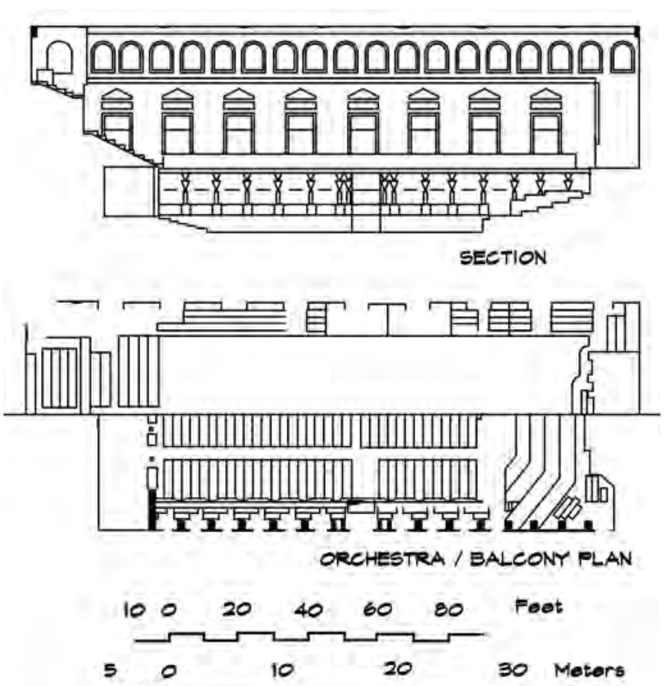

Fig. 1. Grosser Musikvereinssaal, Vienna, Austria (Beranek, 1996).

Technical factors in hall design

Studies by Ando (1985) and Beranek (1996, 2004) have identified quantitative factors that contribute to hall quality. In approximate order of importance, these are: (1) *listener envelopment*, that is, the sense of being surrounded by sound, in particular, in the time period greater than 80 milliseconds after the arrival of the first sound; (2) *reverberant character*, usually quantified in terms of the reverberation time; (3) *diffusion*, an important factor contributing to envelopment; (4) *sound strength*, as determined by taking measurements at various seats throughout the hall of sound delivered from a

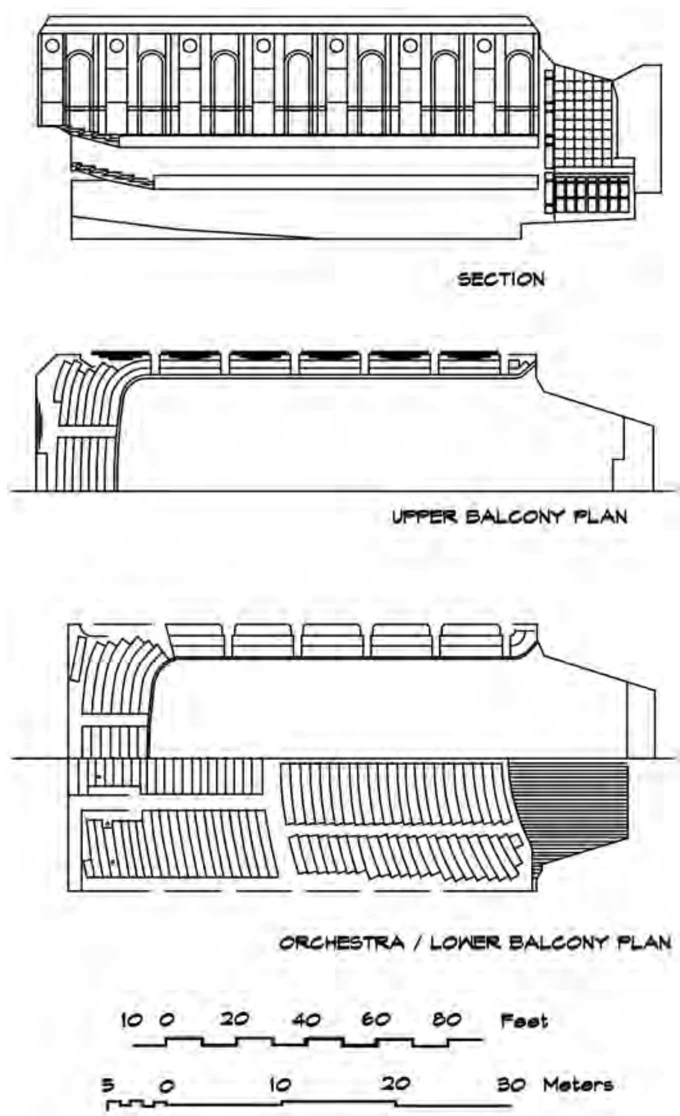

Fig. 2. Symphony Hall, Boston, Massachusetts, United States of America (Beranek, 1996).

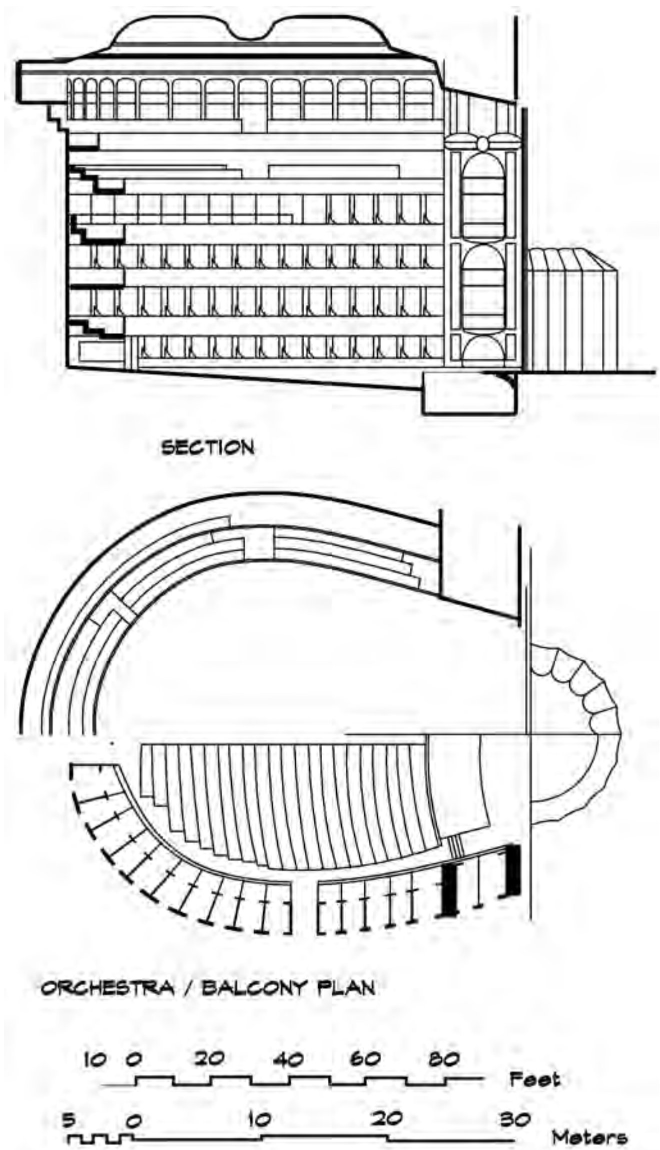

Fig. 3. Teatro Colon, Buenos Aires, Argentina (Beranek, 1996).

fixed source on the orchestra platform; (5) *clarity*, the strength of the initial sound along with early reflections arriving soon thereafter; and (6) *warmth*, the strength of the bass. Additional contributing factors that are not usually considered in these ratings include audience comfort, a low level of background noise, clear sightlines, and convenience. The absence of any of these qualities can offset the other positive factors.

Physical characteristics of successful halls

The features common to successful halls continue to be a subject of spirited debate, study, and technical measurement. Every rule seems to have at least one exception, but there is enough consensus that a very convincing case can be made.

The prominent feature of the most successful halls is their *rectangular shape*. Among the five best, only Teatro Colon varies—having the horseshoe shape of a classic European opera house. The best halls are *narrow*, usually less than 75 feet wide. Vereinssaal is only 65 feet, Symphony Hall 75 feet, Konzerthaus 68 feet, and Teatro Colon 80 feet. The exception is Concertgebouw at 91 feet. The narrow parallel side walls in rectangular halls provide early reflections that increase clarity, along with later side reflections that surround or envelop the listener. The latter reflections include not only the first reflected sound but also additional multiple reflections extending out in time.

The best halls also have *flat* or *gently sloping floors* and *elevated orchestra platforms*. Most platforms are at or above the level of the last row of seats. This is in contrast to a legitimate theater where the seating is raked for better sightlines. A typical stage height in a legitimate theater in the United States is 42 inches, based on the average seated eye height of about 44 inches. In Vereinssaal the orchestra platform is 39 inches, however, the main floor is flat except in the rear where the last few rows rise to about the level of the orchestra. The platform height at Konzerthaus can vary between 31 and 95 inches, but the main floor seating plane is not raked. At Concertgebouw the platform is 59 inches and the floor is flat. At Symphony Hall the platform is 54 inches high and there are two seating configurations. In summer, for the "Pops" concerts, the floor is flat and patrons are seated around tables. In winter, a plywood floor is installed that rises at the rear to a height just above that of the orchestra. Teatro Colon has a gently raked floor and a pit filler that can be raised and lowered. The stage height is not given by Beranek (2004), but appears in photographs to be about 42 inches, consistent with its primary use as an opera house. The seats rise at the rear to about the same height as the stage.

Envelopment is enhanced when there are *wall surfaces available to create multiple reflections* in a plane just over the heads of the audience. This allows sound reflections to be sustained in this horizontal plane without being absorbed by the audience. When the seating is steeply raked or when the orchestra is seated on a low platform, side reflections are grounded out in the seating area after the first reflection. It can be observed that the most highly rated halls have reflective surfaces located in the band above the first floor seating in the same horizontal plane as the orchestra. It is likely that this feature in Concertgebouw helps counteract the width of the room. The wall surfaces need not be smooth; indeed, scattering by diffuse objects can be helpful to envelopment. All of the best halls have significant side wall diffusion.

The reverberant character is quantified by the reverberation time—the time it takes for a sound to die out. In large concert halls, when fully occupied, *the reverberation time ranges from 1.8 to 2.2 seconds in the 500-1000 Hz octave bands*. Shorter times are preferred for music in the classical style (Bach, Mozart and Haydn), which was originally performed in smaller rooms. Longer times are preferred for romantic music (Schubert, Mendelssohn, and Brahms). The reverberant character of these halls is generally uniform. At Vereinssaal, Konzerthaus, and Concertgebouw the mid-frequency reverberation time is 2.0 seconds. Symphony Hall is 1.9 seconds. The exception is Teatro Colon at 1.6 seconds, where lower values are preferred for better speech intelligibility.

Successful halls usually *limit the number of seats* to no more than 2400 and preferably to fewer than 2200.

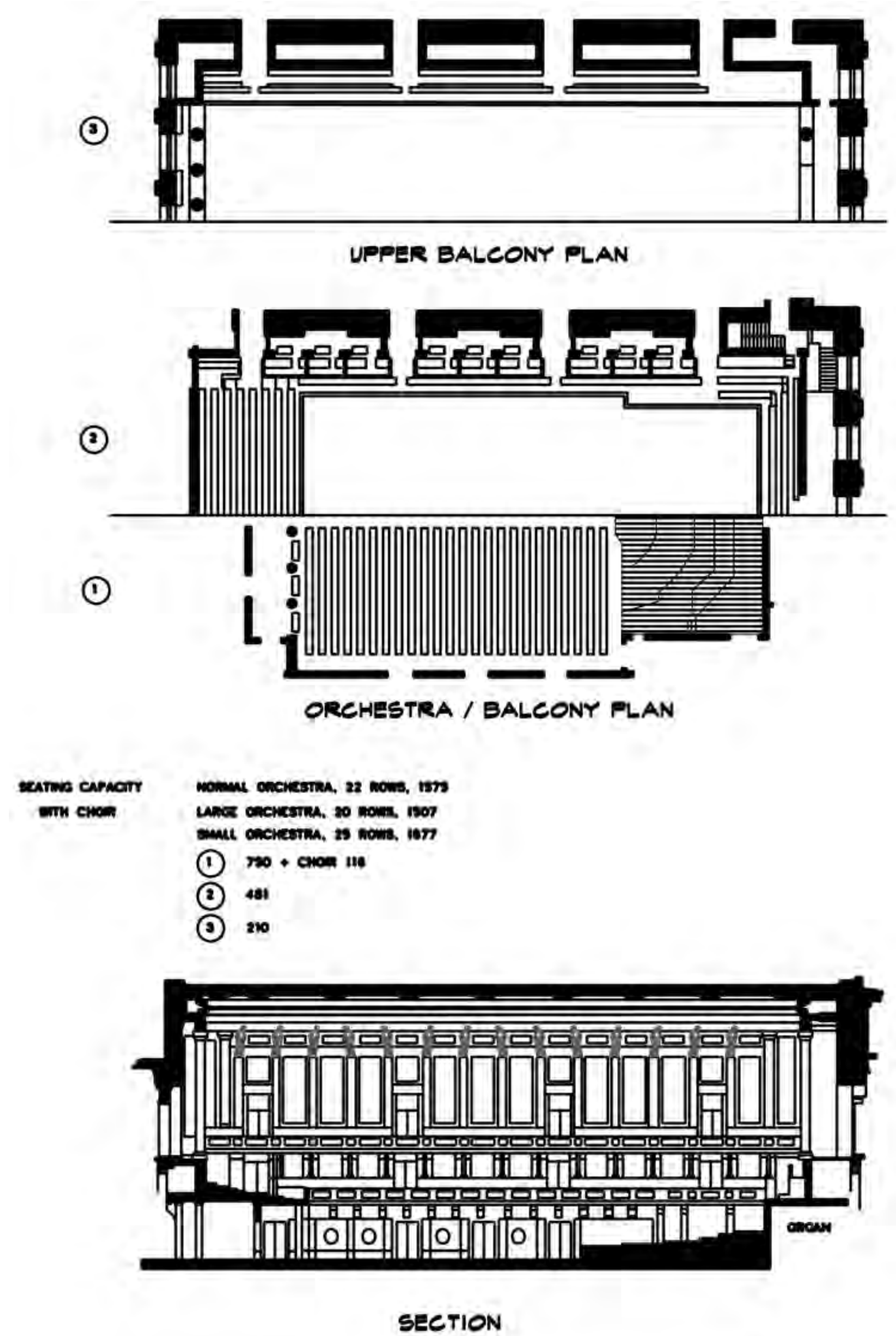

Fig. 4. Konzerthaus, Berlin, Germany (Beranek, 1996).

Vereinssaal has 1750, Teatro Colon 2487, Konzerthaus 1575, and Concertgebouw 2037. The exception is Symphony Hall at 2625. The average seating capacity of the top five is about 2100 and the top ten about 2000. Sound strength is greatest in smaller capacity halls since the audience represents the largest absorbing surface.

Ceiling heights, as measured from the main floor in areas not covered by balconies, *are usually greater than 50 feet*. Vereinssaal is 57 feet, Symphony Hall 61 feet, Konzerthaus 58 feet, Concertgebouw 52 feet, and Teatro Colon 87 feet. All of these *ceilings are highly diffusive*—they are designed to scatter sound in many directions. Additional diffusive elements such as columns, statuary, and chandeliers are frequently added.

Another important factor is the *ability of the orchestra to hear itself*. Reflective surfaces located above and around the orchestra area enhance the musicians' ability to hear each other. In rectangular halls the orchestra is located at one end of the room up against highly reflective surfaces. In these halls the sound is confined to a lateral angle of about 90 degrees while an orchestra in the middle of a room radiates into the full 360 degrees (Hidaka *et al.*, 2008). This increases the sound strength in the rectangular rooms by about 6 dB compared to the surround halls.

Non-rectangular halls

There are other room shapes used in concert hall design. The most common is the surround hall where the audience seating surrounds the orchestra. This style has been used in Berlin Philharmonic Hall, Suntory Hall in Tokyo, and Disney Hall in Los Angeles. Figure 6 shows a sketch of Berlin Philharmonic Hall. Non-rectangular halls can be designed with the goal of achieving the same technical factors as those present in shoebox halls. In the areas of reverberation and clarity, surround halls can achieve results comparable to those found in rectangular halls. Hidaka *et al.* (2008) recently published a detailed comparison of measured data in these two types of halls. Surround halls are not as successful as rectangular halls in achieving envelopment, source strength, and minimizing seat to seat variation. This is particularly evident with directional instruments such as the French horn, trumpet, and piano (with its reflecting board sending the high frequency sounds forward), as well as a soprano voice. In these factors the Hidaka *et al.* (2008) study shows clear differences.

Shoebox halls

Some acousticians and architects are still building halls in the shoebox style. Sala São Paulo in Brazil is a good recent example. The late Russ Johnson, acoustician for Sala São Paulo, told me he thought it might be his best hall. Seiji Ozawa Hall in Lenox, Massachusetts is another fine example.

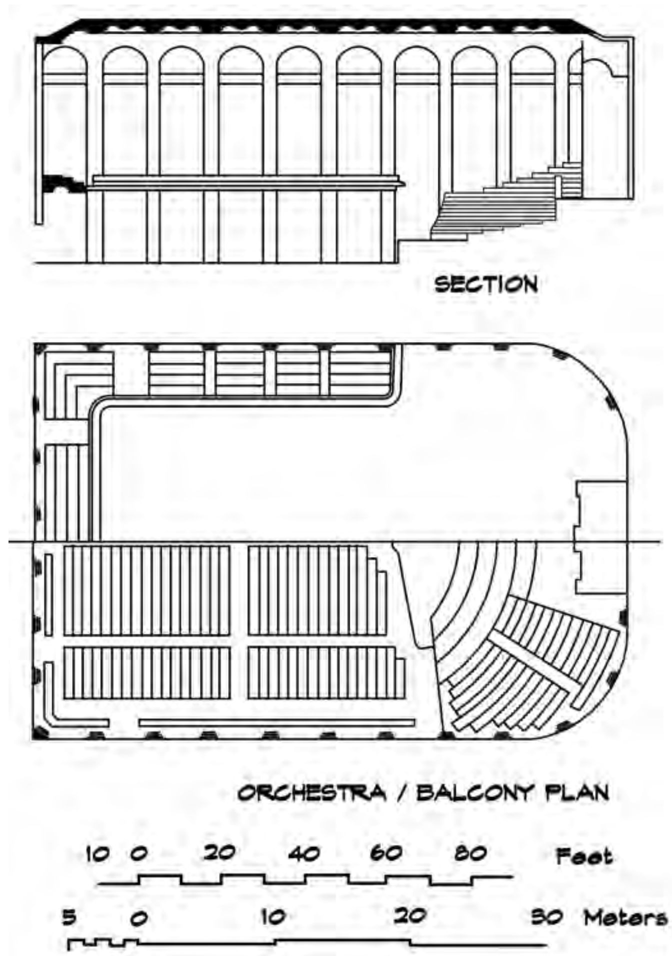

Fig. 5. Concertgebouw, Amsterdam, Netherlands (Beranek, 1996).

It is encouraging that the testimonial evidence is supported by the technical studies. It seems clear that the inclusion of a reflective band above the first floor seating helps maintain lateral reflections and envelopment. This combination of a raised orchestra platform and low rake angle for the seating is a common feature in the world's best halls. In the balconies reflective bands are also present in rectangular rooms and are augmented by overhangs from the upper balconies and ceilings above. If acoustical excellence is of prime importance and shoebox halls sound best, we should be building more of them.AT

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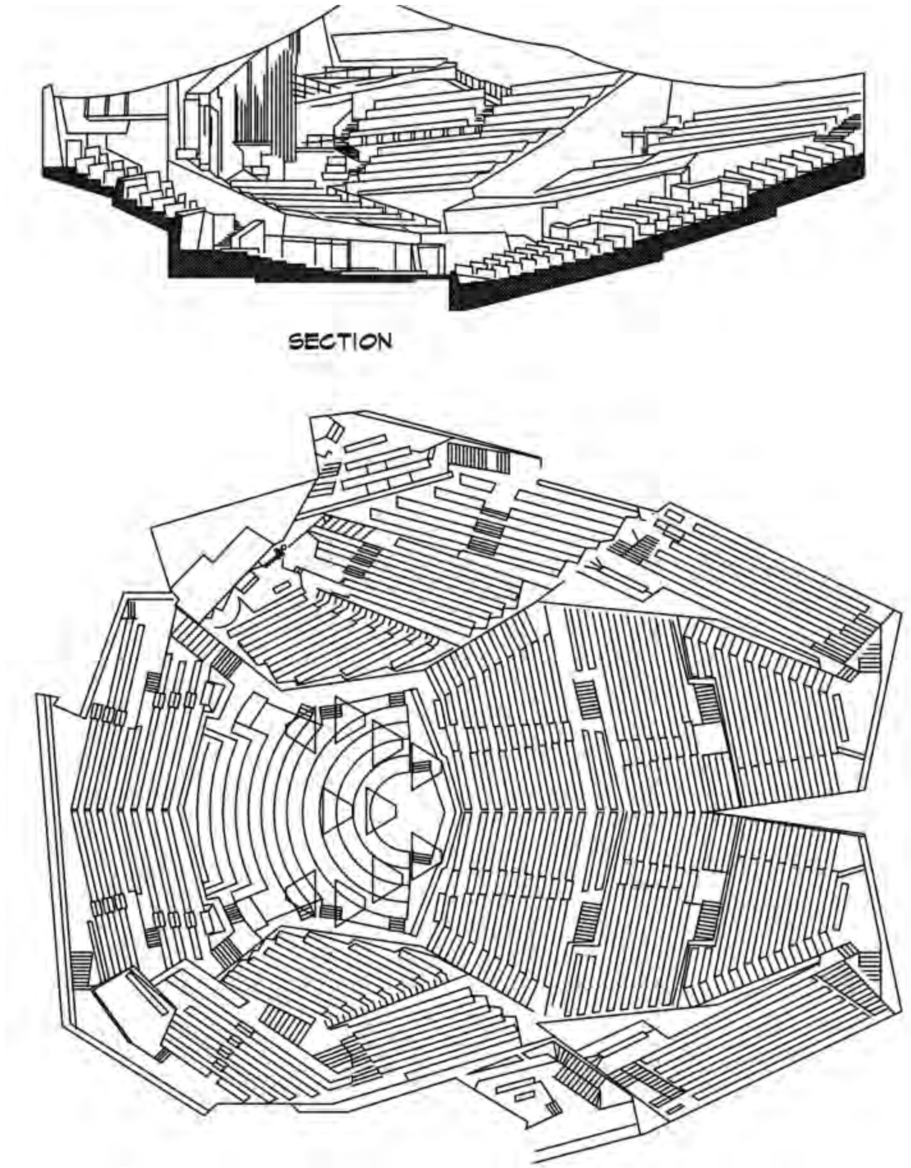

Fig. 6. Philharmonic Hall, Berlin, Germany (Beranek, 1996).

Marshall Long received a BSE from Princeton University in 1965, attended the University of Grenoble in France and the University of Madrid in Spain in 1966, and received MS and Ph.D. degrees in engineering from UCLA in 1971. While still a graduate student, he founded his own consulting firm, now in its 38th year. Marshall Long Acoustics specializes in architectural acoustics, audiovisual design, noise and vibration control, and other technical areas related to acoustics. He enjoys sailing, judo, soccer, reading, and writing, and is living with his family in Sherman Oaks, California. He was recently elected a Fellow of the Acoustical Society of America.

HOW MANY PEOPLE WILL BE AWAKENED BY NOISE TONIGHT?

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Introduction

Noise can disturb sleep and is especially a problem around airports with many night flights. There have been eight major studies worldwide on the effects of noise on sleep that included the study of behavioral awakenings.[1-8] "Behavioral awakenings" means that the individual is awake enough to press a button, and behavioral awakening is the sole measure of effect in American National Standards on this topic. In contrast, the European Union (EU) has concentrated on motility (body movements while asleep) as their major measure of effect. The use of motility as a measure of effect has been rejected in the USA. Imagine telling a judge or planning body, "These increases in noise will cause twenty percent of the population to move ten percent more in their sleep." What concrete meaning does it convey? Compare it to the statement, "These increases in noise will double the number of people awakened—from 20 percent to 40 percent of the population."

"Imagine telling a judge or planning body, 'These increases in noise will cause twenty percent of the population to move ten percent more in their sleep'."

All of the eight studies referenced above provide data that relate the probability of being awakened to the Sound Exposure Level (SEL) of the individual noise events. It was on these kinds of data that both the original and the new standard ANSI/ASA S12.9/Part 6–2008 are based.[9] Figure 1 (Annex B of the new standard) indicates the prediction of the likelihood of behavioral awakenings in response to unique, single events, but it does not provide a means to predict the effect of an ensemble of events distributed in some fashion throughout the night.

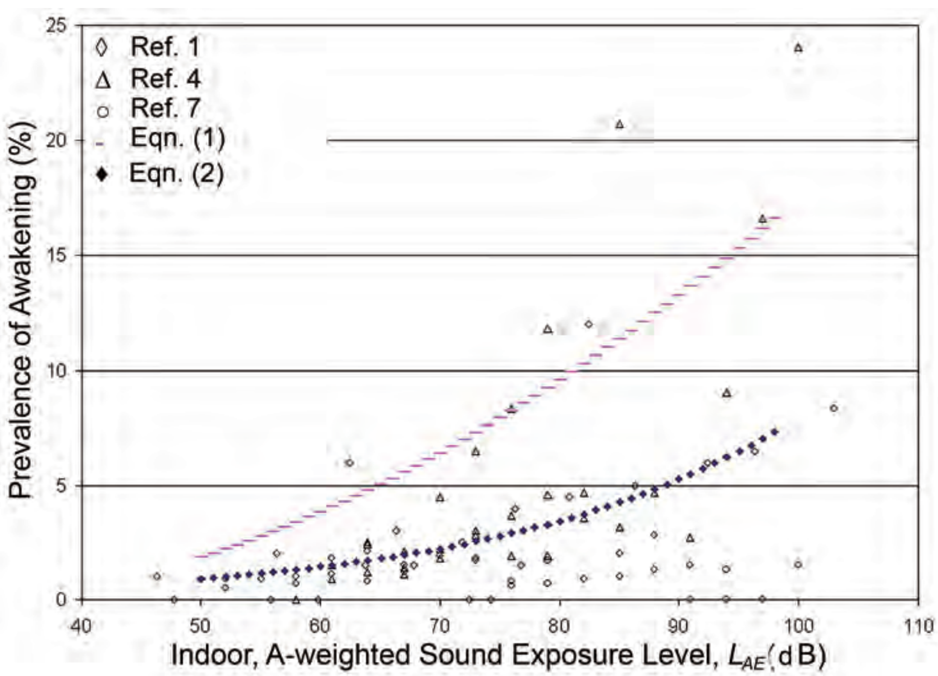

Fig. 1. Probability of awakening versus indoor Sound Exposure Level (SEL) from ANSI/ASA S12.9/Part 6-2008. The dashed curve is for subjects newly experiencing the noise of nighttime discrete noise events (Eq. 1); the solid curve is for acclimated subjects (Eq. 2).

The EU has advanced a method to possibly overcome these shortcomings. This method and regulatory guidance specifies the cumulative metric—annual-average equivalent sound level between 11:00 p.m. and 7:00 a.m. (L_{night})—to assess sleep disturbance.[10] For sleep disturbance produced by aircraft noise, this regulatory guidance addresses (1) the expected maximum number of noise-induced motilities and (2) the increase in mean motility—both as a function of L_{night}.[11] But it is difficult, if not impossible, to relate specific aircraft-noise effects to such cumulative metrics, e.g., "What percent of the population will be awakened?". Again, it is difficult to communicate to decision-makers and to the public the meaning of changes in such cumulative metrics—especially in easily understood terms such as the expected change in percent of the population awakened.

ANSI/ASA S12.9/Part 6–2008

American National Standard Quantities and Procedures for Description and Measurement of Environmental Sound—Part 6: Methods for Estimation of Awakenings Associated with Outdoor Noise Events Heard in Homes has just undergone major revisions that culminated in the new standard published last year. Based on the work by Anderson and Miller,[12] this standard now provides a means to predict the probability of awakening to an ensemble of events distributed in any fashion throughout the night.

Method based on probability of awakening

The method determines the number of people or percent of the population likely to be awakened at least once from a full night of noise events. Most sleep disturbance data are reduced to a relationship of the form of a dose-response curve similar to those shown in Fig. 1. The Federal Interagency Committee on Aviation Noise recommends a functional relationship for subjects newly experiencing the noise of night-time discrete events.

$$P_{A,\text{single}} = 0.0087(L_{AE} - 30)^{1.79} \quad (1)$$

where $P_{A,single}$ is the probability of being awakened by a Sound Exposure Level of L_{AE}

Such relationships cannot be applied directly to determine awakenings that may result from a full night of noise events. However, such a dose-response relationship can be used to determine the probability that a single event will produce an awakening. This probability may then be converted into a probability of NOT being awakened (1 minus the probability of being awakened). Next, the probability of NOT being awakened all night by multiple events is computed as the joint probability of not being awakened by any of the night-time events. Finally, the probability of being awakened at least once by any of the night-time events is one minus the probability of not being awakened at all. Equation (2) expresses this approach.

$$\begin{aligned} P_{\text{awake once, multiple}} &= 1 - P_{\text{sleep thru,multiple}} \\ &= 1 - \prod_{a=1}^{N} \left(P_{\text{sleep thru,single}}\right)_a \\ &= 1 - \prod_{a=1}^{N} \left(1 - P_{\text{awake,single}}\right)_a, \end{aligned} \quad (2)$$

where:
a = index across all N noise events during the night, and
$P_{awakesingle}$ is the probability of being awakened by the nth single event.

Therefore, if Fig. 1 gives the probability of awakening an

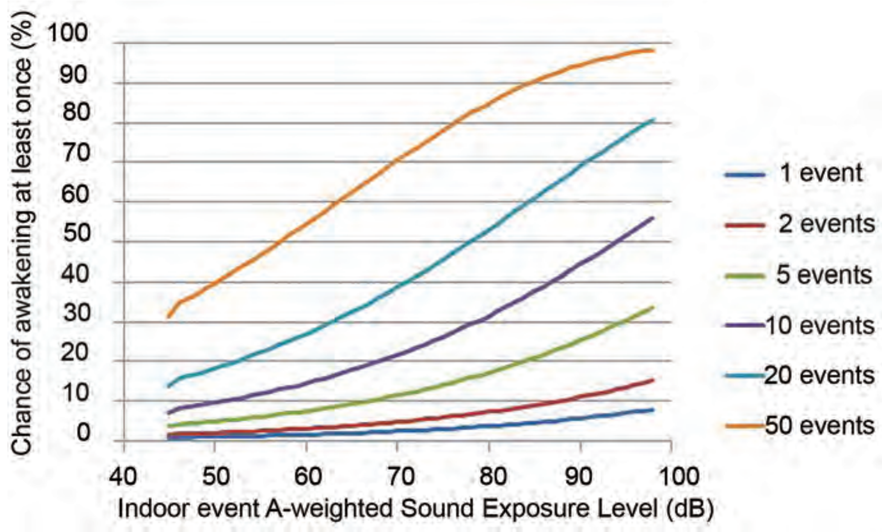

Fig. 2. Chance of being awakened at least once versus event Sound Exposure Level for multiple, like-noise events

average person by a single noise event (acclimated curve—solid line), then application of this method for multiple noise events (all with the same Sound Exposure Level) gives Fig. 2 that shows the probability of awakening when this average person is subjected to multiple, like-noise events during the night.

Refinement of dose-response curve

By applying logistic regression to raw awakening data, more variables may be included in the dose-response curves. Data for these regressions, obtained in people's homes by Sanford Fidell and his co-workers, have been previously reported in the acoustical literature,[3,4,6,7] and were provided to Harris Miller Miller & Hanson Inc. (HMMH) by the Air Force's sponsor of Fidell's studies. Data were from studies in communities around Denver International Airport, Los Angeles International Airport, and Castle Air Force Base.

Data were of the form illustrated in Fig. 3. In this figure, each vertical column represents the results for one subject; subject numbers are given on the horizontal axis. For each subject, the indoor sound exposure level (SEL) of each event (i.e., how loud and how long), its time of occurrence, and whether or not it resulted in a behavioral awakening were contained in the data set. Hence regressions could include not only SEL, but also time of night and subject. (Anderson and Miller[12] have analyzed these data in terms of both *time since retiring* and *individual sensitivity* but the ANSI Standard incorporates only the *time since retiring* data, and only *time since retiring* is included in this article.)

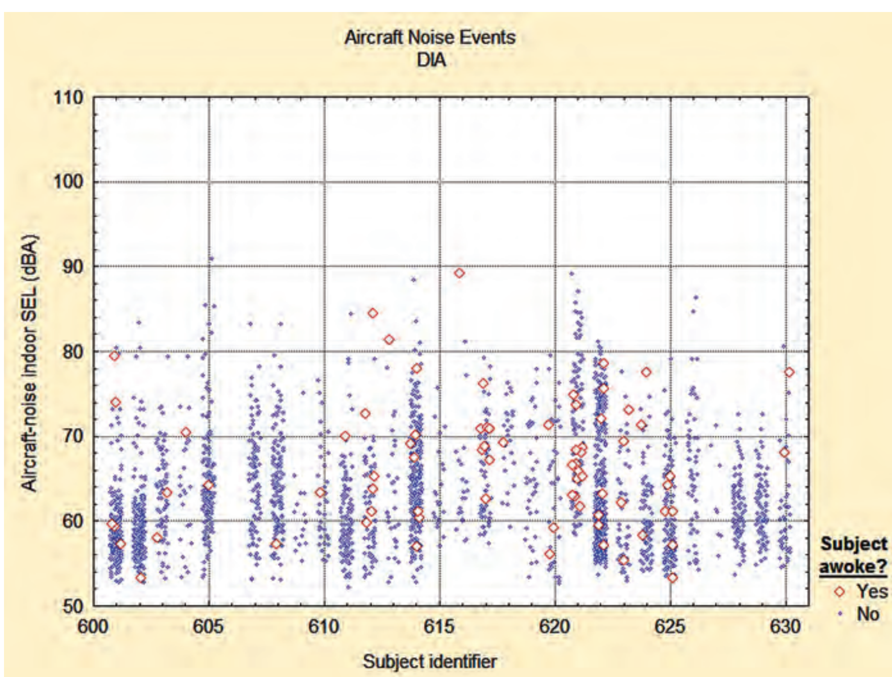

Fig. 3. Aircraft noise events experienced by subjects at Denver International Airport.

The analyses of these two data variables (Sound Exposure Level and time since retiring) provided results of the form:

$$p_{awake,single} = \frac{1}{1+e^{-Z}} \quad (3)$$

where

$$Z = \beta_0 + \beta_L L_{AE} + \beta_T T_{retire} + \beta_S d_s \quad (4)$$

and

$\beta_0, \beta_L, \beta_T$ = Constants

L_{AE} = Indoor Sound Exposure Level

T_{retire} = Time since retiring (minutes)

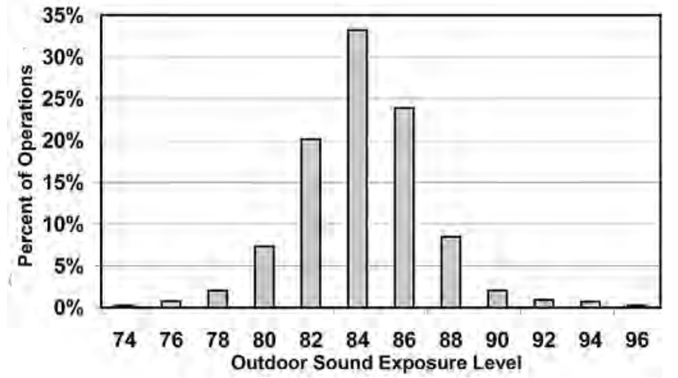

Fig. 4. Assumed distribution of aircraft-produced, outdoor Sound Exposure Level values at approximately 3 ½ miles from the airport.

Table 1 lists the values of the constants from the standard for when one has only SEL data and for when one has both SEL and *time since retiring* data.

Table 1: Values of Eq. (4) constants for the two methods used to compute awakenings

Awakening Dose-Response Relationships	β_0	β_L	β_T
ANSI (Sound Exposure)	-6.8884	0.04444	0
ANSI (Sound Exposure Level and *time since retiring* [minutes])	-7.594	0.04444	0.00336

Application to realistic scenarios

By using the probability of awakening method and the two different dose-response relationships defined by Eq. (3) and Eq. (4), the percent of people awakened can be computed for different realistic scenarios. For this article, the awakenings are computed at a single point with assumed distributions of noise events. The assumptions include a realistic distribution of A-weighted SEL values, three different numbers of night-time aircraft noise events, and three different outdoor-to-indoor noise reductions.

Figure 4 gives the assumed distribution of aircraft-produced outdoor A-weighted SEL. This distribution was measured by a permanent noise monitor located about 3½ statute miles from the airport (at the approximate location of the 65 dB day-night sound level for that airport).

Three different distributions of nighttime noise events are assumed, see Table 2. For purposes of this comparison, these events are grouped into thirds of the night. These distributions are intended to represent what might occur when increases in operations are not matched by increases in airport capacity. If distribution #1 represents an existing condition, then distribution #2 and distribution #3 might both be the result of a significant increase in operations at the airport, with no increase in capacity—operations arrive later at night (distribution #2) or leave earlier in the morning (distribution #3).

Table 2: Assumed distributions of nighttime noise events

Noise Events by Hour			
Starting:	Dist #1	Dist #2	Dist #3
10pm 11pm Midnight	20	35	20
1am 2am 3am	5	5	5
4am 5am 6am	20	20	35
Total	45	60	60

Awakenings are computed assuming the three different outdoor-to-indoor noise reductions listed in Table 3.

Table 3: Assumed outdoor-to-indoor (A-weighted) noise reduction

Outdoor to Indoor Noise Reduction		
15 dB (Window Open)	23 dB (Window Closed)	30 dB (Sound Insulated)

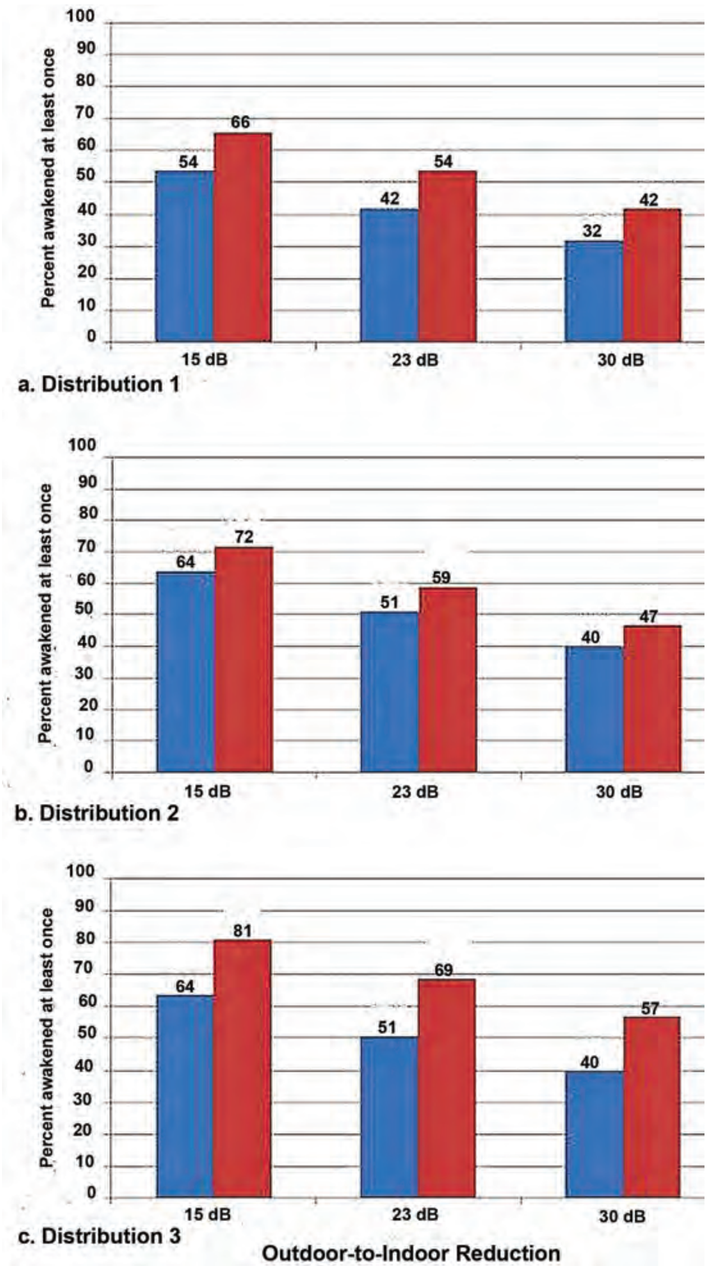

Fig. 5. Results for the different relationships as indicated. Blue represents the relationship based on Sound Exposure Level alone; red represents the relationship based on both Sound Exposure Level and time since retiring.

Results

Figure 5 gives the percent of the population awakened at least once for each scenario. The results for the two different relationships demonstrate some expected trends. Both relationships show decreasing awakenings with increasing outdoor-to-indoor sound reductions, and both show increased awakenings with increased operations, except that, as expected, ANSI (SEL only) shows no difference between distribution #2 and #3, because they both have the same number of operations, but at different times of night. Notably, ANSI (SEL and *time since retiring*) systematically shows higher rates of awakening. This occurs because of the large increase in probability of awakening during the early morning hours as compared to early in the night and during the middle of the night. This trend is most pronounced for distribution #3 that has 35 operations during the early morning hours as compared with 20 operations during the early morning hours for distributions #1 and #2.

Conclusions

ANSI/ASA S12.9/Part 6–2008 provides a pragmatic general method for estimating the awakening effects of nighttime noise events. By applying this method to the two dose-response relationships described in the standard, this article demonstrates the ease of making predictions and illustrates typical relative differences that can be expected between the two relationships. As suggested, the methods can be used to assess not only the effects of changes in night-time operations, but also the benefits of providing sound insulation to homeowners.

The two relationships produce roughly similar results. However, the relationship—ANSI (SEL only)—that uses only the indoor SEL as a variable obviously shows no time-of-night effect—an effect that was strongly indicated ($p < 0.01$) in the regression analysis of Anderson and Miller,[12] and has been observed by others, e.g., Brink and Schierz.[13] The authors judge this phenomenon important in assessing the effects likely to occur if and when night-time noise events become more prevalent.**AT**

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Three generations of Millers

Nick Miller started his work in environmental acoustics in 1970 at the University of North Dakota, completing a Master's thesis based on scale modeling of sound propagation in urban canyons. In 1973, he began working at Bolt, Beranek, and Newman Inc. in highway noise and regulatory acoustics. He worked with the U.S. Environmental Protection Agency, the Federal Highway Administration, and several state agencies analyzing, developing, and implementing noise control laws and regulations. In 1981, he helped found Harris Miller Miller & Hanson Inc., and has devoted full time to aviation noise. He has worked on most aspects of aviation noise and vibration, including the effects of aircraft noise on people, on building vibration, environmental noise studies of new or lengthened runways, computer model validation and refinement, and quantifying the effects of aircraft overflights on national parks and park visitors.

A pair of Schomers

Paul D. Schomer has all his degrees in Electrical Engineering, specializing in acoustics for both his M.S. (Berkeley-1966) and his Ph.D. (Illinois-1971). He has extensive experience, publications, and patents in the areas of environmental noise and its assessment, human and community response to noise, instrumentation and methodology for the measurement and monitoring of noise, architectural acoustics, and acoustical measurements of building parameters. He is a consultant to industry and government, an adjunct Professor of Electrical and Computer Engineering (Acoustics) and member of the graduate faculty of the University of Illinois, and a research leader in acoustics. His recognition by his peers as an international leader in the area of environmental noise is demonstrated by his chapters in reference books, his over 35 refereed publications, his leadership in Standards organizations and professional societies, and his awards and honors. Dr. Schomer is also Standards Director for the Acoustical Society of America.