

# **Acoustical Intimacy in Concert Halls: Does Visual Input Affect the Aural Experience?**

**(Multisensory integration and the concert experience)**

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## **DEDICATION**

This paper is dedicated to A. Harold Marshall, my mentor in the field of architectural acoustics. A friend and colleague since 1974, Harold generously shared his knowledge and enthusiasm, and inspired me by his own example to develop and exhibit my professional confidence.

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# **ACOUSTICAL INTIMACY IN CONCERT HALLS: DOES VISUAL INPUT AFFECT THE AURAL EXPERIENCE? (\*)**

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## **1 INTRODUCTION**

### **1.1 Intimacy, Acoustical Quality and Objective Factors**

Of the major acoustical attributes describing the perception of music in concert halls, acoustical or auditory intimacy (herein referred to as Intimacy) is the least understood in terms of its objective sound field correlates. The purpose of this investigation is to provide a better understanding as to what Intimacy is, and to determine the objective factors which contribute to it, particularly where applied to larger concert and opera house venues. These factors are of course physical in nature including dimensional and visual characteristics of enclosed spaces in addition to the objective measures of the sound field. We are investigating at what constitutes Intimacy and in the larger sense exploring the role of visual input in determining our evaluation of the listening experience.

The past two decades have seen the development of the digital computer and the resultant ability to take complex objective measurements in concert halls. These data over a multitude of halls have been studied and correlated with the subjective qualities and factors associated with them, and have been reported extensively in the literature. The most prominent collection of information along these lines are in the books by Beranek<sup>1</sup> and Barron<sup>2</sup> which reference studies such as those at Göttingen<sup>3</sup> and Berlin<sup>4</sup>. A comprehensive summary of the development of acoustical objective and subjective factors can be found in the tutorial paper by Beranek<sup>5</sup> published in JASA in 1992.

### **1.2 Perceptual Constancy and Visual Influence on What We Hear**

This paper discusses the influence of visual input on how we perceive the auditory as well as overall experience of a performance. Section 5 of this paper reports several types of visual stimuli as affecting auditory perception. Data and tests from performing spaces are reported in Sections 3 and 9 showing how listeners use visual inspection of distance from the sound source to compensate for the drop in sound level by perceiving the loudness to remain essentially constant, independent of source-receiver distance. Also, high early energy (early reflections) are seen to create the impression of Intimacy, the feeling of a small room, when occurring in a large hall. These influences point to what sensory psychologists refer to as “perceptual constancy”<sup>6</sup> and in this case “auditory constancy.”<sup>7</sup> This is the phenomenon of there being stability in our perception. This is shown to occur by conferring the impression of an event as it is or is assumed to be, based upon our past experiences, rather than to the actual stimulus of the event itself.

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(\*) This is the expanded version of the published paper of the same title delivered by the author before the British Institute of Acoustics (IOA), London, July 19, 2002. For citation purposes, the reference is “Proceedings of the Institute of Acoustics, Vol. 24, Pt. 4, July 2002.”

### 1.3 The Performance as Integrated Experience

Section 4 of this paper discusses multisensory integration and the well-known view that all experience is fundamentally multimodal. We have evolved as a species by integrating converging sensory input so that it makes the most sense and is the least ambiguous. The product of these integrative processes is “perception.”

The perception of an event, say a symphony concert or an opera, is the result of the integration of not only the senses but of information previously stored in the brain relative to preferences, biases and in general our past experience in the same milieu. It would be hard to imagine that one would easily extract the acoustical information from the greater experience.

As one views Fig. 1, the rhetorical question one might ask is, “Are these people here for the acoustics?” We may be viewing an opening night at the Milan Teatro Alla Scalla, with the women in gowns and the men in tuxedos. The stage will soon be full with larger-than-life sets, glittering costumes and perhaps even live animals.

We see that these people are taking part in a cultural event, which surely has social, dynamic and visual aspects which are every much as important as the acoustics. Obviously, going to a concert or opera is much more than a unisensory, singular acoustical event. We find that our senses have strong and meaningful interactions. Indeed, while laboratory testing can provide valuable data, the most meaningful information on the nature of acoustical quality must come from the real world of the full experience, from the performing space itself.



**Figure 1 – Teatro Alla Scalla, Milan**

## 2 INTIMACY AS A CONCEPT

### 2.1 Subjective Acoustical Factors and Common Experience

Subjective factors which have been determined relevant to the perception of music in concert halls include Reverberance, Loudness, Clarity, Spatial Impression, Warmth and Intimacy. There are of course many other acoustical descriptors such as Texture, Balance, Blend, Ensemble and so on. Beranek's<sup>1</sup> book is a good source with a discussion of all of the relevant acoustical factors. Table I lists the six primary subjective acoustical attributes along with their simple description and related commonly accepted objective factor.

The acoustical words and concepts in the table relate in varying degrees to our common experience as listeners in concert halls. Take the judgment of reverberance for instance; this is a readily understood concept for most people. Another generally understood acoustical term is that of loudness, a concept common to virtually everyone's daily experience. Evaluation of the relative value of these two factors in a concert hall would rather easily be made by listeners asked to make such judgments.

SUBJECTIVE ATTRIBUTE	DESCRIPTION	OBJECTIVE FACTOR
REVERBERANCE	REVERBERATION	RT
LOUDNESS	SOUND STRENGTH	G
CLARITY	CLARITY	C80
SPATIAL IMPRESSION	IMAGE BROADENING ENVELOPMENT	LF(early) LF(late)
WARMTH	WARMTH	G(125 Hz)
<u>AUDITORY INTIMACY</u>	FEELING OF CLOSENESS TO THE PERFORMER	?

Table I – Primary acoustical factors of large performing spaces. See Beranek<sup>1</sup> for objective factor terminology. (LF = Lateral Energy Fraction)

Intimacy, on the other hand, does not lend itself readily to interpretation, especially by those not experienced in the realm of critical listening in concert halls or other acoustical environments. Whereas reverberance and loudness are somewhat singular in their experience, Intimacy appears to be multidimensional in character in that it is more of a feeling, comprised of a combination of concepts relating what we hear to the perception of the space surrounding the performance and indeed to the observation of the performance itself.

Another way to express its complexity is to say that Intimacy is probably not an independent or orthogonal subjective attribute. Rather, as has been suggested by Kahle,<sup>8</sup> it may be a dependent factor which is strongly correlated with other subjective factors, as well as with objective geometric and dimensional factors (confirmed both by the ear and visual inspection). A practical example showing the complex nature of Intimacy is the finding of the author through conducting listening tests that the average, inexperienced listener doesn't really know what Intimacy means relative to music and finds it difficult to define. An example of this difficulty is indicated in the experimental data on the subjective testing of Intimacy presented in Section 9.

## **2.2 Defining Intimacy and its Acoustical Origins**

The Intimacy referred to in this paper applies to the audience experience as relating to a performance on stage. This is as opposed to the issue of Intimacy for the performer which is the space as experienced on stage relative to the response of the local and larger room environment (see Section 10 for a brief discussion of performer Intimacy issues).

The traditional definitions of "intimate" point to the difficulty of applying the term to an actual dynamic, physical experience involving the perception of the performance of music. These definitions include, "private or personal, closely associated, familiar." There are few published references to Intimacy in the listening context prior to Beranek's<sup>9</sup> seminal work on acoustical design and quality in 1962 where he said that "a hall has Intimacy if music in it sounds as though it is being played in a small room." He also said that an intimate hall has "presence." Several references relate Intimacy to the perception of the size of the room, whereas others refer to feeling close to the action.

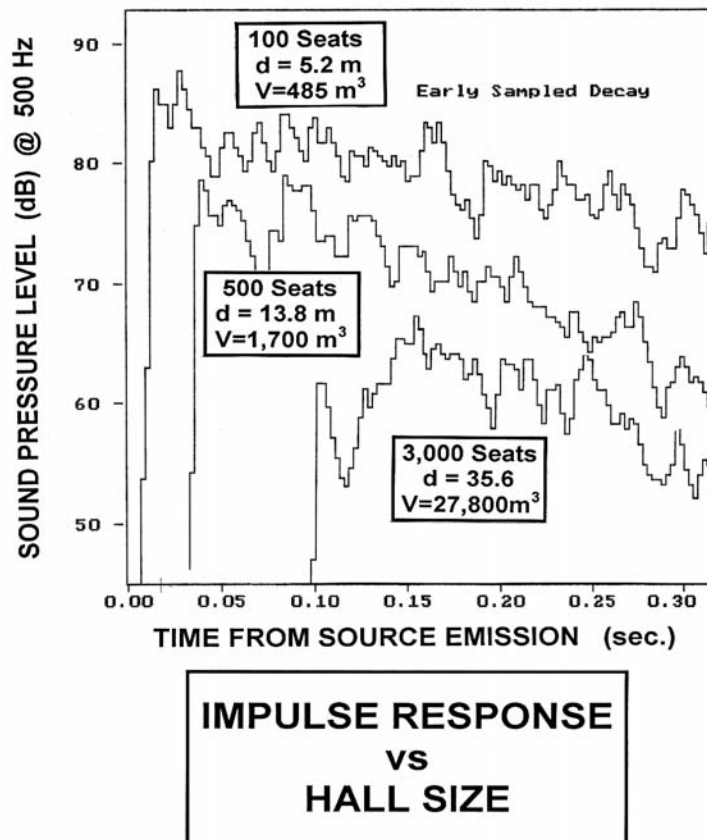
Barron<sup>2</sup> has defined Intimacy to "one's degree of identification with the performance, whether one feels acoustically involved or detached from it." Beranek<sup>10</sup> selected the term Intimacy to "characterize the listening attribute of closeness of communication between the listener and the orchestra" or other source of music.

The origin of intimate sound comes from a few centuries ago when music was performed by small groups of musicians for people in small rooms. In most cases, the attendees knew each other or at the least were known to the patron providing the entertainment. The setting was by definition "intimate" and the term conjures the feeling of the small size of the performance space and the sound field which exists therein.

## **2.3 Intimacy and the Acoustics of Small Spaces**

The acoustical characteristics of small rooms are well known through listening experience and room acoustic measurements. Chamber music was written with the small and intimate setting of the room and the audience in mind. The properties of such spaces which contribute to the overall setting and intimate experience include:

- Proximity to the Performer – This is signified by a relatively high direct sound level, with a short time delay between the movement of the performer and the arrival of the direct and early sound. This sound is confirmed by visual inspection of proximity to the source.
- Loudness – A high value of sound strength due to a small room constant and strong early reflections.
- Reverberance – A relatively high value for the usually smaller room volumes involved due to the use of hard surfaces and little inherent absorption.
- Proximity to the Room’s Boundaries – This creates a visual context which relates to high values of early reflections and strong lateral reflections.
- Architectural Diffusion – Such rooms generally have well articulated surfaces, coffered ceilings, statuary and other architectural artifacts which provide a high degree of diffusion and “texture” to the sound experience.
- Acoustical Brilliance – The nature of smaller rooms of the chamber period is that the treble frequencies are accentuated with a noted lack of warmth from the low tones.



**Figure 2 – Comparison of impulse responses of different sizes of performing space showing changes in delay, level and density of early reflections. Each space was unoccupied.**

Comparison of impulse responses between small and large performing spaces illustrates the above properties as seen in Fig. 2. With a standard source signal, an impulse will be stronger and will show a dense pattern of early energy in the smaller room.

The impulse responses shown in Fig. 2 were measured in three different sizes of performing space, each excited by a standard reference source. We see that as the room gets larger, with a greater number of occupants, 1) the transit time of the direct sound increases to a typical seat, 2) the direct sound level decreases, 3) the total sound level becomes significantly less, and 4) the density of the early sound decreases. The three spaces shown were measured by the author with the same standard source and test equipment.

## **2.4 Definition of Intimacy from Survey of Acousticians**

### **2.41 Survey of Acousticians**

A questionnaire was sent to 41 acousticians from around the world with experience in visiting, evaluating and designing concert halls and performing spaces. These people are generally well known in the field of architectural acoustics. The purpose of the questionnaire was to determine prevailing opinion on the issue of Acoustical Intimacy and its relationship to the physical factors found in large concert halls. A total of 20 responses was received, with 17 used in the analysis reported here. The ratings of the author are not included in the data. A copy of the questionnaire and a discussion of the data analysis approach is given in Appendix I.

### **2.42 Survey Results on the Definition of Intimacy**

The survey results yield interesting comments and opinions as to the meaning of Intimacy. 75% of respondents listed “closeness to the performer” as one of their definitions. The next most common definition related to the sense of “the room sounding smaller.” Other descriptions included “sharing the space with the musicians,” and feeling: “Immersed in the music,” “being drawn-in to the performance,” “a connection with the performer,” “at home,” and “that the performer is playing for you.”

It’s important to note that a feeling of “closeness to the performer” has a physical distance component which itself is primarily confirmed by visual input.

### **2.43 Objective Acoustical Factors Derived from Survey Descriptors**

When applying the listening experience to a large space, the perception of closeness or proximity to the source can be related to several objective parameters as discussed in Section 2.3. The most obvious issue is that “closeness” is primarily perceived visually, through observation of the space, even before the acoustical event begins. And, since the relative strength of the direct sound is unchangeable, the strength of the early reflections, and overall total sound strength of the room are the geometric design factors which can hope to contribute to the feeling of “closeness to the performer.” These same physical attributes also relate to the room sounding smaller than it actually is.

## **2.5 Acoustical Factors Relating to Intimacy from the Literature**

### **2.51 Issue of Experimental Results versus Real-World Integrated Perception**

As will be seen in the discussions below, there is some disagreement among researchers on the relevance of the objective factor “initial-time-delay gap” (ITDG) to the acoustical quality of concert halls and specifically to the subjective factor of Intimacy. In this debate, the methodology employed is critical. An important issue is that of laboratory testing versus the actual perception of the music event in a concert setting.

Marshall<sup>11</sup> summarizes the difference: Scientific laboratory results “may or may not have any relevance in the real world of seats, people, carpets, walls, floors, and ceilings. The difference between an unidimensional result produced with recorded music in anechoic conditions by a synthetic sound field and the integrated perception of a listener to live music in the real world is vast. The relevance of the one to the other depends, at the most elementary level, on the use of delays and levels for the synthetic ‘reflections’ that are realizable in the physical dimensions of rooms. One can be quite clear that however good the ‘scientific’ work, in the last analysis the result must be perceptible to expert listeners in the real world. The best that the laboratory experiment can do is to provide hints and clues as to the way in which human binaural hearing processes reflections of music in rooms to enhance or to detract from the musical experience.”<sup>11</sup>

Most research conflicting with the putative importance of ITDG is laboratory based. But, as will be seen below, even the results from real concert hall studies show conflict between Beranek’s experiential determinations and Barron’s statistical correlations between objective measurements and judgments by experienced listeners in actual halls.

### **2.52 Beranek and ITDG**

Over the past decade, Intimacy has tended to become synonymous with the objective factor “initial-time-delay gap” or ITDG. In his publications, Beranek has directly connected the two factors with the concept that Intimacy also relates to “loudness of the overall sound since the listener assumes that a performance sounds louder in a small room than in a large one.”<sup>12</sup> While ITDG isn’t technically defined in a standard, Beranek defines it as “the time between the arrival of the direct sound from the stage to the arrival of the first reflection at a measuring point.”<sup>13</sup> This measuring point is stated as being a position near the center of the main floor.<sup>14</sup> Preferred ITDG values are stated to be  $\leq 25$  msec., and in general, the shorter the time delay gap, the more intimate the experience.<sup>1,5,15</sup>

Beranek states in his most recent book<sup>16</sup> on concert halls and opera houses that with a short ITDG, more reflections can occur in the first 80 msec. after arrival of the direct sound, and that more early reflections produce a greater feeling of Intimacy. Part of the reason for this result is that more early reflections contribute to greater loudness even in a large room. Beranek states that others who have used only one or two reflections after the direct sound in tests and have found ITDG not correlated with Intimacy have not performed a meaningful experiment.<sup>15</sup>

Beranek’s ITDG, therefore, should be seen as a real world, concert hall factor relating in each case to the overall conditions of each hall. The importance of the factor is not seen in the number itself but in its value allowing other factors to come into play. The potential problem with this approach is in allowing one number derived from one location to represent the entire acoustics of

a hall on average. A strong argument could be made for the desirability of acoustical factors correlating both between seats in halls and between halls themselves.

### **2.53 Intimacy, ITDG and Work of Researchers**

There has been a potential problem relating to the interpretation of Beranek's work by other researchers. Beranek's ITDG value is specifically determined, for any space, at one location near the center of the main floor, usually around 2/3 of the distance from front to back on that level. This location is intended to be indicative of the early reflections of the space in general; for instance, a narrow hall will have on average earlier delays at the other seats as well, and would have a greater density of reflections in the early sound field. Researchers have perhaps incorrectly interpreted ITDG to mean "the time delay of the first reflection at any given seat in question," or "the time delay of the first reflection for the subjective experiment being discussed."

Researchers are not generally in agreement with ITDG being a strong factor, let alone being the sole major factor in Intimacy. Ando<sup>17,18,19</sup> performed subjective preference experiments with music sound fields using a single "echo" as well as multiple early reflections. These simulator experiments found that a) for a single early reflection, the preferred time delay was equal to the "duration of autocorrelation function (ACF)" which for music had values ranging from 32 to 128 msec., b) for multiple reflections (up to four), the preferred value of the "strongest reflection" was equal to the ACF of the music signal, again with values as those stated above. These of course are significantly greater than the 25 msec. cap suggested by Beranek. From this, Ando also found that the first reflection is not important if it's not the strongest reflection.<sup>19</sup> These experiments may or may not be relevant to the issue of preferred ITDG values since they are performed in a simulator with a limited number of early reflections; note Beranek's comment in Section 2.52 above linking ITDG to the number or early reflections in the early sound field. A discussion on Ando's simulator findings relative to Beranek and others' findings can be found in Beranek's paper,<sup>20</sup> as well as in Section 4.4 of Ref. 21.

In a study of early sound field changes in auditoria, Cox et al.<sup>21</sup> tested subjects' ability to perceive the differences in the sound field by altering the delay of the first reflection, which they called "ITDG," and found that the differences of arrival time of the first reflection had a negligible effect on perception of the sound field. In this case, "perception of the sound field" were differences in source width. When normalizing the tests to constant source width perception, the subjects could hear no discernable difference between test samples. The conclusion was that there was very little subjective difference associated with a changing of the "initial time delay gap." While they may have misapplied the definition of ITDG, the results nevertheless may cast doubt on the importance of the first reflection being within a given temporal window. But as with Ando's simulator experiments, a limited number (up to six) reflections was used in their paired test comparisons. Therefore, whether the results are meaningful relative to ITDG is not clear.

Barron's studies<sup>22,23</sup> are, on the other hand, from data derived from the judgment of real halls by many listeners during live concerts. He found that the perception of loudness is directly correlated with the objective sound strength, and that Intimacy is best correlated to the total sound level. His results found no correlation between "ITDG" and subjective Intimacy. In these studies, however, "ITDG" refers to the delay time of the first reflection at each seat in which a judgment was made (and at which objective data were measured), so Barron's statistical analysis and conclusion vis-à-vis ITDG (the single hall position measure) isn't technically correct. However, if one expects a measure to work within a hall as well as between halls, these results indicate a problem with ITDG being the correct factor to represent Intimacy.

Hidaka<sup>24</sup> has recently published a paper in which the number of early reflections at the listener's position in a hall is determined through a mathematical analysis of the impulse response. He attributes the subjective impression of "texture" to the sequence and density of these early reflections and shows a correlation between ITDG, the density of early reflections and acoustical quality.

### 2.54 Intimacy and the Early Sound Field

Correlating room acoustic measurements with listening experience in specific rooms, both Hyde<sup>25,26,27,28</sup> and Toyota, et al.<sup>29</sup> have reported that seats with high levels of early energy are considered to be more intimate, independent of the distance from the source. Toyota's reflected energy cumulative curves (RECC)<sup>29,30</sup> show the buildup of reflected sound energy over the first 160 msec. in a large concert hall and indicate that the rank order of total sound level  $G$  between seats is determined by the early reflections occurring within the first 80 msec. The seats with the greatest early reflected energy and total sound level are reported by Toyota to be rated by listeners as being the most intimate. For Toyota's actual RECC plots, see Fig. 1 of Ref. 26.

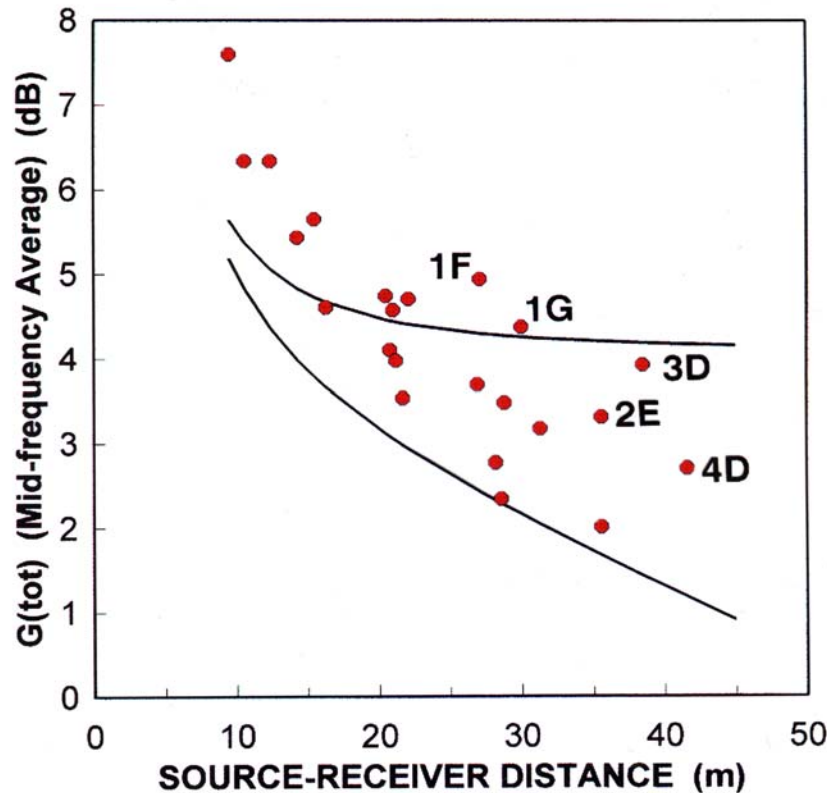


Figure 3 –  $G_{tot}$  versus Distance relative to “Revised”<sup>31</sup> and classical theory (solid lines) for Segerstrom Hall. Data points for the most distant test seats in the four seating levels are labeled.

The phenomenon of increased Intimacy with high early energy has also been reported by Hyde<sup>26,27</sup> in the case of the 3000 seat Segerstrom Hall in Orange County California. Measurements in the back of each of the four seating sections as indicated in Fig. 3 show levels of  $G$  significantly greater than the expected “revised theory”<sup>31</sup> values (lower curve) found for the

space in general. [G values predicted by classical theory are shown in the upper curve of Fig. 3.] These greater levels occur due to the acoustical design of the hall. With objective levels being the same value for two seats, the seat which is farther from the source is found to be subjectively louder. Further discussion of this situation can be found in Barron's paper on "Loudness."<sup>32</sup>

When a farther seat has the same strength G as a closer seat, it is judged to be more intimate. It appears that that the compensation in perception of loudness due to visual input has a related effect on the perception of Intimacy. Since sound strength G and Intimacy are found to be directly linked, this result is not surprising.

The contribution of the early sound field to Intimacy has been reported by Lavandier et al.<sup>33</sup> in a study where subjects rate reverberant spaces as "remote" whereas when the sound field becomes less reverberant, C80 increases and the sound is perceived as being "distinct." As C80 increases further, the "clarity effect" changes to a feeling of "proximity," with the perception of the source being more "nearby." High C80 of course can mean the existence of high early reflections.

Kahle's<sup>34</sup> survey of the subjective factors in concert halls has yielded some interesting results on subjective correlates with Intimacy. His work has found a strong positive correlation with subjective loudness as well as an independent correlation with low frequency subjective loudness "clearly indicating that there is a link between bass frequencies and the question of Intimacy." He also has found a strong correlation with what he calls "Contrast" or the definition of attacks in the music. In other words, Intimacy is positively correlated with "a strong emergence of useful temporal intervals in the room response."<sup>8</sup> This is linked to objective distance, meaning that the closer we get to the source, the greater the Contrast, and the more intimate it sounds. Finally, Kahle has found no correlation of Intimacy with subjective reverberance and subjective loudness at high frequencies.<sup>8</sup>

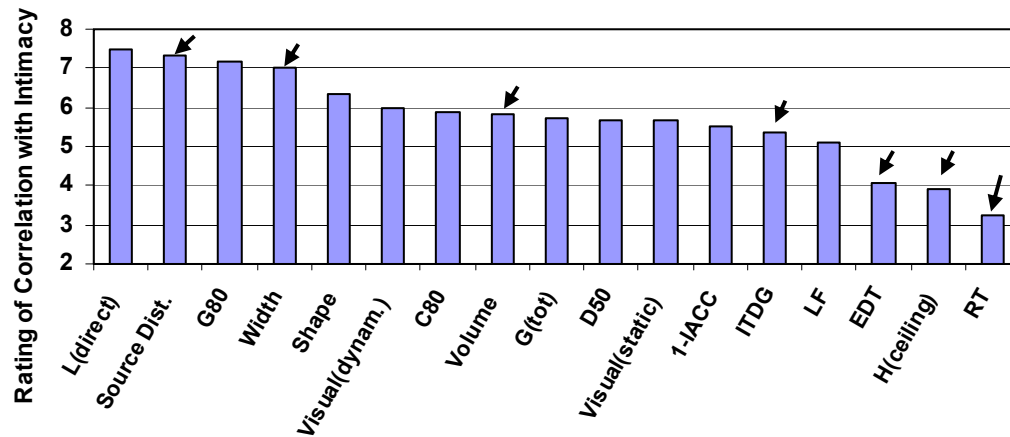
## **2.6 Survey of Acousticians on Objective Factors Relating to Intimacy**

Results of the questionnaire (Appendix I) on the objective components of Intimacy are summarized in Fig. 4. On a scale of 1 to 10, respondents were asked to rate the objective factors they believe are correlated with the perception of Intimacy, with 1 indicating "not correlated" and 10 indicating "highly correlated." Each rating was to be an opinion based upon each respondent's personal listening experience.

Highest correlations were found with direct Level (and of course source-receiver distance), G80, room width, shape, dynamic visual input (which is partially linked to distance from the source) and C80. All factors but EDT, ceiling height and RT received a rating of 5 or greater. It would be tempting to over-interpret the results in the middle of the chart where the factors from "Shape" to "LF" exhibit little statistical difference. These were all judged above "5" perhaps meaning that there was a consensus that all of these values were more on the side of "correlated" than "uncorrelated" with Intimacy.

Beranek<sup>35</sup> has offered an interpretation of these results relative to ITDG. After the early sound field is taken into account, Intimacy is judged to be highly correlated with hall width. Visually, a narrow hall is also judged to be more intimate than a wide one. Since hall width and ITDG (at the center-hall position) are themselves highly correlated, it can be said that ITDG is also well correlated with Intimacy.

It appears that Intimacy may be broadly dependent upon many objective factors. Of interest as the major topic of this paper is whether the visual aspects of a space have an influence on how Intimacy is perceived.



**Figure 4 – Summary of opinion on the correlation of objective factors with Intimacy. The arrows indicate an inverse correlation.**

## 2.7 Summary of Results Pointing to Objective Factors of Intimacy

From the definitions of Intimacy, the literature and survey of acousticians, a pattern of acoustical and dimensional objective correlates related to Intimacy is presented. To summarize, these are:

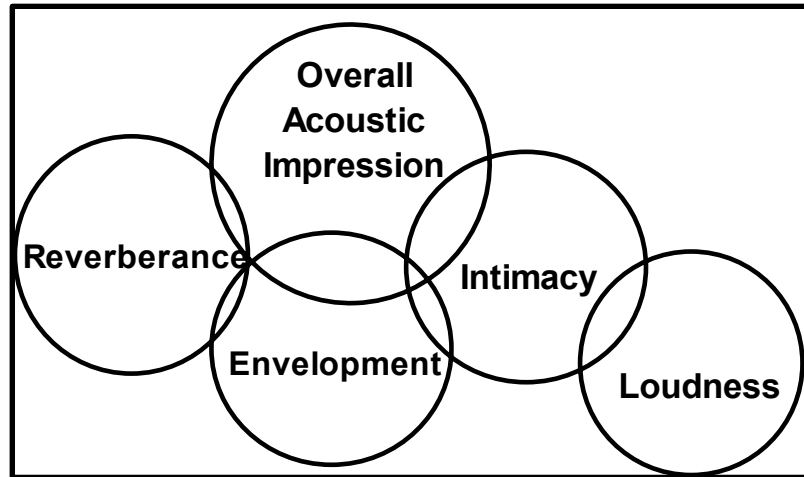
- Strength of the direct sound (inversely proportional to source-receiver distance)
- Strength of the early reflections
- Room width
- Strength of the total sound
- Degree of lateral energy (related to room width)
- Visual input – both static and dynamic cues

Clearly, all of these factors are related to the size and geometry (design) of a room with smaller being more intimate. For designers of large concert halls and opera houses, the issue at hand is that of how these factors are achieved through architectural design. In other words, since the strength of the direct sound can't be manipulated naturally, the perception of "proximity to the source" must be achieved through architectural means.

## 3. CONCERT HALL SURVEY POINTS TO VISUAL INFLUENCE ON WHAT WE HEAR

Barron's<sup>22,23</sup> extensive survey of British concert halls undertaken in the 1980s reported the combining of both objective acoustic measurements with the subjective evaluation of the same spaces during live concert conditions. Of importance here is that these results were derived from the real world experience, including the integrated visual input, by surveying listeners who attended concerts in the halls in which objective data also were measured.

The study found three independent factors to be correlated with “overall acoustic impression” as being “Reverberance,” “Envelopment” and “Intimacy,” and importantly found a correlation between Intimacy and subjective loudness. Since Intimacy was also found to be directly correlated with total sound level  $G_{tot}$ , the connection between Intimacy and distance (a visual impression) is strongly suggested. Figure 5 is taken from Ref. 22, indicating these relationships.



**Figure 5 – Venn diagram of correlation between subjective factors from Barron’s study of British concert halls. (from Barron<sup>15</sup>)**

Most interesting from these studies is the finding of relationships between sound strength, Intimacy and the perception of distance and size of the space. Barron found<sup>36</sup> that subjective loudness was directly related to total sound level ( $G_{mid}$ ) and to the source-receiver distance ( $r$ ) by the general relationship

$$\text{Loudness} = k (G_{mid} + 0.076 r) + K \quad (1)$$

where  $k$  and  $K$  are scaling constants and the loudness units are arbitrary. What is surprising here is that distance term is positive meaning that a sound of the same objective sound level is perceived as louder for a listener farther from the source. The net result is that this loudness perception increase with distance compensates for the natural drop-off in level  $G$  over distance thus giving the perception of constant loudness with distance. It appears that visual input relative to distance causes the listener to compensate for the drop in the objective sound level.

With the room’s natural sound level drop-off rate and the distance compensation rate (coefficient of  $r$ ) being similar, Barron summarizes “This leads to the conclusion that listeners may have a subjective expectation of loudness based on typical average behavior in concert halls (revised theory) and respond if loudness is louder or quieter than expectations.”<sup>32</sup> “Expectations” in this case refers to what is anticipated on the basis of visual perception of the location of the listener relative to the source and to the space in general. This concept of constant perceived loudness is discussed in Sect. 4 on “perceptual constancy.”

Tests by the author showing links similar to Barron’s between sound strength  $G$ , subjective loudness, distance and Intimacy are discussed in Section 9.

## **4 CONCEPT OF PERCEPTUAL CONSTANCY IN CONCERT HALL ACOUSTICS**

### **4.1 Perceptual Constancy in Sensory Psychology**

There is a phenomenon in sensory psychology referred to as “perceptual constancy.”<sup>6</sup> This is the phenomenon of stability in our perception; it allows the brain to extract a stable world from an ever-changing sensory input. In other words, it allows objects to appear stable in the face of their continually changing stimulus features.

Perceptual constancy relative to stimuli processed by the brain through the retina presents the most obvious examples in our experience. Relative to vision, constancy denotes the tendency of humans to see familiar objects as having standard shape or size, for instance, regardless of changes in the angle of perspective or distance.

Perceptual constancy tends to prevail as long as the observer has appropriate contextual cues. For instance, the perception of size constancy depends on cues that allow one a valid assessment of his distance from the object. With distance accurately perceived, the apparent size of an object tends to remain remarkably stable, especially for highly familiar objects that have a standard size.

Shape constancy allows us to identify objects even when we view them from different angles. This is where projection of the object on the retina is very different at an angle from the actual known shape of the object. An example is that of a rectangular wall viewed from the side. It will not have a rectangular projection on the retina, yet it is perceived as a rectangular wall.

The impression of the object tends to conform to the object as it is, or is assumed to be, rather than to the actual stimulus itself. Other visual examples of constancy include “brightness constancy” and “color constancy.”

### **4.2 Auditory Constancy**

There is little in popular literature on the subject of constancies in hearing, which aren’t as obvious as those of vision.

Auditory constancy is a concept which may apply to the case in concert halls found by Barron in Sect. 3 and the author, Sect. 6, where the perception of loudness is essentially constant relative to the distance from the sound source. It means in psychophysical terms that a direct correspondence does not occur between the sound stimulus and the resulting perception. In functional terms, according to Lang<sup>7</sup> auditory constancy “brings a reduction of the information, transmitted from the sounding event to the hearing phenomenon. This reduction is obviously economically important . . . because, as a rule, it can be assumed that the ‘constant’ percept screens out irrelevant stimulus components which are not necessary for the purpose of recognizing events or for the purpose of orienting oneself in the world of sound.”<sup>37</sup>

### **4.3 Loudness Constancy**

Reports of loudness constancy phenomena can be found in the literature. Lang, et al.<sup>38</sup> report “the psychophysical relation between intensity (sound level) and loudness cannot be conceived to be unidimensional and also should not be isolated from other parameters of sound and of audition,”

and one would presume not be isolated from other input parameters including senses such as visual stimuli.

Chomyszyn<sup>39</sup> has expanded upon the work of Chowning<sup>40</sup> who has suggested that loudness constancy might take place in a room environment in a way analogous to size constancy in vision. Chomyszyn makes an interesting observation linking visual to loudness constancy: “If ‘size constancy’ appears in the auditory world, the loudness of the sound source will be perceived rather than the strength of the sound wave at the listeners’ ears in a loudness judgment of such sounds. For the two sounds of equal intensity (and the same or similar timbre) the sound played with a greater effort and carrying a higher amount of reverberation would be perceived as louder. According to the hypothesis, for the listeners these cues should suggest that the sound was played from a greater distance, hence it must have been louder at the source.”<sup>39</sup> Thus, with visual input of the relationship of the source to the receiver, the percept of equal loudness with greater distance can be rationalized.

Zahoric and Wightman<sup>41</sup>, as Chowning, also find loudness constancy to be similar in many ways to visual size constancy, with results under distance-varying conditions producing inaccurate estimates of source distance. Their explanation of loudness constancy is based upon sound energy cues from the reverberant field.

#### **4.4 Constancy, Loudness, Intimacy and Distance Perception**

The two acoustical issues apparent within the reach of this research paper which are connected to the concept of constancy, are 1) the perception of constant loudness with distance discussed in Sect. 3 and 9 of this paper, and 2) the issue of creating a greater degree of Intimacy in large spaces by increasing the early energy through increased early reflections thereby creating the auditory illusion of a closer source.

## **5 MULTISENSORY INTEGRATION – AUDITORY AND VISUAL INPUT**

### **5.1 Perceptual Phenomena and Psychology of the Integrated Experience**

All experience is fundamentally multisensory. That is, we have evolved as a species by integrating converging sensory input in order for the information to make the most sense and be the least ambiguous. The product of these integrative processes is “perception.”<sup>42</sup>

There are significant differences between “seeing” and “hearing” as opposed to the perception of an event which uses both senses. Generally, the visual modality predominates. Where the intensities of stimuli are similar, the visual effect on auditory perception is greater than the effect of sound on visual perception. The ventriloquism effect is a well known example.

[On the issue of the visual modality predominating, the following anecdote is presented. From the world of opera, a colleague and friend who is a well-known bass with the Deutsche Oper Berlin offers this account, “When you have a visual stimulus clearly indicating something audible, you may very well think you hear it. I have heard of colleagues who simply drop out of the high note, and some people would swear they had sung it!”<sup>43</sup>]

As acousticians strive to design even better performing spaces, they constantly deal with the issue of “preference” and what this entails for each observer of a music event. Ando has often mentioned in his lectures that preference is a “primitive reaction” to the condition in question, which in our case is the acoustical environment. This essentially means that preference is not the result of the cognitive process, but occurs without thought, below the cortex, as part of a sensory feed-back process.

Since sensory systems have evolved to work together, the synergy between auditory and visual systems are generally evident in our experience. One common example is the perception of speech in a noisy room. Visual cues significantly enhance the processing of auditory inputs providing the functional equivalent of altering the signal-to-noise ratio of the stimulus by up to 15 to 20 dB<sup>44</sup> depending on the “stimulus set” and context of the information (for instance, if the words and phrases are commonly known to the listener). The extreme of this processing example is that of lip-reading, where there is no auditory signal at all, yet the information is transmitted and perceived via visual stimulation. Further to this, magnetic resonance imaging (MRI) brain studies<sup>45</sup> show that the sight of lip movement alone actually stimulates activity in the auditory cortex.

There are many examples in sensory psychology where seeing a source actually affects what we perceive we hear. In other words, with visual input the brain process actually alters the perceived frequency content of the source. A well known example of this is the McGurk effect<sup>46,47</sup> as indicated in Table II where one “hears” a speech signal with eyes closed but with visual input of the speaker’s lips forming another sound, one perceives a third sound, not the same as what one “heard” originally.

### **McGURK EFFECT**

<b>CONDITION</b>	<b>PERCEPTION</b>
<b>EYES CLOSED, SPEAK SOUND A</b>	<b>“HEAR” SOUND A</b>
<b>EYES OPEN, OBSERVE LIPS FORMING SOUND B</b>	<b>LISTENER PERCEIVES SOUND C</b>

**Table II – Test conditions and results using video-tape, demonstrating the McGurk effect.**

The brain’s multisensory integration system actually modifies the signal of the auditory input. This is a palpable example of receiving a signal yet “hearing” a different event depending upon what one sees. One would expect that this sort of sensory input integration would happen in the concert hall context where the visual aspects of the event are of similar intensity as the auditory.

## 5.2 Visual Aspects of the Concert Hall Experience

To acousticians, the auditory experience is generally the singular issue of concern in the evaluation and study of performing spaces and indeed in their enjoyment as well. Of course, attending a concert or opera is entirely a multisensory experience and the visual aspects of it are hypothesized as being very important, even relevant to the assessment of overall acoustical quality. Beyond visual stimuli, we know from our own concert and opera observations that even aspects such as comfort and the ease of moving about can affect our evaluation of the space.

### 5.21 Static Visual Stimuli in the Performing Environment

Visual input in the context of the performance space is comprised of both static and dynamic cues. Static visual input relates to the perception of the observer's distance from the performance as well as the physical relationship to the room's boundaries and the degree of elevation and angle off of the room's axis. Also related to the boundaries are their size and orientation, texture and color, and the visual framing of the performance area. Also involved is lighting of the performance area and architectural lighting of the space in general.

#### 5.211 Perception of Source-Receiver Distance

Source-receiver distance is a major element relating to the feeling of Intimacy in performing spaces. The main question here is that of which acoustical stimuli contribute to distance perception and to what degree. It is well known that the perception of distance is difficult to accurately judge in a free-field without *a priori* knowledge of the intensity of the source. This relative intensity cue is even less useful in an enclosed space which has unique acoustical properties and a relatively constant level of reflected energy.

Seminal work on the auditory perception of distance in small rooms by von Békésy<sup>48</sup> found that the ratio of direct to reflected sound and their associated time delay were major distance cues. The direct to reflected energy ratio is an absolute value and independent of the source intensity. There are difficulties with this model, however, especially for larger rooms where the direct level becomes insignificant relative to the early reflected energy which the ear integrates with the direct. Furthermore, in large rooms, the reverberant field varies less with distance, again rendering the energy ratio less relevant to distance perception.

Zahoric<sup>49</sup> has recently reported that our sensitivity to the direct-to-reverberant energy ratio is quite low, with thresholds ranging from 5 to 6 dB. This suggests that this energy ratio by itself “only provides a coarse coding of sound source distance because threshold values correspond to greater than 2-fold changes in physical distance.”<sup>49</sup> Zahoric<sup>50</sup> has also found, using virtual environment simulation, that listeners' judgments of perceived distance “consistently underestimate physical source distance.” Further, he reports that the degree of distance underestimation increases with increased source distance.<sup>51</sup> Zahoric<sup>52</sup> also reports the effect of “visual capture” in perceiving the distance to the source relative to the spatial location of the source. All of these phenomena are attributed to the existence of the reverberant field in the auditory signal.

Recent work by Bronkhorst<sup>53</sup> has developed accurate distance perception models which take into account the integration of the early reflected energy with the direct. Further work<sup>54</sup> has found that greater interaural crosscorrelation (IACC) of the signal results in a strong decrease of the perceived distance and an increase in the accuracy of predicting distance from the sound source.

This suggests that distance perception relies on binaural information rather than on the time-domain representation of the sound.<sup>55</sup> Bronkhorst's findings also show that strong lateral reflections tend to reduce the perceived source-receiver distance and thereby increase Intimacy. In summary, these data suggest that we can to some extent discriminate distance using an "early/late" energy ratio cue, but that it is a binaural cue based upon interaural time delay (ITD) differences which occur when lateral reflections are dominant in the early sound field. These cues are less reliable in large rooms and distance prediction at distances greater than around 10 m may be unreliable. It should be noted that all tests reported here are auditory only, and have used no visual cues.

In summary, the only way an observer can determine actual distance from the source with certainty is through visual inspection.

### **5.212 Comments on the Effects of Lighting on Auditory Perception**

Little is found in the literature relative to the effects of lighting level on the perception of sound and/or the quality of sound in the concert and opera experience. Ando, et al.<sup>55,56</sup> studied the effects of light level on sound field preference judgments in the simulator environment. They found small but not insignificant contributions of lighting level to the overall preference of listening level for music. However, there was no particular relationship found between preferred listening level and lighting level.

There is anecdotal evidence of the influence of lighting level on the auditory experience from both the author and colleagues with experience in the evaluation of concert halls through listening and measurements. A noted theater designer has attributed to a famous actress the statement, "There isn't an acoustical problem a good follow-spot can't fix."<sup>57</sup> In general, the consensus is that, as audience lighting levels decrease and thus the lighting focused upon the source on the stage increases, the apparent loudness of the source increases (along with visual acuity). At the same time, the intensity of the experience in general increases. This sort of visual integration and influence on perception is further demonstrated in Section 5.3 below. It can be concluded that the listening experience is probably related in some way to the lighting relationships and levels of the environment.

### **5.213 Comments on the Effects of Color on Auditory Perception**

The author is not aware of technical research on the effects of room color on the perception of sound in the performing environment. There exists at least one study<sup>58</sup> in the field of environmental noise where the auditory judgment of loudness was tested in virtual environment simulations where the color of a train passing-by was varied, while keeping the sound level constant. The result was that a red train was judged as louder than other colors (crème, blue and green). That a color difference in source appearance can create a statistically significant difference in the perception of the sound field under these conditions is at the very least interesting.

Egan<sup>59</sup> reports that conductors seem to prefer white and gold interiors to blue interiors, and it is well known that musicians believe that wood is essential for successful concert halls. There is anecdotal evidence from several colleagues of the author that indeed the color of a performing space appears to have a psychological influence on the listener. In the case of rooms with light and/or blue colors, the music experience has been judged as being "cool." In the case of rooms in darker, wood-toned and/or red colors, the music experience has been judged as being "warm."

Whether these descriptions are sound field perceptions or merely a description of mood is not clear, and technical research on the subject may not be warranted.

## **5.22 Dynamic Visual Stimuli in the Performing Environment**

Visual dynamic input relates to the movement of the performer including the conductor, the synchronicity of movement and cadence of string and other players and the movement and physical expression of the soloist. The degree to which an observer integrates and uses this information clearly depends on the amplitude of movement and the size of the dynamic image which is inversely related to distance.

Indeed, it is suggested that it is the magnitude of the visual input relating the source-receiver distance that determines the amount of “information” and magnitude of the experience transferred to the observer. The visual angle subtended by an object on stage is inversely proportional to the distance from the object; in other words, if the distance is doubled, the apparent size (on the retina) of an object on stage is essentially halved. It therefore can be said that the magnitude of dynamic movement and/or expression is significantly influenced by the distance to the observer. While this statement may be contradicted by the discussion on perceptual constancy given in Section 4, it is possible that the subtended size of the object is important when the visual input stimulus is dynamic and contains the physical expression of musician and performer.

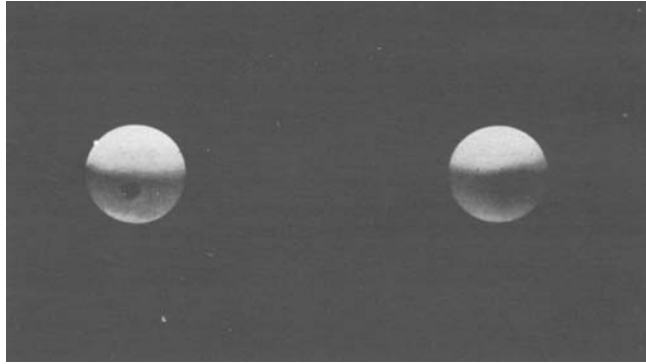
As with speech, music is produced in rhythmic patterns often with a low frequency modulation spectrum of about 4 to 5 Hz, corresponding to articulation peaks on the order of 200 msec. The observer’s degree of exposure to the cadence, magnitude of movement, even the location of actual instruments which produce the different sounds, may be said to enhance the experience by adding visual information coherent with the acoustical field. It is hypothesized here that this distance related effect of dynamic visual input is closely related to the concept of Intimacy on the basis that source-receiver distance is a bimodal factor.

## **5.23 Summary – Factors of Visual Input**

Both static and dynamic visual stimuli relate to distances and boundaries and therefore relate to major architecturally important issues producing the acoustical field. The fundamental issue of distance (the size and volume of the enclosure) determines acoustical properties such as the direct sound level, early sound field, and reverberation time. Further, size and design related acoustical properties include sound strength  $G$  through the room constant (highly dependent on the number of seats), and the degree and direction of early and late reflections. Other factors which may affect acoustical quality are lighting, color and, in general, comfort.

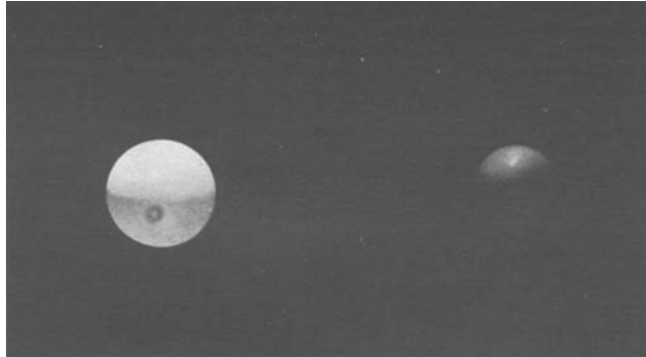
## **5.3 Example of Intensity versus Perception**

There are many experiments in perceptual psychology showing that the perception of an external stimulus is predominantly determined by primary (i.e. simple) cues, and thus without the necessity to rely on higher-level perceptual and cognitive processes. One such example with parallels in the concert hall experience is that of observing two balloons of equal distance which are of varying size and brightness, and judging the relative distance of the two from the observer. When the size and brightness of both balloons are the same, as seen in Fig. 6a, an observer sees them as two glowing spheres at equal distances from him. If the brightnesses are left the same and the relative sizes are changed, the larger balloon appears somewhat nearer. If the brightness is varied, the brighter appears to be nearer.



**Figure 6a – Balloons same size and brightness, appear to be the same distance from the observer.**

Figure 6b shows two balloons at equal distance, with the less bright and smaller balloon appearing farther from the observer. From many psychological studies it is found that when faced with such a situation in which an unlimited number of possibilities can be related to a given pattern, the “organism” calls upon its previous experiences and assumes that what has been most probable in the past is most probable in the immediate occasion.<sup>60</sup> In this case, we “bet” that the two balloons, being similar, are probably identical (i.e. of equal brightness), and therefore that the one which seems brighter must be nearer. Another way of saying this is that the world each of us knows is a world created in large measure from our experience in dealing with the environment in question.<sup>60</sup>



**Figure 6b – Balloons at same distance but with different size and brightness, appear to be different distances from the observer.**

#### **5.4 Intensity Analogy Applied to Intimacy**

The analogy with sound is obvious. From our experience, the greater the intensity of the source, the less the distance from it and thus the perception of being closer to it. Conversely, distance can therefore be compensated for by increasing the sound level relative to the value expected for a given distance. In other words, increasing the early reflections (early integrated sound) can create the impression of a shorter distance from the source, and therefore by definition create a more intimate sound. This concept is also supported by the phenomenon of perceptual constancy discussed in Sect. 4.

## **5.5 Other Stimuli Affecting Perception in Performing Spaces**

Other physical stimuli can affect the overall experience and perception of a performance which are less obvious than the stronger visual and auditory events that prevail.

One's reaction to the building's and/or hall's aesthetics can have influence on the overall rating of the experience if not the acoustics specifically. Aesthetics could mean the design, lighting, colors, textures and materials and probably a combination of these elements that come together for each individual in a way which either enhances or detracts from the experience.

Aesthetics can affect one's sense of comfort and orientation in either positive or negative ways. One friend of the author has mentioned that the large rectilinear cubist shapes utilized as diffusion on the shell and ceiling of the Minnesota Orchestra Hall, for in stance, was so distracting and aesthetically unpleasant as to confuse his judgment of the acoustics of the space. He simply wasn't able to relate to the quality of the sound and event due to the discomfort of the visual aesthetic.

Thermal comfort in the form of appropriate temperature and humidity is a physical factor which may also have an affect on the receiver's ability to enjoy the performance.

Continuous background noise from mechanical equipment or the lighting system can be distracting and interfere with the quality of the experience, especially at a pause in the music, or during quiet passages. Even more distracting are the impulsive noises of wristwatch alarms, pagers and cell phones. Coughing, and the crackling of wrappers and programs are also known to be cause annoyance and degrade the overall performing experience.

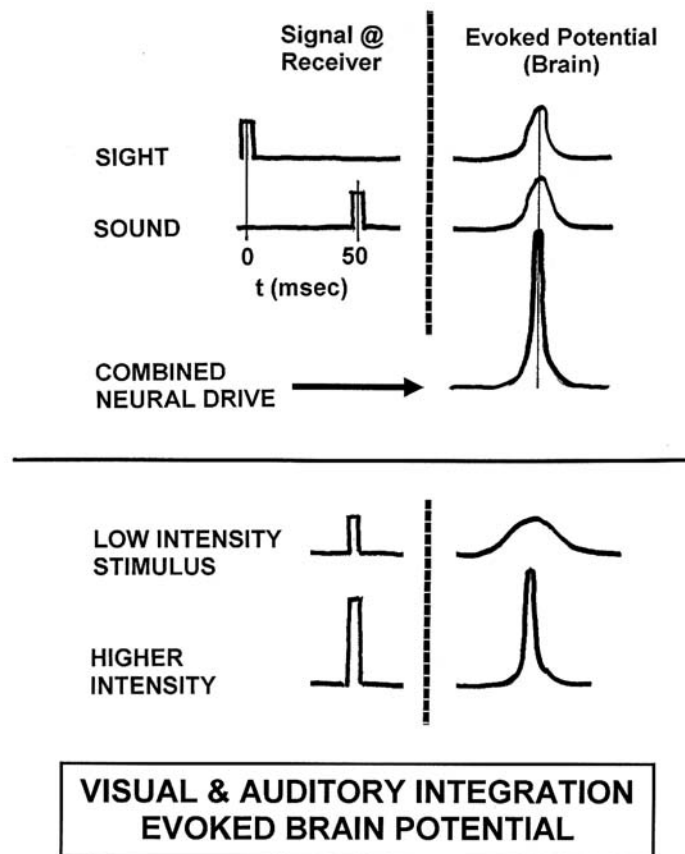
## **6 PHYSIOLOGICAL EXPLANATION FOR INTEGRATION OF AUDITORY AND VISUAL STIMULI AND HYPOTHESIS FOR APPLICATION TO INTIMACY IN SMALL AND LARGE ROOMS**

### **6.1 Auditory and Visual Processing in the Brain**

It's not surprising that there exists a natural cooperative interaction among auditory and visual sensory systems in the brain's wiring. Such a connection exists even as low as at the brainstem level, in the form of pathways between the inferior and superior colliculi.<sup>61</sup> The result of this synergy is an increase of the overall reaction speed of processing stimulus signals, and the increase in magnitude of the evoked potential (EP) of the combined auditory and visual signal in the brain.

Reaction times for visual and auditory input are found to be in concordance with the intimate setting of the chamber music experience. It is found that reaction to an auditory stimulus is faster than to a visual stimulus, the difference being on the order of from 40 to 60 msec. due to the longer processing time of the retina as compared to the inner ear.<sup>42</sup> Therefore, when a visual stimulus precedes an auditory stimulus by the difference in their processing times, the two inputs converge simultaneously in the brain and are coherent.

This concept is represented in the top portion of Fig. 7 where a nominal sound signal delay of 50 msec. aligns the EP brain response of the two stimuli. The result is that the reaction time to the combined stimuli becomes significantly shorter. At the same time, the amplitude of the EP or “combined neural drive” (see Fig. 7) of the combined stimuli is significantly greater than it would be to either stimulus alone. This amplitude increase for the combined stimulus event (auditory and visual) is analogous to an increase in the magnitude (and one would presume of the quality and satisfaction) of the experience itself.



**Figure 7 – Graphic representation of brain integration and evoked potential with auditory and visual stimuli.**

The shortened reaction time affects the efficacy of understanding and amplifying information since increased reaction time (in this case a sharper spike in the EP) effectively increases the signal-to-noise ratio of the signal. It increases the capability of understanding the first signal before the second signal comes along, ensuring more complete processing of the event.<sup>62</sup> In summary, more neural drive and shorter response time work together to create a more intense and complete experience. The combination of auditory and visual stimuli therefore affects the perception of the event itself.

Another factor illustrated at the bottom of Fig. 7 is that the greater the intensity of a stimulus, even if independent of another (magnitude of the visual alone, or magnitude of the auditory input, alone) the greater the reaction time and amplitude of the EP, even for that stimulus alone. The concert/performance experience confirms this, for instance. Quick movement on the stage is more easily discerned when brightly lit, and rapidly played passages are more easily discriminated when played more loudly.

## **6.2 Stimulus Integration and Intimacy in Small and Large Rooms**

Application of the above discussion to the listening experience in halls is tempting. The processing delay phenomenon between the eyes and ears indicates the maximum integrated “experience” will occur at listener distances of from around 10 to 17 meters from the performer. A performing space with the audience within the greater distance could easily have around 400 to 600 seats. It is hypothesized here that the EP delay integration model articulated above be applied by using it to determine the upper limit on the size of a room providing an Intimate experience based on visual and auditory stimuli. This would define a room having around 600 to 1000 seats, assuming the use of balconies in the larger case.

It could also be argued that, for the greater distances of larger spaces, increased intensity of auditory input be used to make up for the time alignment mismatch which occurs between visual and auditory inputs. This argument supports the idea discussed in Sect. 5.4 that greater early energy in a room’s design reinforces the effects of the direct sound level and that a greater sound level reinforces the same experience commensurate with a smaller room. A significant result of the increased intensity is that of increased Intimacy.

## **7 ACOUSTICAL STUDIES INDICATING VISUAL INFLUENCE ON AUDITORY PERCEPTION**

There is evidence in the literature beyond sensory psychology experiments that the perceptual modalities of seeing and hearing interact and reinforce one another in complex relationships. Toole and Olive have published a number of papers on the perception of music, primarily through electronic systems involving loudspeakers, microphones and different listening environments. In one double blind experiment,<sup>63</sup> subjects listened to music over loudspeakers which were either visible or hidden behind screens. The quality of different loudspeakers was tested with the primary variable being that the listener knew the manufacturer and retail price of the speakers which were visible. It was found that such knowledge, keyed by visual input, was the major determinant of quality, with listeners being less responsive to audible differences and therefore more responsive to their biases. The degree of bias was also found to be greater when the audible difference between test sources was small.

[Similar bias issues are found in the sensory preference evaluation of wine depending upon whether the results are derived from “blind” tasting (no knowledge of the wine’s identity) as opposed to having knowledge of the wines being evaluated (where biases override the palate and sensory perceptions).]

There are obvious parallels with concert hall listening, one being that visual input from the hall itself (both aesthetic as well as distance related) can affect the judgment of perception of the hall’s acoustical quality. In addition, biases relating to the hall’s reputation, or the reputation of the performer/orchestra can also affect judgment. Where the acoustical difference between halls

is great, effects of bias may be less dominant. Conversely, where the acoustical differences between halls is small, a listener's biases may be more dominant in the final judgment of acoustical quality. The role of personal bias is therefore seen as a significant factor in perception and judgment, and must therefore be accounted for and weighed when evaluating perceptual results.

Woszczyk, et al.<sup>64</sup> report work on the matching of auditory and visual information and how their cooperative interaction reinforces human awareness of the stimulus. This matching of bimodal data is found to “trigger perceptual synergy between modalities and promote inter-modal fusion.” The visual input “reduces the ambiguity of sound and helps to define its purpose.”<sup>65</sup> They report matching factors important for a synergetic perceptual interaction between the auditory and visual. Those relating to the concert hall experience include “temporal and spatial coincidence,” “congruence of auditory input with visual movement,” and “balance between image size and the loudness of sound.” The importance of these factors is emphasized when formulating or conducting listening tests relative to the concert hall experience. They also cite work<sup>66</sup> showing that improved visual input has a commensurate effect on the perceived quality of the sound for the same event. This again reinforces the connection between the two modalities and the roles of distance and sound strength in the perception of Intimacy and overall sound quality.

A study by Larsson, et al.<sup>67</sup> at Chalmers University applies the auditory-visual matching principles of Woszczyk<sup>64</sup> to bimodal virtual environments for the purpose of developing accurate electronic acoustical test simulation. Their findings point to work by Carlsson<sup>68</sup> who found that subjective properties such as auditory source width, source-receiver distance and perceived room size are highly influenced by visual information concerning the listening environment. A summary of their findings includes: **Perceived Reverberation Time (PRT)** was found to be affected by visual input; it was greater in the absence of visual information, **Auditory Room Size** was found to be related to **PRT** and was affected by visual information, **Perceived Source-Receiver Distance** was rated as being greater (more distant) in the absence of visual input, and **Auditory Source Width** was found to be influenced by visual information. They also found that the type of signal (orchestral motif, solo instrumentalist, vocalist) affected the results.

More recent work by Larson, et al.<sup>69</sup> reports on the auditory-visual interaction in real and virtual rooms and the important conclusion that simulation fidelity in virtual test environments is an important factor in the results testing for acoustical quality of performing spaces. Västfjäll, et al.<sup>70</sup> further report experiments showing that results from cross-modal interaction studies in performing spaces is contingent on the quality of the stimuli.

To summarize, visual stimuli have been found to be a significant determinant of the acoustical perception of a space, and need to be taken into account in subjective testing. Simulator testing must be a real, quality virtual environment. The best testing environment, if feasible, is of course within the real hall environment itself, lending particular credence to the real-world results reported in Sections 3 and 9 of this paper.

## **8 SURVEY OF OPINIONS ON AUDITORY-VISUAL ASPECTS OF THE CONCERT HALL EXPERIENCE**

In the same survey reported above, and outlined in Appendix I, acousticians were asked to give their opinions as to whether the visual relationship between the listener, room and the performance affects the perception of acoustical factors. Figure 8 shows the results of this survey

of prevailing opinion, where there is near unanimity that Intimacy is “definitely” influenced by visual stimuli. All acoustical factors in Fig. 8 except reverberation are thought to at least “perhaps” be influenced by visual input by over 70% of the respondents.

Some respondents felt that all factors were visually influenced, with Prof. Jens Blauert of Ruhr-Universität Bochum, knowledgeable in the field of spatial hearing and communication acoustics, remarking “humans are multimodal receivers.”<sup>71</sup> Second to Intimacy itself, “overall acoustical quality” was considered to be highly influenced by visual stimuli.

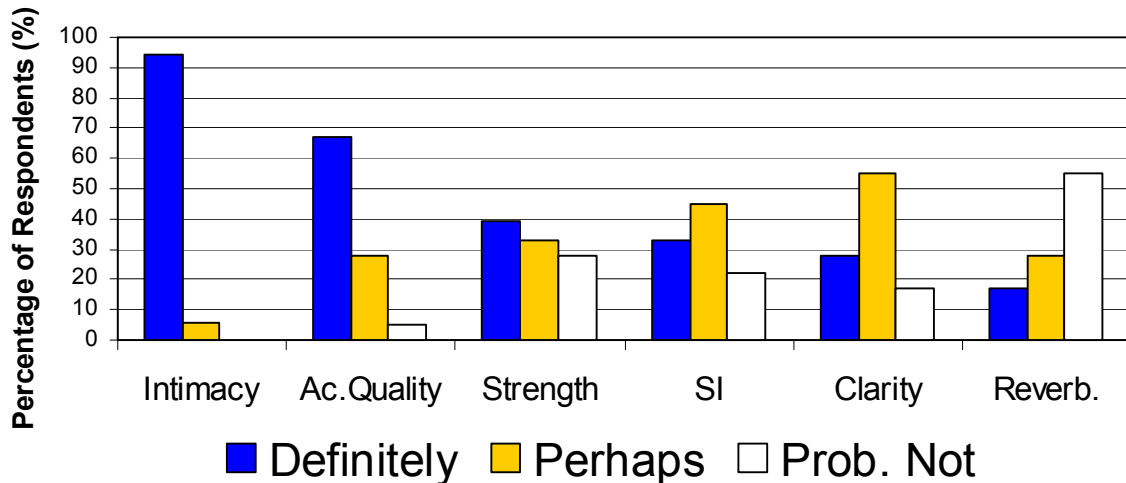


Figure 8 – Opinion survey on the existence of visual influence on sound field perception. (SI = Spatial Impression)

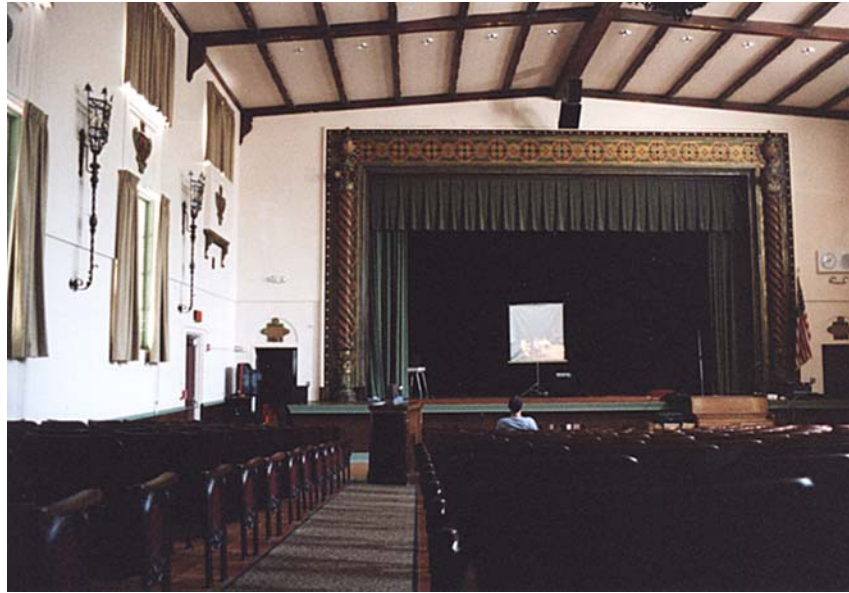
## 9 TESTS FOR LOUDNESS AND INTIMACY IN 500 SEAT RECITAL HALL

A real-hall auditory and visual test setup was created by the author to further examine the relationships found by Barron between subjective loudness, sound level, distance and Intimacy as well as to confirm the concept of the perceptual constancy of loudness found with distance as demonstrated by Eq. 1, Sect. 3, and as discussed in Sect. 4.

### 9.1 Test Setup and Procedure

Listening tests using various music motifs were undertaken by the author in a 500 seat shoebox recital hall in which objective acoustical measurements at the listening positions were made. Two test seats were used. Position A was at the front of the room near the stage as seen in Fig. 9a. Position B was at twice the distance as Position A from the source, near the rear of the hall as seen in Fig. 9b.

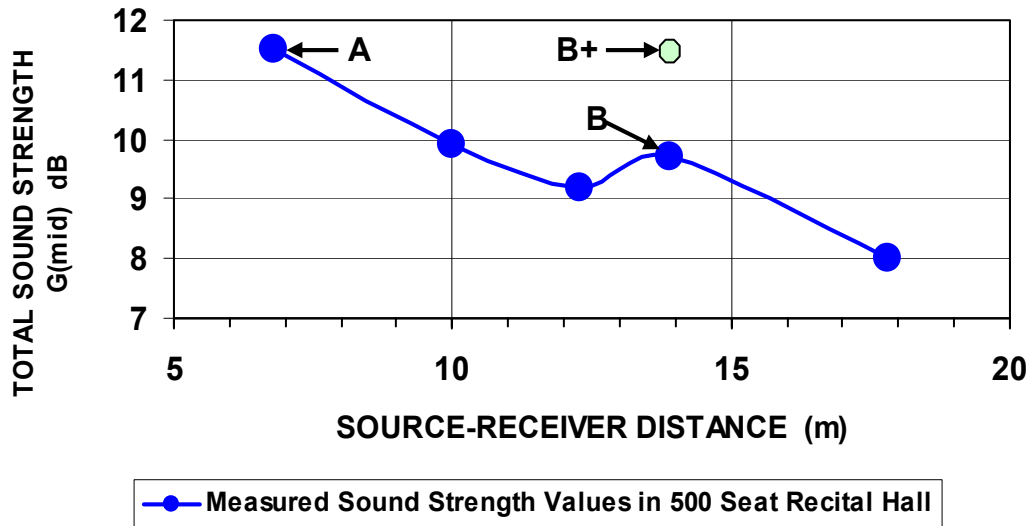
Subjects were exposed to short passages of anechoic music (four motifs) at Positions A and B without any adjustments to level, thereby yielding the natural drop-off of sound strength  $G$  in the space. Subjects at Position B were additionally exposed to the same level as at Position A (called Event B+) by adding two delays of 20 and 55 msec. which were  $25^\circ$  (left) and  $40^\circ$  (right) off axis respectively. The relative sound strength values  $G$  measured at these positions in the hall are shown in Fig. 10.



**Figure 9a – Test subject shown in listening Position A near the front of the hall.**



**Figure 9b – Test subject shown in listening Position B. Projected image of chamber ensemble group is shown on stage near center speaker source (See Fig. 11).**



**Figure 10 – Relative listening test sound levels. Levels at Position B are 1.8 dB lower than at Position A. Event B+ is at the same sound level as Position A.**

To complete the visual setting, a photo of a chamber ensemble on a stage was projected on a large screen on the hall’s stage at the location of the central speaker as shown in Fig. 11. Average music sound levels between 67 and 76 dBA were used as appropriate for the music motif and the reverberant conditions of the test recital hall.



**Figure 11 – Projected chamber ensemble on stage near source speaker for listening tests.**

The subjects were not considered to be “experienced” listeners, with music and performance not being a part of their everyday lives. They were exposed to the sound fields in various combinations and asked to judge the relative “loudness” and “acoustical intimacy” of each event

by marking a bipolar scale with increments of “1” to “10” indicated. In judging Loudness the semantic scale ran from “quiet” to “loud.” For judging Intimacy the scale ran from “remote, distant” to “involved, close.” No remarks were made to test subjects indicating an interest in the visual aspects of these acoustical factors and responses. A copy of the questionnaire and the pre-test introduction and instructions are given in Appendix B.

## 9.2 Results on Loudness Perception

The results of the testing for Loudness show the expected linear and positive relationship between subjective loudness and average motif sound level as seen in Fig. 12.

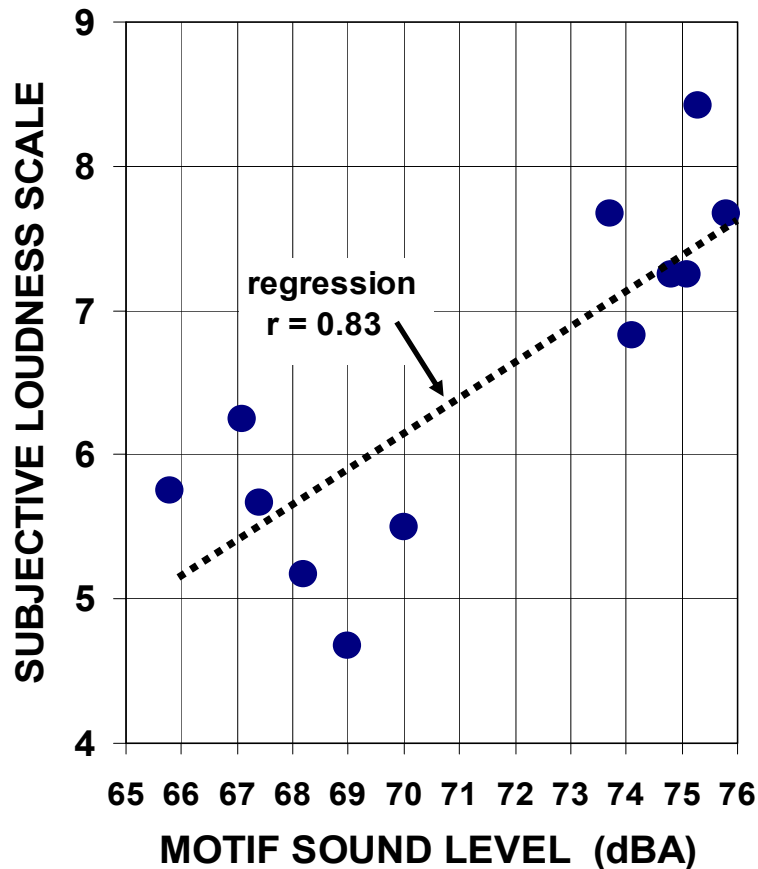


Figure 12 – Loudness versus Sound Level in 500 seat recital hall (see Fig. 9)

The results in judging relative Loudness are similar to Barron’s findings given in Section 3. Moving from Position A to Position B where the level at B is lower, the result of all judgments was that the subjective loudness was essentially the same as at Position B. Multiple regression analysis of the data yields the following relationship:

$$\text{Loudness} = k' (G_{\text{mid}} + 0.162 r) \quad (2)$$

where  $r$  is the source-receiver distance,  $k'$  is a scaling constant and the loudness units are arbitrary. For these test results, the scaling constant is found to be  $k'=0.51$ . As with Barron’s results, the coefficient of  $r$  is found to be positive.

With the drop-off rate in level between the two seats being -0.146 dB/m for these tests, the coefficient of r in Eq. 2 indicates that in this hall, under the visual test conditions presented, the perception of loudness is essentially constant with distance from the source.

The relationship between subjective loudness and distance in the test recital hall is shown in Fig. 13 for two conditions. The lower curve uses the measured values for G for this space as a template for loudness by applying Barron’s “revised theory”<sup>31</sup> to the subjective loudness scale of the test. In other words, if the perception of loudness were based solely on the objective sound level, this is the relationship expected between the two factors in this hall, with its energy distribution based upon Barron’s “revised theory.”

The upper curve represents the results of the subjective testing, plotting the derived multiple regression of Eq. 2. The variation in G (lower curve) is balanced by the coefficient of r, indicating a near-constant perception of loudness with distance for this auditory-visual test environment. Again, the results are similar to Barron’s with the difference being that his distance coefficient is derived from many halls and many locations, whereas the distance coefficient of Eq. 2 is the result of an experiment in one hall between two locations. The results, however, appear to support the basic contention of there being a visual/distance link to the perception of loudness with music in a performing space. The concept of perceptual constancy of loudness in a performance space again appears to be confirmed.

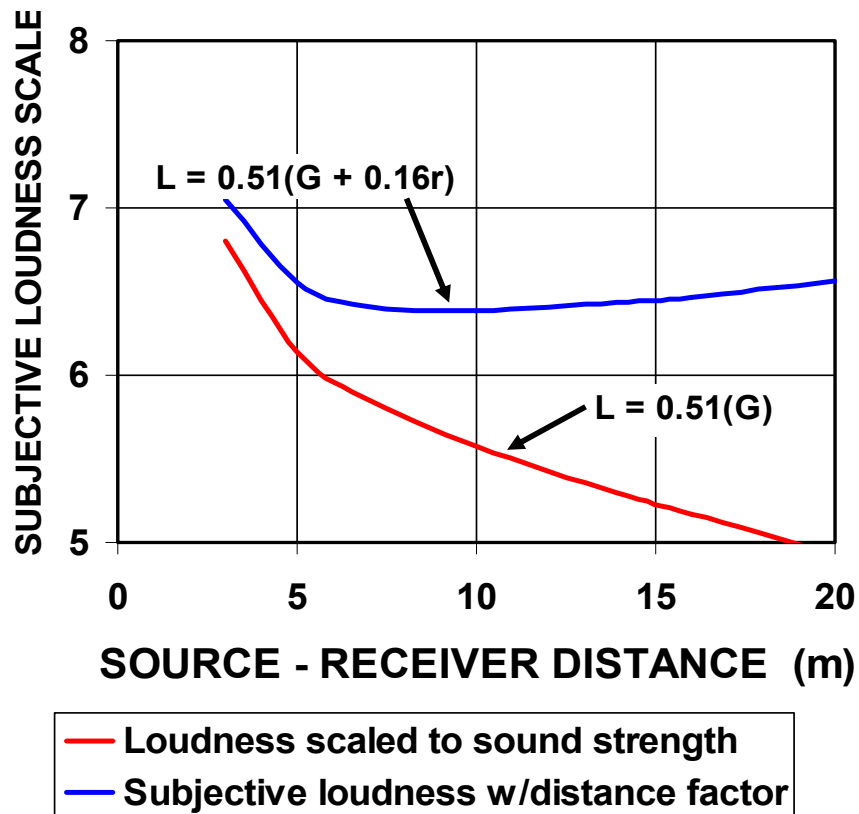


Figure 13 – Subjective loudness versus distance test results in 500 seat recital hall. See text above for explanation of curves.

Previous work has been reported by Hyde<sup>72</sup> on the ability of listeners to discriminate changes of loudness in the early sound field. He found that subjects could distinguish the difference in sound strength  $G$  at a just noticeable difference (JND) of 1.0 dB. In the experiment at hand (see Fig. 10),  $G_{mid}$  decreases by 1.8 dB between Posits. A & B, yet the average judgment of listeners is that the loudness remains constant. This result further reinforces Barron's finding discussed in Sect. 3 that visual stimuli play a role in the perception of loudness in performing spaces.

### 9.3 Results on the Perception of Intimacy

In the same subjective tests, the judgment of the relative change in Intimacy presented a broad range of values on the test bipolar scale (see Appendix II). Test subjects, in general, had less success in understanding the concept Intimacy and in judging the putative differences in Intimacy between seats and at varying sound levels. Greater variation in response was found between music motifs when judging Intimacy, than when judging loudness as can be seen in Fig. 14. A slight increase in relative Intimacy was found as a function of objective sound level, however, with a correlation coefficient of only  $r=0.26$ . Judgment of relative changes in Intimacy included data from "Event B+." As in Sect. 3, we again connect the effect of loudness increase with visual distance to support the contention that the perception of Intimacy is related to visual input.

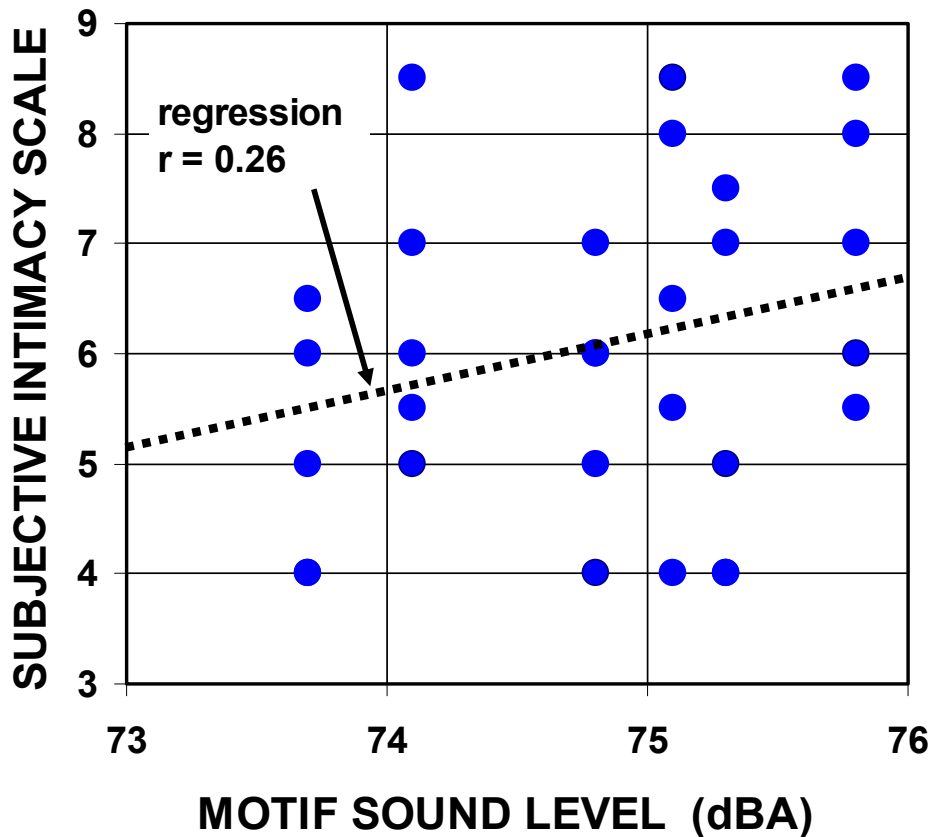


Figure 14 – Subjective Intimacy test results in 500 seat recital hall.

## 10 INTIMACY AND THE PERFORMER

Intimacy is also an important issue for performers. In this case, its definition involves the performer's "contact with the audience"<sup>73</sup> as well as between the players. Sanders<sup>74</sup> reports a comprehensive survey of chamber music musicians and their response to chamber music halls throughout the country of New Zealand. The main criteria of judgment for the performers were Intimacy and "communication between players." The results of the study indicate the three most important factors relating to a positive overall impression of a hall for the musicians were "support," "balance," and "ease of ensemble." All of these subjective factors can be related to the early sound field in the vicinity of the performer since distance between performers is on average constant, regardless of the size of the room. Of particular interest in this study is the range of size within the group of top-rated halls, with volumes from 2,800 m<sup>3</sup> to 13,000 m<sup>3</sup>. This points to the importance of the "local acoustical environment" as determined by the architectural design of the performer area, relatively independent of the size of the performing space.

Ando<sup>75</sup> has discussed the importance of lighting level in facilitating, in the case of a solo performer (singer) greater nonverbal communication between the musician and listener. "The performer would like to see the faces of the audience and to make contact with them during the performance, in order to recognize the audience's mood and to feel its intensity. Thus, more light in the hall than is customary is recommended for seeing the faces of the listeners seated in front of the musician."<sup>75</sup> This requirement for the performer may be in conflict with some of the lighting issues discussed in Section 5.212 of this paper from the point of view of the audience.

## 11 CONCLUSIONS

From listening experience in performing spaces, most acousticians believe that auditory intimacy (herein called Intimacy) has a visual component. Evidence from room acoustic measurements, subjective surveys and controlled listening tests has indicated that visual stimuli indeed influence our perception of the auditory event in that all experience is multisensory.

There is direct evidence that visual factors affect our perception of subjective loudness where the visual stimulus of distance from the source serves to alter the impression relative to the sound field; that is, the sound level decreases with distance but the perception of loudness does not. Intimacy and loudness are found to be directly correlated, and the evidence of a strong visual influence on them is compelling.

Sound field components in small spaces essentially define Intimacy and the issue for achieving Intimacy in large halls becomes one of reproducing as many of these components as possible. Since the direct sound level and source-receiver distance are unchangeable design factors, Intimacy is achieved by providing significant sound strength  $G$  from rich early reflections and through maintaining as small a room constant as possible.

The concept of perceptual constancy is found to support the acoustical findings of this investigation. The creation, in large rooms, of the major factors found in small performing spaces helps provide more Intimacy in the larger space. This is particularly true when creating the impression of a shorter source-receiver distance by providing greater early energy through early reflections in the room's geometry (design). A significant cue providing this illusion of a closer and more Intimate distance is visual.

In summary, concerts and operas are multisensory events with visual input having a clear influence on what we "hear" and experience.

## **12 POST SCRIPT – COMMENTS ON VISUAL INTIMACY IN A SMALL CHAMBER PERFORMANCE ROOM**

Recent experience of the author with chamber music and recital performances in small rooms reinforces the issue of visual influences on the experience for both the audience and the performer(s). A local chamber music series has been bringing world class performers to our small community in the Napa Valley by offering the beauty of the area plus the fine wine and food as an incentive to visit. These are musicians who normally play to large concert halls and opera houses with capacities from 2500 to 3000 seats. This year's program (2002-2003) features names such as Pinchas Zukerman, Karita Matilla, Yefim Bronfman, Garrick Ohlsson, Radu Lupu and Emanuel Ax.

The recital chamber seats 350 people, has a plan area of 175 m<sup>2</sup> and a volume of approximately 1,340 m<sup>3</sup>. There is small stage, radius seating and a three row balcony over the stalls. The front row of seats is at the stage edge, 2 m from the performer. The maximum seat-to-stage distance is 11 m, with the average distance to the performer being perhaps 6 to 7 m. There is no spot or task lighting on the stage, so the entire room is uniformly lit at a moderate level. (See Sections 5.212 and 10 on lighting.) The performers can see each and every face. Further, as is common in small communities, most people in the room know many of the others so there is a sense of familiarity and community in the room. The setting feels intimate in about every sense of the word.

Conversations with the music directors<sup>76</sup> confirm the performer's experience as perceived by the audience. From the musicians' point of view, they mention the difference between this chamber setting and the large concert or opera house experience where the house lights are down and there is no real visual connection with the audience. Here the performers find it almost "terrifying to perform in a small room where each face can be seen,"<sup>76</sup> and where everyone is so close to the stage. As they perform and give their energy and expression to the audience, so they also receive back a response from the audience. There is a continuously changing exchange of expressions and body language from the audience which profoundly affects the performer. One can see the performer react, in some cases rather emotionally, especially during the ovation. When the audience exhibits its excitement and appreciation, the performer reciprocates, and at times appears to be overwhelmed. They are touched by the ovations, and at times appear to stagger off the stage as if drained by the exchange. The performer is truly moved by the experience, and the audience lingers in warm amazement.

This experience is the essence of the meaning of intimacy. Nowhere is acoustics thought of as a separate entity, if it is thought of at all. The experience is about the visual, spiritual and cultural connection using music as the medium and vehicle, within the small room, between the performer and the audience.

## **13 ANECDOTAL COMMENTS INVITED ON MULTISENSORY INTEGRATION IN THE CONCERT/OPERA EXPERIENCE**

Since this paper was delivered at the IOA in London, July 19, 2002, there has been a large response from colleagues who have many stories to tell about the multisensory concert and opera experience. Written comments of stories and anecdotes are invited by the author, to be compiled for future discussions.

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- The respondents of the opinion survey questionnaire.

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# **APPENDIX I**

## **Questionnaire on Auditory Intimacy (attached)**

### **Part 1 – Definition of Intimacy**

Each respondent's comments were tabulated and reported in Section 2.4.

### **Part 2 – Opinion of Objective Factors Related to Intimacy**

The results of this question are reported in Section 2.6 and graphed in Fig. 4. Since many respondents left some of the factors blank (no score), the arithmetic average of each factor only with a score was reported. The two factors with the least responses were “Visual (dynamic)” and “1-IACC,” each having six judgments. The other factors had an average of eleven responses from the total number of seventeen respondents contributing to the data field.

### **Part 3 – Opinion of Visual Relationship with Acoustical Factor**

Every respondent checked each option. Two respondents checked “definitely yes” for all factors. The results of this question are discussed in Section 8, and graphed in Fig. 8.

**QUESTIONNAIRE**  
**from Jerald R. Hyde, FASA**  
**FAX: (707) 963-7959**

ATTENTION:  
 SUBJECT: Survey of Acoustical Issues for IOA paper  
 FAX NO.:

Dear

I am undertaking an opinion survey of acousticians who have experience in visiting, evaluating and designing concert halls. The purpose of this is to determine prevailing thought on the issue of Acoustical Intimacy and its relationship to the physical factors found in larger concert halls. These factors include all measurable objective sound field parameters along with the dimensional and visual aspects of spaces. Information which comes from this survey will be reported in a paper I am giving before the IOA in London this July. The title of the paper is "Acoustical Intimacy in Concert Halls: Does visual input affect the aural experience?"

NOTE: The names and responses of all respondents will be held in strict confidence. A summary of results will be gladly shared with all who respond. Partial responses accepted.

1. Please give your definition of Acoustical Intimacy.

2. On the basis of your personal listening experience, please rank the objective factors which in your opinion are correlated with the perception of Acoustical Intimacy (some factors may be negatively correlated). For each factor chosen, please rank from 1 to 10 according to the degree to which you believe the factor is correlated, with 1 being "not correlated" and 10 being "highly correlated." Where applicable, a negative number indicates an inverse relationship. Factors in list below may be left blank. NOTE: Measured values are at mid-frequencies except LF and IACC. Objective measures may include but not be limited to:

G(total)_____	G(early@80)_____	Level(direct)_____
ITDG_____	RT_____	EDT_____
LF_____	1-IACC_____	C80_____
D50_____	Volume_____	Rm.Width_____
Ceiling Ht._____	Shape_____	Visual(static)_____
Visual(dynamic, performer movement)_____	Stage-Listener dist._____	
Other_____	Other_____	

3. Do you believe that the VISUAL relationship between the Listener, the Space and the Performance affects the perception of:

<u>One Check for Each Factor</u>	<u>definitely yes</u>	<u>perhaps</u>	<u>probably not</u>
Acoustical Intimacy			
Reverberation			
Loudness			
Clarity			
Spatial Impression			
Overall Acoust. Impression			
Other? _____			

4. Any comments or additional thoughts are appreciated. Attach another page as necessary.

## **APPENDIX II**

### **Room Acoustical Listening Experiment Subjective Judgments of Music**

#### **General**

This experiment and its results are discussed in Section 9. Individual listeners were invited to the recital hall and asked to sit in the middle of the room facing the stage. An introductory statement describing the experiment was read to them and they were shown both Seats A and B which were marked with a placard. They were also familiarized with the subjective judgment score sheets.

Attached are three documents used in the listening tests:

**Room Acoustical Listening Experiment** – The text on these two pages were read to each subject after which questions, if any, were answered.

**Test Score Sheets** – These describe the two semantic bipolar scales to be marked by each subject according to the instructions read to them.

**Sequence of Seat Positions and Source Types** – These are also attached.

Room Acoustical Listening Experiment  
Jerald R. Hyde, FASA  
May 2002

**INTRODUCTION**

You will be exposed to short passages of music lasting around 20 sec. while sitting in two different seat locations. Seat A is near the stage in the front of the room, and Seat B is farther back in the auditorium.

In order to try to simulate a real music experience, a performance representation is projected on the stage near the loudspeaker which plays the music. The music is not enhanced, so you are hearing only the source plus the natural acoustics of the room.

You will be asked to make certain judgments about how you perceive each music passage and you will mark your score sheet accordingly.

There are four separate passages of music. You will move between the seat locations for each set of the four passages. I will direct you as to when to move your location.

**THE SOUND EVENT JUDGEMENTS**

For each passage of music, you will be asked to make two judgments. You will judge your perception of two qualities about the music experience in each of the two seats in this auditorium.

The first sound quality is your perception of the “loudness” of each passage. The score sheet will have a bipolar semantic scale for you to mark your perception of loudness rating it from “1” to “10”. “1” indicates very quiet and “10” indicates very loud. We are looking for your perception of the relative loudness values of each event. Please don’t make assumptions about what you might hear as a consequence of location in the room, since I will be altering the sound field for each passage. Again, your task is to merely rate the relative loudness of each passage on a scale of 1 to 10.

The second sound quality is your perception of the acoustical Intimacy you feel with each passage. Acoustical Intimacy is generally described as “one’s degree of identification with the performance, whether one feels acoustically involved, or, detached from the performance.” Other feelings associated with Acoustical Intimacy relate to the perception of proximity to or distance from the source, and whether one is detached or involved with the event; whether one hears the room as small (intimate) or large.

So, the question with Acoustical Intimacy is whether you feel close or drawn in and connected to the performance, or does it feel remote and distant as if it were “over there?” Your bipolar scale would indicate “1” as being remote and distant, and “10” as being involved with and close to the performance.

### **SUMMARY**

For each passage you will mark your judgment of the two sound qualities, Loudness and Acoustical Intimacy. You will have four score sheets, one for each of the four music tracks.

Here is a survey score sheet. Please have a look at it and tell me if you have any questions.

**SUBJECTIVE JUDGMENTS OF MUSIC**  
**St. Helena Elementary School Recital Hall (SHES) – 500 Seats**

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DATE \_\_\_\_\_

SUBJECT NO. \_\_\_\_\_

TEST TRACK \_\_\_\_\_

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SEAT \_\_\_\_\_  
RUN #1

Quiet 1 \_\_\_\_\_ 2 \_\_\_\_\_ 3 \_\_\_\_\_ 4 \_\_\_\_\_ 5 \_\_\_\_\_ 6 \_\_\_\_\_ 7 \_\_\_\_\_ 8 \_\_\_\_\_ 9 \_\_\_\_\_ 10 Loud

**Judgment of Loudness**

Remote Distant 1 \_\_\_\_\_ 2 \_\_\_\_\_ 3 \_\_\_\_\_ 4 \_\_\_\_\_ 5 \_\_\_\_\_ 6 \_\_\_\_\_ 7 \_\_\_\_\_ 8 \_\_\_\_\_ 9 \_\_\_\_\_ 10 Close Involved

**Judgment of Acoustical Intimacy**

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SEAT \_\_\_\_\_  
RUN #2

Quiet 1 \_\_\_\_\_ 2 \_\_\_\_\_ 3 \_\_\_\_\_ 4 \_\_\_\_\_ 5 \_\_\_\_\_ 6 \_\_\_\_\_ 7 \_\_\_\_\_ 8 \_\_\_\_\_ 9 \_\_\_\_\_ 10 Loud

**Judgment of Loudness**

Remote Distant 1 \_\_\_\_\_ 2 \_\_\_\_\_ 3 \_\_\_\_\_ 4 \_\_\_\_\_ 5 \_\_\_\_\_ 6 \_\_\_\_\_ 7 \_\_\_\_\_ 8 \_\_\_\_\_ 9 \_\_\_\_\_ 10 Close Involved

**Judgment of Acoustical Intimacy**

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SEAT \_\_\_\_\_  
RUN #3

Quiet 1 \_\_\_\_\_ 2 \_\_\_\_\_ 3 \_\_\_\_\_ 4 \_\_\_\_\_ 5 \_\_\_\_\_ 6 \_\_\_\_\_ 7 \_\_\_\_\_ 8 \_\_\_\_\_ 9 \_\_\_\_\_ 10 Loud

**Judgment of Loudness**

Remote Distant 1 \_\_\_\_\_ 2 \_\_\_\_\_ 3 \_\_\_\_\_ 4 \_\_\_\_\_ 5 \_\_\_\_\_ 6 \_\_\_\_\_ 7 \_\_\_\_\_ 8 \_\_\_\_\_ 9 \_\_\_\_\_ 10 Close Involved

**Judgment of Acoustical Intimacy**

**TEST PROCEDURE**  
**SEQUENCE OF SEAT POSITIONS AND SOURCE TYPES**  
**SHES 500 SEAT AUDITORIUM ACOUSTICAL TESTS**  
**MAY 2002**

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TRACK	POSITION	SOURCE
9	A	D
	B	D
	B	D + $\delta$
10	B	D
	B	D + $\delta$
	A	D
15	A	D
	B	D + $\delta$
	B	D
16	B	D
	B	D + $\delta$
	A	D

[NOTE: D +  $\delta$  is called "Event B+" in the text, Section 9.1]