12 February 1971, Volume 171, Number 3971 SCIENCE

Auditory Backward Inhibition in Concert Halls

The parallelism between vision and hearing suggests new features in room acoustics.

Georg von Békésy

Immersed as we are in the cacophony of an overcrowded world, perhaps a good musical performance in a grand concert hall is one of the last auditory stimuli that is still desirable. Unfortunately, however, sound transmission in a concert hall is greatly complicated by the reflections from the walls of the structure.

The problems of the concert hall are of three major types.

1) The performance of the musician and his instrument. Many experiments have been made to determine the reasons for the differences in sound transmission of individual stringed instruments of a given type. There seems to be, for every instrument, a typical direction in which the sound radiates. Even today it is not clear whether, for instance, the sound from a violin should radiate directly toward the audience as a whole or more toward the ceiling so that it can be reflected from there to the audience in the back of the concert hall. Furthermore, is the optimum direction of radiation the same for all the frequencies emitted by the violin? It is obvious that, for the violin which radiates a large part of its sound, for all frequencies, toward the ceiling, any absorption by the ceiling should be avoided. The same thing holds true for the side walls. This is just one example of the close interaction between the musical instrument and the architecture of the concert hall. Most of the musical instruments developed during the 18th century were built to fulfill the requirements of a small concert hall. Today we have larger audiences, and we would therefore like to improve upon the construction of earlier musical instruments so that the sound of today's instruments can fill large concert halls.

2) The physical transmission of a sound from the performer to the listener in a concert hall. The ancient Romans were interested in this problem; the first treatise on the subject was probably that of Vitruvius (*1*). In Vitruvius' time, the transmission of sound was considered similar to the transmission of a light beam, and reflections from a wall were considered very important. This approach to acoustical problems was very successful, especially for high frequencies. It was already known at that time that a musical performer should have a reflecting wall behind him. Whereas in outdoor theaters the role of a reflecting wall can be easily controlled, in a closed room like a concert hall much more is involved. It was mainly the work of Sabine (*2*) which demonstrated the concept of room reverberation—that is, that the sound reflected from one wall in a closed room is again and again reflected from the other walls, so that a diffused sound field is created. This sound field represents acoustic energy accumulated in every cubic foot of the room. The time interval within which this accumulated sound energy can be dissipated is of great importance in determining the acoustic quality of a structure. The only way to dissipate the accumulated energy is to have, in addition to the absorbent surfaces of the audience, absorbent walls.

Later work in the field of architectural acoustics by Knudsen (*3*) and by many other researchers in the United States and Europe indicated that the two concepts—that of reflected sound and that of reverberant sound—should be combined. The ratio between the loudness of direct sound and the loudness of reverberant sound is an important factor in determining the quality of concert halls. A description of concert halls throughout the world which are considered to be of excellent quality is given by Beranek (*4*).

3) The most complex factor in concert hall acoustics is the reaction of the listener to the complicated mixture of direct and reverberant sound. He definitely does not act as a microphone, but he is able to partially reject ("inhibit") sound waves or completely cancel them out, depending on their direction of impact, their intensity, and the interval between the times of emission and of arrival.

Five Different Types of Inhibition

There are at least five different types of inhibition in the auditory system which modify the loudness, the location, the volume density, and the apparent extension of a sound source. All five differ for a continuous tone and for a transient one. Besides being inhibitory, the nervous system integrates some of the sounds into a single sensation. When the architecture of a room enhances this sensation of integration, we say that the room has good acoustics. Most of the pertinent experiments indicate that inhibition can be

The author is professor of sensory sciences at the University of Hawaii, Honolulu 96822.

just as important as the sensations produced by the stimuli themselves. Let us consider the five types.

First, if we consider only two sound stimuli—for example, the direct sound and the sound reflected from one wall—we find that inhibition is present even if there is no delay between the arrival of the two sounds. The localization of the sound source then depends on the relative loudness of the direct and the reflected sound.

The second type of inhibition is very well known. It is produced by small differences (of the order of 1 millisecond or less) in the time a sound reaches the two ears, and it is responsible for directional hearing. If both ears are stimulated by a sound simultaneously, we localize the sound source in the median plane of the head. But if there is a time difference, we localize the sound source to the side which receives the sound first. With a time difference of 1 millisecond we have the impression that we hear the sound only with one ear. This type of inhibition was well described by von Hornbostel and Wertheimer (*5*) and later fully discussed by von Hornbostel (*6*). We may call this type of inhibition "forward inhibition" because the first stimulus inhibits all the stimuli that are later presented to the other ear. It is a continuous type of inhibition: an increase in the difference in the times of arrival of a sound at the two ears produces a continuous movement of the localization of the apparent sound source. The maximum time interval for this activity is only about 2 milliseconds. If the delay is greater than 2 milliseconds we have two separate sound sensations, one in each ear. This second type of inhibition makes it possible for us to separate in space the sounds from the different instruments of an orchestra.

The third type of inhibition might be called "backward inhibition." It is also often associated with the phenomena of "masking" or "metacontrast." Backward inhibition is active in the time-difference range between 30 and 120 milliseconds. It is a peculiar type of inhibition: a second stimulus presented about 60 milliseconds after presentation of the first stimulus is able to inhibit or apparently erase the first stimulus. It is a type of erasure related to short-term memory. The phenomenon is not new; Exner (*7*) was probably the first to describe it, in 1868. The description was elaborated by Bant (*8*) and by Monjé (*9*). A summary of backward inhibition, including more modern research, has been given by Raab (*10*).

Inclined as we are to believe that events in the brain occur in an orderly sequence, we have always been somewhat amazed by a phenomenon in which one stimulus can be completely erased by a second stimulus arriving much later (about 60 milliseconds later). But if we assume that every stimulus starts a process in the brain which lasts perhaps 200 milliseconds, we can make backward inhibition acceptable if we further suppose that this process can be inhibited at any moment during the 200-millisecond interval by the onset phenomenon of the second stimulus. With a delay greater than 200 milliseconds no inhibition occurs and both stimuli are recognized, separately.

Backward inhibition is illustrated in Fig. 1. There the interval between the times of arrival of the two stimuli is 60 milliseconds; the shaded areas represent brain processes. The bottom graph of Fig. 1 illustrates how the onset of the second stimulus shortened the process initiated by the first stimulus and reduced the magnitude of the sensation.

It is well known, from demonstrations of lateral inhibition in Mach bands, that a stimulus can be reduced by a second stimulus in its neighborhood in space (*11*). Pertinent experiments show that every stimulus at one point of a sense organ with a large surface area produces an area of sensation which is surrounded by an area of inhibition; thus, a second stimulus applied in this area is inhibited. In the case of Mach bands, no time difference between presentation of the two stimuli is involved. In backward inhibition we have only to assume that the onset phenomenon of the second stimulus can inhibit and block out the neighboring processes already occurring in the nervous tissue. In this way backward inhibition becomes a consequence of the well-observed lateral inhibition, such as is seen in Mach bands. Backward inhibition is only one of the phenomena which indicate the importance of the onset phenomena in sensory perception.

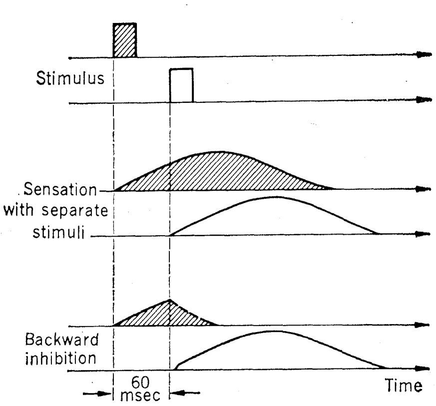


Fig. 1. The principle of backward inhibition. A short stimulus (shaded area in top diagram) produces a neural activity (shaded area in middle diagram) of much longer duration than the stimulus. This neural activity can be stopped by the action of a second stimulus presented much later than the first. The neural activity produced by the first stimulus is thereby reduced in magnitude and duration (shaded area in bottom diagram).

A fourth type of inhibition becomes obvious when we listen to a tone with a constant amplitude. Despite the fact that there is no change in the stimulus, we have the impression that the loudness is periodically interrupted or decreased for short moments. It was Lehmann (*12*) who pointed out that the pattern of brain processes suggests series of time quanta. The length of the time quantum is between 800 and 1200 milliseconds. Whenever a phenomenon starts, the brain integrates it to that length of time. After that there is a short pause, and then the integration starts afresh. We know this phenomenon well from listening to telegraph signals. Its application to room acoustics was illustrated in experiments (*13*) in which it was demonstrated that the apparent length of a decaying reverberant sound can be shortened by this type of blackout. It is a type of inhibition that exerts its influence mainly on stimuli which last about 800 milliseconds.

Another type of inhibition is central inhibition. It can produce a longer-lasting blackout or decrease in the magnitude of a sensation. It is often called shift of attention.

All these different kinds of inhibition play a role in one situation or another. Since they are central processes they seem to be analogous for the various sense organs (*14*). This sometimes makes investigation very easy and, to a certain degree, better established, since observations obtained for one sense organ corroborate results obtained for a different sense organ. In the next section I discuss the role of backward inhibition in vision, and I then go on to discuss its application in the field of room acoustics.

Backward Inhibition in Vision

In recent decades there has been increased interest in backward inhibition in vision [see (*15*)]. There are many ways of showing that backward inhibition is a powerful phenomenon and that it can lead to complete cancellation of the stimulus presented first. A method of showing the magnitude of the inhibition is given in Fig. 2, for binocular vision. Two black frames with diagonal shading are placed before the observer's eyes, one before each eye. The two frames are of exactly the same size, but, as Fig. 2A shows, the direction of the shading is different. When looking at these two frames in a binocular stereoscope the observer experiences a rivalry between the two fields; he may see the stripes going from left to right, or he may see the reverse pattern.

In our experiment a large black disk with a slit about 3 millimeters wide is rotated before the observer's eyes as he views the square frames. According to the direction of rotation of the disk, the left eye or the right eye receives the picture first. The speed of rotation of the disk determines the time difference between the two presentations. With a time difference of about 60 milliseconds between the presentations, the two black frames fuse perfectly, and the observer sees, inside the fused frames, the stripes going in the direction of those in the square presented last. The eye which saw the stripes first seems to be completely eliminated. By reversing the direction of rotation (Fig. 2A), the experimenter can reverse the direction of the stripes. If the fusion of the frame is well adjusted in the stereoscopic viewer, the effect is quite surprising and easy to repeat. In our experiment the square was 2 centimeters on a side and was viewed from a distance of 30 centimeters. Observers who are trained to fuse images of the two eyes do not need a stereoscopic viewer for this experiment; isolating the field of view of each eye by placing a black paper between the two eyes is sufficient. The rotating disk was 10 centimeters before the eyes. The stripes were drawn in black on translucent plastic and homogeneously illuminated from the back.

The backward inhibition represented in Fig. 2B is well known and demonstrates especially well the way in which contours influence each other. If, first, in place of the stripes in the frame a large black dot is presented to one eye and later a small black dot surrounded by a white surface is presented to that eye, the white surface around the small black dot can produce a white ring surrounded by a gray ring as a remaining image of the large black dot. This indicates that the white surface around the small black dot that was presented later is able to dominate, to a certain degree, the brightness pattern. The inhibition around the edge of a small dot has often been described as an "edge effect." But, as is shown in Fig. 2C, if in the two frames the luminance fades out in opposite directions from the center, we still do not see, when there is a delay between presentations to the two eyes, a homogeneous gray surface inside the frame, as a result of stereoscopic fusion. Maximum brightness is seen on the same side as the maximum luminance in the image presented second.

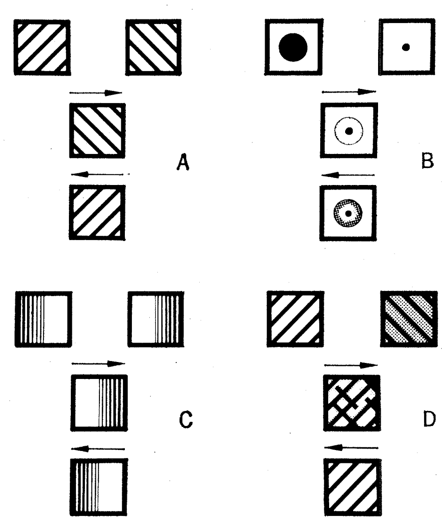


Fig. 2. The principle of backward inhibition in vision. (A) If the two top frames are presented to the two eyes simultaneously, they are fused and produce one or the other of the sensations shown in the middle and bottom frame. It is possible to switch the observer's sensation from one diagonal pattern to the other by introducing an interval of about 60 milliseconds between presentation of the two frames. This is accomplished by placing a disk with a 3-millimeter slit between the observer's eyes and the frames, rotating the disk, and changing the direction of rotation. (B) Similar phenomena can be obtained with a large dot and a small dot (see text), and also (C) when no edges are involved but only a slowly increasing brightness pattern (see text). As A, B, and C indicate, in vision the second stimulus can completely inhibit the first. (D) This is the case even if the strength of the second stimulus is reduced by a density filter of 2.0. It is not the case with a density filter of 2.3.

We can go even farther, placing a milky plastic, or half of a Ping-Pong ball, before each eye and flashing a different color before each eye. In this case we have a homogeneous illumination of the whole retina, and no edges are seen. Even in this case with binocular vision there was no fusion of red and green to a gray; rather, the color last presented appeared just as bright as if it alone had been presented.

If we use the pattern shown in Fig. 2A, but cover the right-hand frame with a gray density filter of 2.0, which reduces the luminance ten times, we can still see the stripes when the slit is rotated from left to right. This indicates that, even when the luminance of the second stimulus is reduced by a factor of 10, the second stimulus can still inhibit the effect of the stimulus presented 60 milliseconds earlier. However, with a density filter of 2.3, for most observers the backward inhibition is partial, as is shown in Fig. 2D for left-to-right movement of the slit. Most stripes are seen as intermingled, and only for a movement from right to left is the pattern of the darker frame completely inhibited. This was to have been expected. The strength of the density filter with which intermingling occurs depends on many variables—on the luminance of the white stripes inside the frame, on the luminance of the surrounding area, on the time difference between the two exposures, and also on some individual differences. In the case of our experiments the luminance of the white stripes and of the surrounding area was 5.4 millilamberts, and the eye was light-adapted to this luminance.

The question arose, Does backward inhibition on one section of the retina involve the whole retina or only the particular portions of it? To test this we duplicated the two frames of Fig. 2A, so that there were, in all, four frames. We placed the two with stripes tilted in the same direction in front of the upper half of the retina and the two with oppositely tilted stripes in front of the lower half of the retina. By using two rotating disks with slits and rotating them in opposite directions, we obtain in the upper and lower half of the eye an opposite inhibition. It is always the stimulus that is presented second that dominates.

Many experiments were performed to determine what time difference would result in an optimum backward inhibition. Under the conditions described, it was found that 60 milliseconds ± 30 percent was the value that most observers considered to be optimum. In general, if the delay is longer than 120 milliseconds, two separate sensations are produced, which can be distinguished. For shorter delays there is a combination of the two patterns.

Due to the simplicity of the equipment, the experiments mentioned were performed stereoscopically, with both eyes, but when a tachistoscope was used and both stimuli were presented to one eye only, the same phenomena were obtained.

Backward Inhibition in Hearing

Backward inhibition in hearing is well known and easy to demonstrate for bursts of tone or noise if they are presented to both ears by earphones. In such experiments, instead of using disks with slits, we used rotating disks to each of which two contacts had been fixed to present tone bursts to the two ears, with a delay between the bursts. Reversal of the direction of rotation of the disk easily demonstrates backward inhibition similar to that found for vision. (The literature on this subject is given in references *16* to *18*.) In the 1960's, Samoilova (*17*) was the main investigator of backward inhibition; recently Elliott (*18*) has made more expansive studies in this field. Backward inhibition in hearing can be achieved monaurally or binaurally, and the results are about the same in the two cases. The magnitude of the inhibition depends to a very large extent on the length of the delay, the loudness of the stimuli, the difference in the loudnesses of the two stimuli, and the frequency range involved. Generally speaking, it is found that a time difference of 60 milliseconds is effective in hearing as well as in vision.

Inhibitory phenomena observed by means of earphones differ in many ways from the inhibitions occurring in room acoustics. In room acoustics we have a three-dimensional sound field and we always have forward inhibition of the 1-millisecond type, producing localization of the sound source, combined with backward inhibition of the 60-millisecond type. Only in very rare cases do we have pure backward inhibition rather than a combination of forward and backward inhibitions.

Therefore, to simulate room acoustics we have to use loudspeakers. As is shown in Fig. 3, we used one loudspeaker (No. 1) to simulate the original sound source in the concert hall and a circle of loudspeakers (Nos. 2) to simulate the reflections from the walls. All the loudspeakers in the circle had exactly the same phase, and the delay relative to loudspeaker No. 1 was the same for all of them. In further research, obviously, the small delays between the arrival times of sounds from the various loudspeakers in the circle and any small changes that may occur in their sound output must be investigated. In our experiments the circle had a radius of 60 centimeters and was formed by 12 loudspeakers of sequential serial numbers. The loudspeakers were mounted with wires on a ring, so there were only small reflections from the mounting. Bursts of tone and noise of 35-millisecond duration were used, and the time difference between the arrival of sound from loudspeaker No. 1 and from the loudspeakers in the ring was 60 milliseconds.

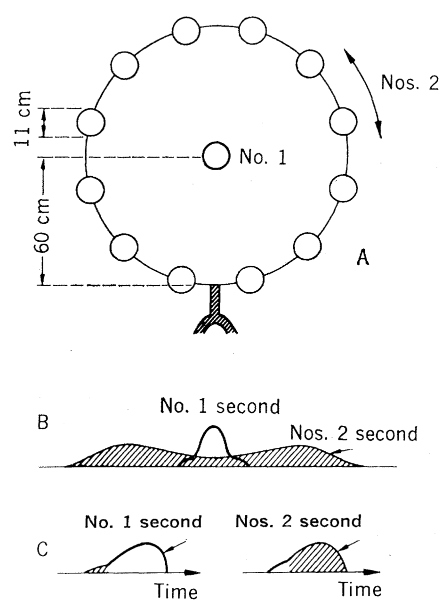


Fig. 3. (A) A central loudspeaker (No. 1) and a ring of loudspeakers (Nos. 2) are used in combination, with an interval of 60 milliseconds between arrival of the sound of speakers 2 and 1, or vice versa. (B) If the central speaker is presented second, this inhibits to a very large degree the sound of the speakers in the ring, and the extension of the sound image around the central speaker is reduced. If the speakers in the ring are presented second, they almost completely inhibit the sound of the central speaker and we have an apparent extension of a sound image, represented by the shaded area in B. (C) Diagram showing that the stimulus presented second accounts for a longer time interval in the perception than the stimulus presented first does.

The observer, who stood 2.5 meters outside and in front of the circle, was first asked to describe the local sound density of loudspeaker No. 1 and to make a drawing of the way the sound faded at the sides. To make such a drawing of the local sound density, a certain amount of training is needed. One can readily realize that a click has a very small area of extension and a very high local loudness density. Thus, in a drawing in which the loudness density is represented by heights on the ordinate, we have a curve that is narrow and high. A 1000-hertz tone burst, on the other hand, will have a much greater extension than a click, and, for the same overall loudness, a much lower loudness density. Low-frequency sounds in general have a much greater extension and lower density than noise bursts. In studies of vision, observers can be trained well for this type of experiment. We can illuminate a grayish surface with a flashlight and ask the observer to describe, with a sketch, the way the brightness fades at the edges of the illuminated spot. Later we compare the observer's brightness drawings with the actual luminance measurements for different areas of the screen. By changing the absolute value of the luminance and the extension of the illuminated spot, it is easy to train an observer to make reproducible observations.

Figure 3B shows schematically how the local loudness density is distributed if the sound from speaker No. 1 is presented 60 milliseconds after the equally loud sound from speakers in the ring. For this situation the extension of the sound source seems to be quite small and the sound seems to come mainly from speaker No. 1 (unshaded area). But if we present the sound from the speakers in the ring second, the sound image has a large extension (Fig. 3B, shaded area). In this case the effect of lateral inhibition is so strong that (Fig. 3C, right) the sound from speaker No. 1 is hardly recognized, except in the beginning, when there is a hint that it is present; later the sound from speakers in the ring account for the whole sensation. On the other hand if the sound from speaker No. 1 is presented second, the sound from the speakers in the ring seems to disappear (Fig. 3C, left).

Since, in room acoustics, the echoes from the walls arrive later than the direct sound, it is to be expected that backward inhibition plays an important role and that it can reduce the loudness of the original sound source, as Fig. 3C, right, indicates.

The curves of Fig. 3, B and C, represent mean values for three observers for a loudness level of 90 decibels and a pure tone of 1500-hertz frequency for the speakers in the ring and of 1000-hertz frequency for speaker No. 1. The measurements were made in a room that was lined with absorptive material, to keep reflections from wall and ceiling to a minimum. The loudness-density distribution represented by the ordinate in Fig. 3B is projected to the plane of the speakers in the ring—the plane in which speaker No. 1 is also located. When asked to sketch the time pattern of Fig. 3C, the observer was given a certain length (representing duration of the sound) and asked to draw within this length the time dominated by sound from speaker No. 1 and that dominated by sound from the speakers in the ring.

The relative apparent lengths of the sound presented first and the sound presented second (Fig. 3C) are influenced by many factors. If one of the tones is clipped so as to produce square waves, adjusted to the earlier loudness, and presented second, a further increase in dominance is obtained. A frequency-dependent absorption by the wall can play an important role in determining the quality of a concert hall.

Varying the time difference between 30 and 120 milliseconds indicated that 60 milliseconds is an effective time interval for backward inhibition. In general, with an interval of 60 milliseconds, the tone presented second shortens the time of the whole sound pattern more than it does when the interval is shorter or longer than 60 milliseconds. A decrease in the apparent length of the inhibited tone burst is always accompanied by a decrease in its loudness.

The loudspeakers were placed as shown in Fig. 3 to represent the bowl of a concert hall, with a sound source and nearby reflecting walls, represented by the ring of speakers. But in many of our experiments speaker No. 1 was placed outside the ring of speakers. If speaker No. 1 was moved laterally in the horizontal plane, the position of the loudness density curve for speaker No. 1 moved correspondingly.

In the experiment of Fig. 4 the speakers were placed so as to simulate the diffused reflections from (A) the back wall and (C) the ceiling of a room. The dimensions of the ring of speakers was the same as in the earlier experiments, but the observer was between the two sound sources, 2.5 meters from speaker No. 1 and 2.5 meters from the ring of speakers. The local loudness density for different distances is illustrated in Fig. 4A. When the sound from speaker No. 1 is presented second, the whole sound image is in the neighborhood of that speaker; the effect of the speakers in the ring is practically negligible. But if the sound from the speakers in the ring is presented second (a situation which corresponds to the reflection of sound from the back wall in a concert hall), the sound image is pulled away from the original sound source and comes closer to the observer. This effect seems to be optimal when the delay between the sound from the single speaker and that from the ring speakers is about 60 milliseconds. If we imitate the reflections from the ceiling of the concert hall, again (Fig. 4C) the sound image is drawn away from the initial sound source (the single speaker) to the ring speakers, whose sounds represent sounds reflected from the ceiling. In all these cases, for the observer the loudness of the sound from the single speaker was the same as the loudness of the sound from the ring speakers when the two sounds were presented separately. Again, the frequencies of the tone for the single speaker and the ring speakers were 1000 and 1500 hertz, respectively. This type of shift in the localization of sound makes the sound image produced by a single singer or violinist in a concert hall much larger than the sound image we observe in a chamber without echoes, or outdoors where there are no reflections from walls.

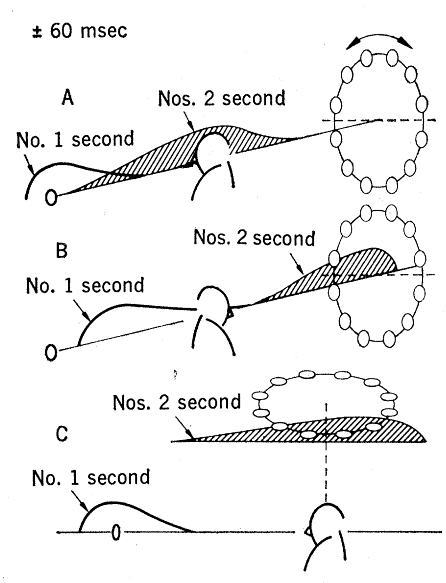


Fig. 4. (A) Loudspeaker No. 1 is in front of the observer and the ring of speakers (Nos. 2) is behind him. If speaker No. 1 is presented second, it eliminates the loudness sensation produced by the speakers in the ring. But if the speakers in the ring are presented second, then the loudness area (shaded area) shifts to the vicinity of the observer. (B) The observer faces the ring of speakers; otherwise the experimental conditions are the same as in A. (C) The ring of speakers is above the head of the observer; otherwise the experimental conditions are the same as in A.

The time pattern of loudness is, in the cases of Fig. 4, the same as that shown in Fig. 3C. When sound from the ring speakers behind the observer reaches him 60 milliseconds later than the sound from the single speaker, the second stimulus reduces the loudness of the first, and shortens its duration as shown in Fig. 3C. But it must be pointed out that, in the three-dimensional situation, where forward inhibition is combined with backward inhibition, in the case of sound the first presentation is not completely suppressed, as it is in vision.

Very similar results were obtained when the frequency of both tones was 1000 hertz, but in one case the waves were sinusoidal and in the other case square waves, so that the tones could be discriminated.

Backward Inhibition in Concert Halls

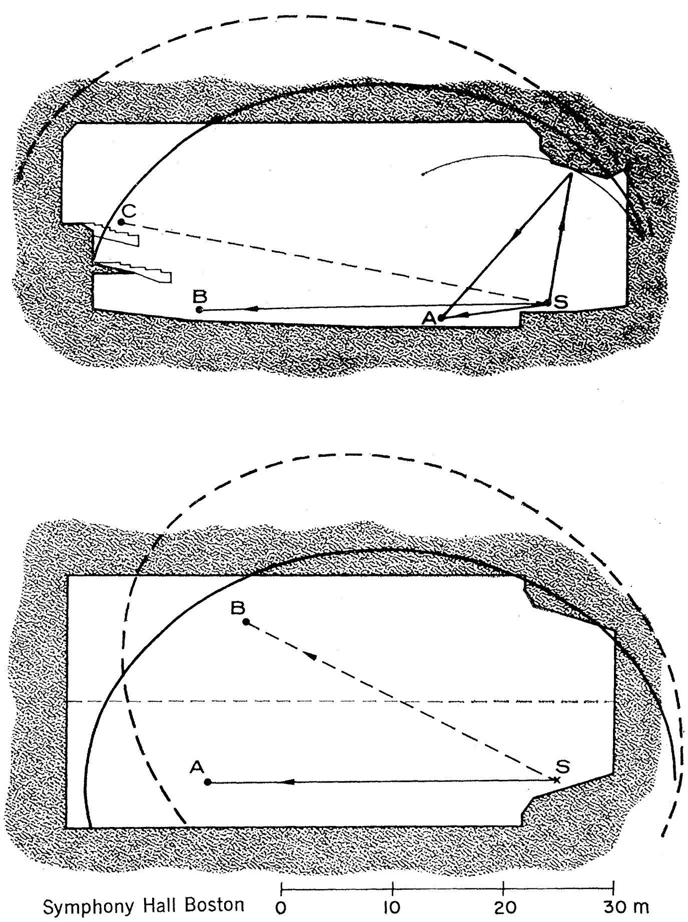
In a concert hall there are basically three different types of sounds which are transmitted from the performer to the listener: the direct sound, the reflected sound, and the reverberant sound, which is the integration of all the back-and-forth reflections between the walls and ceiling and the audience. The physical part of this sound transmission has recently been very successfully investigated, and the result has been improvement in transmission from the performer to the listener. The progress was mainly achieved by taking onset and offset phenomena into consideration, as Jordan (*20*) pointed out. For discussion of this latest development in architectural acoustics, see (*19*).

But now that the physical problem seems to be solved, room acoustics is becoming more and more a psychological problem and, to a certain degree, a problem of inhibition. All five known types of inhibition play a role in judgments of the quality of a concert hall. Apparently backward inhibition is a major factor.

Knowing that a difference of 60 milliseconds between the arrival times of direct sound and the first reflected sound can reduce the direct sound that emanates from the performer, we have determined the difference between these two arrival times for a listener in two different concert halls. Figure 5, top, is a longitudinal section of Symphony Hall in Boston. If S is the sound source and B is an observer, the solid line SB represents the direct sound for that observer. Sixty milliseconds corresponds to a sound-propagation distance of 20 meters; the solid ellipse with focal points S and B gives the locus of possible reflecting surfaces from which the first reflection would arrive at B 60 milliseconds later than the direct sound. As may be seen, the actual ceiling (shaded area) might produce many such reflections.

Some observers are of the opinion that acoustics in the upper balcony of Symphony Hall are much better than those on the ground floor. In Fig. 5, top, the direct sound to an observer seated in the upper balcony is represented by the dashed line SC, and the locus of surfaces from which the first reflection would arrive at C 60 milliseconds later than the direct sound is given by the dashed ellipse. As may be seen, a listener in the balcony does not receive reflections of 60-millisecond delay time from the ceiling. The reflections that reach him are those that are delayed a much shorter time. This difference can account for the relatively smaller amount of backward inhibition for an observer in the balcony.

Figure 5, bottom, shows schematically a bird's-eye view of the ground floor of Symphony Hall. If the listener is at A, and if the sound sources on the stage are at S, he will receive many reflections of 60-millisecond delay time from the opposite wall. This can explain the observation that a listener sitting at one side of the concert hall sometimes finds it difficult to hear an orchestral instrument which is on the same side of the hall. An amateur cellist far back in the audience on the ground floor, supposing that the sound should be transmitted easily along the



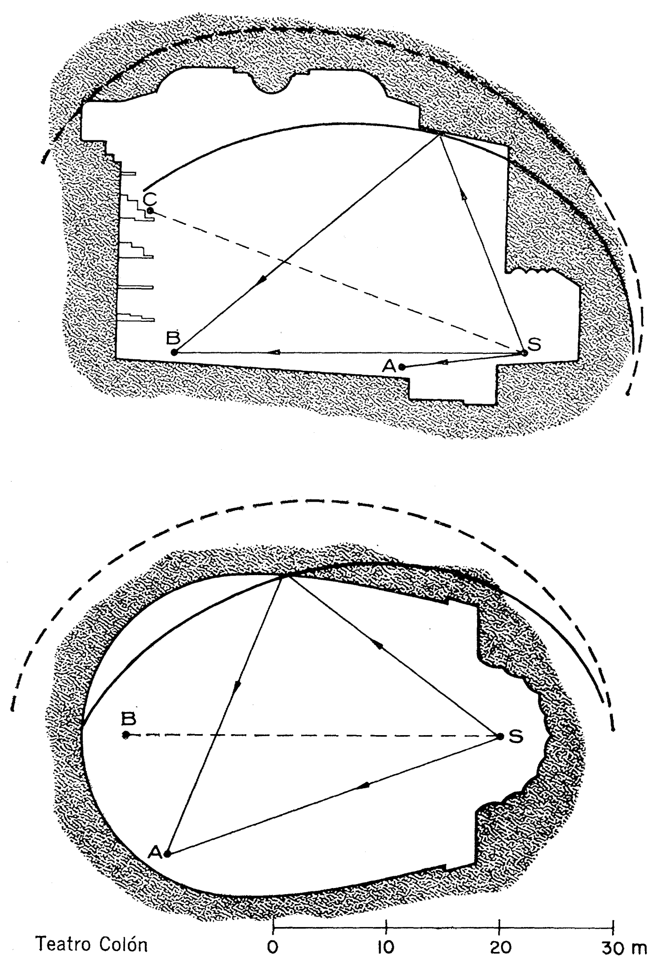


Fig. 5 (left). Longitudinal section of Symphony Hall, Boston. (Top) B is a listener on the ground floor of the concert hall, and S is the sound source. The solid ellipse shows the locus of all the points for which the reflected sound would arrive at B about 60 milliseconds later than the directly transmitted sound (SB). These points seem to coincide with the surface of the ceiling, so backward inhibition is expected in this situation. C is a listener seated in the top balcony. The dashed ellipse (corresponding to the solid ellipse for B) indicates that, for listener C, backward inhibition is of less importance than it is for listener B. (Bottom) Schematic bird's-eye view of Symphony Hall, showing that the degree of backward inhibition for listeners A and B, both seated on the ground floor, can be quite different because, for A, the interval between the arrival of direct sound and of sound reflected from the side walls is 60 milliseconds, and this is not the case for B [from Beranek (*4*)]. Fig. 6 (right). Diagrams of the Colón Opera House, Buenos Aires, corresponding to those of Fig. 5 for Symphony Hall, Boston. The Colón Opera House is well known for its good acoustics, especially for singers. Here again (top) backward inhibition is of less importance for a listener seated in the balcony than for one seated on the ground floor. (Bottom) Backward inhibition is of more importance for a listener near the side wall of the theater than for one in a central position.

side wall, may complain when he does not hear the cello on his side of the hall. At the same time, a listener may hear an instrument in the orchestra very well if he and the performer are near opposite side walls of the concert hall. The dashed ellipse in Fig. 5, bottom, indicates that a listener at *B* in Boston's Symphony Hall would receive very few reflections of 60-millisecond delay time.

Similar drawings were made for the Colón Opera House in Buenos Aires. The diagram of Fig. 6, top, is very different from the corresponding diagram for Symphony Hall in Boston. Again, the acoustics seem to be less good for listeners in seats on the main floor than for listeners in the upper balcony—for example, at *C*, where there seems to be little backward inhibition in the 60-millisecond delay range for sounds made by a singer on the stage. Since in this auditorium the orchestra is in the pit, the direct sound from the orchestra is small and the singer's voice is dominant—a characteristic for which this opera house is well known. Figure 6, bottom—a schematic bird's-eye view of the ground floor—shows the expected difference in the amounts of backward inhibition at locations *A* and *B*.

In judging the importance of direct sound relative to reflected sound, we have to take into consideration the fact that, because of its longer path, the reflected sound is, in general, weaker, even under the best reflecting conditions. This difference in the strength of the sound is relatively small for listeners in the back seats, since an increase of 20 meters in the pathway is a small percentage of the increase in path length. This is not the case for listeners in seats close to the sound source. In those seats, as Fig. 5, top, indicates for a seat at *A*, the pathway of the reflected sound is 2½ times the length of the pathway of the direct sound. In this case the strength of the sound will be decreased by a factor of about 6. This will naturally decrease the role of backward inhibition.

In the preceding description only backward inhibition for the listener has been considered, but it should not be forgotten that, in a good concert hall, one of the second main requirements is that the performer receive from the concert hall an acoustic feedback which enables him to judge the quality of his performance. It is very difficult for a performer to play in a concert hall that has too large a damping effect because, as they say, the hall does not respond. In most concert halls the delay between the production of sound by the performer and its reflection back to him from the walls and the back of the hall is so long that backward inhibition does not play a role. It is different in small rooms.

Outlook

Since the introduction of a large variety of sound-absorbing materials and the increase in our knowledge of sound pathways and reverberation in concert halls, the physical part of the transmission of sound from the performer to the listener seems to be under control. If the size of concert halls has to be increased further, loudspeakers can be added, and, as the Hall of Congress in Moscow demonstrates, the quality of the sound can be extremely good.

The interesting thing is that seemingly we do not want to have perfect sound transmission. There would be no difficulty today in developing a violin with an electric loudspeaker instead of a wooden sounding board. But for some reason we definitely prefer a Stradivarius to an electric violin. The same thing seems to hold true for concert halls. We expect our concert hall to have a certain personality, just as we expect this of a conductor or a well-known orchestra or a violin. There are many music lovers who have traveled around the world and who remember well how a performance sounded in a particular concert hall. An opera singer in the Colón is something absolutely different from the same singer in the Vienna Opera House. Nobody seems to want standardization in this field, even when we take into account the fact that, by introducing artificial reverberation, we could adjust the reverberation to the needs of the musical piece and even change it during the performance. For an engineer, a hall with such a capability would seem to be an improvement over an auditorium of fixed acoustics. The attitude of concert-goers might change if, through electronics, we could make an ordinary violin sound like a Stradivarius.

Under these circumstances, room acoustics becomes a psychological problem in the area of hearing. We are only in the early stages of this development, and at this time it is even difficult to determine whether a direct sound is more important than the first reflected sound, or what ratio we would like to have for the loudness of these two sounds.

With development of the computer, there are new experimental possibilities, as Schroeder (*21*) has pointed out, for creating artificial echoes and reverberations. Another improvement can easily be made by describing the concert halls of known good quality in a more precise way, with a more or less standardized vocabulary, which does not now exist in the field of music. To become more definitive, the vocabulary of the musician has to approach that for the physical properties of sound.

The measuring techniques in acoustics are still not appropriate for measuring changes like onset and offset phenomena, just as in vision it is only recently that equipment has been developed to measure the contours of a picture. Unfortunately, the nervous system reacts mainly to changes. The study of room acoustics will contribute to the development of physical instruments that will come closer to measuring the phenomena that are important to the nervous system, rather than the phenomena that are easily measured by a physicist. Unfortunately we have no equipment for directly measuring inhibition, especially in situations where inhibition consists of a combination of forward and backward inhibition. The two types seem to oppose each other to a certain degree. We can investigate that opposition by judging the acoustics of a concert hall, not under normal conditions, but with one ear stopped. With monaural hearing the grading of a hall is, in general, different from the grading done under normal conditions, because, with monaural hearing, forward inhibition is decreased. The interaction between forward and backward inhibition is one of the psychological problems of the future in the field of room acoustics.

References and Notes

1. M. Vitruvius, *De Architectura.*
2. W. C. Sabine, *Amer. Archit.* **104**, 257 (1913).
3. V. O. Knudsen, *Architectural Acoustics* (Wiley, New York, 1932); ——— and C. M. Harris, *Acoustical Designing in Architecture* (Wiley, New York, 1962).
4. L. L. Beranek, *Music, Acoustics and Architecture* (Wiley, New York, 1962).
5. E. M. von Hornbostel and M. Wertheimer, *Sitzungsber. Akad. Wiss. Berlin* **15**, 388 (1920).
6. E. M. von Hornbostel, *Psychol. Forsch.* **4**, 64 (1923); *Jahresber. Phys. Exp. Pharmakol.* **9**, 753 (1928); *Handbuch der normalen und pathologischen Physiologie* (1926), vol. 11, p. 602.
7. S. Exner, *Sitzungsber. Wien. Akad. Wiss.* **58**, 601 (1868).

8. N. Bant, *Pflügers Arch. Gesamte Physiol. Menschen Tiere* **4**, 325 (1871).
9. M. Monjé, *Z. Biol.* **87**, 23 (1928).
10. D. H. Raab, *Psychol. Bull.* **60**, 118 (1963).
11. F. Ratliff, *Mach Bands: Quantitative Studies on Neural Networks in the Retina* (Holden-Day, San Francisco, 1965); G. von Békésy, *Sensory Inhibition* (Princeton Univ. Press, Princeton, N.J., 1967).
12. A. Lehmann, *Die Körperlichen Äusserungen psychischer Zustände* (1905).
13. G. von Békésy, *Experiments in Hearing* (McGraw-Hill, New York, 1960).
14. ———, *Amer. Psychol.* **23**, 707 (1969).

R. Stigler, *Pflügers Arch. Gesamte Physiol. Menschen Tiere* **134**, 365 (1910); G. A. Fry, *Amer. J. Physiol.* **108**, 701 (193 B. H. Crawford, *Proc. Roy. Soc. Ser. B* **134**, 283 (1947); M. Alpern, *J. Opt. Soc. Amer.* **43**, 648 (1953); E. Averbach and A. S. Coriell, *Bell System Tech. J.* **40**, 309 (1961); P. A. Kolers, *Vision Res.* **2**, 277 (1962).
16. R. L. Miller, *J. Acoust. Soc. Amer.* **19**, 798 (194 I. J. Hirsh, *ibid.* **31**, 759 (1959); J. M. Pickett, *ibid.*, p. 1613; D. H. Raab, *ibid.* **33**, 137 (1961).
17. I. K. Samoilova, *Biofizika* **1**, 79 (1956); *Probl. Fiziol. Akust.* **4**, 38 (1959); *Biophysics* **4**, 44 (1959).
18. L. L. Elliott, *J. Acoust. Soc. Amer.* **34**, 1116 (1962); *ibid.*, p. 1108.
19. R. Thiele, *Acustica* **3**, 291 (1953); W. Furrer, *Raum- und Bauakustik für Architekten* (Birkhäuser, Basel, 1956); V. L. Jordan, *Proc. Int. Congr. Acoust., 3rd*; M. R. Schroeder, *J. Acoust. Soc. Amer.* **40**, 549 (1966); *Science* **151**, 1355 (1966).
20. V. L. Jordan, *Appl. Acoust.* **1**, 29, 152 (1968); *ibid.* **2**, 59 (1969).
21. M. R. Schroeder, *J. Acoust. Soc. Amer.* **47**, 424 (1970).
22. Supported by NSF grant GB-5768 and PHS grant NS-06890 from the Institute of Neurological Diseases and Blindness.

Lake Erie: Pollution Abatement, Then What?

Long-term eutrophication may be utilized to advantage.

Jerry H. Hubschman

Some time ago, while reviewing the status of research on Lake Erie, a well-known biologist startled and amused his audience of ecologists by suggesting that the western end of the lake be given up as lost. He proposed that a dam be built across the island region from Cedar Point to Point Pelee, effectively separating the western basin from the rest of the lake. This confined water mass would constitute a sewage lagoon for the waters of the Detroit, Maumee, Raisin, and Portage rivers. Retention time would allow aerobic degradation to take place before the overflow would enter the lake proper. His message was clear to all those familiar with the plight of Lake Erie. Something had to be done before this valuable aquatic resource was polluted beyond the point of possible recovery. Traditionally the attitude has prevailed that "the answer to pollution is dilution." Considerable effort has been directed at developing schemes to increase the handling capacity of receiving waterways. In short, these efforts were directed at the symptoms rather than the cause. The cause was seldom attacked because waste disposal has always been considered a legitimate water use. This attitude will, I hope, diminish in time, but old ideas die hard.

The author is professor of biology at Wright State University, Dayton, Ohio 45431.

Eutrophication Will Continue

At this point in time, circumstances may well support the symptomatic approach. In his treatment of our massive environmental problems, Bernarde (*1*) suggests that

> The present state of development of our technological society makes it mandatory that we accept a certain degree of pollution. We are still far from developing new methods of liquid-waste disposal that will make dumping in rivers obsolete. The fact is that industry and residential communities alike would be forced to shut down if unified public opinion demanded pollution-free waterways. It is, therefore, in the best interests of the community to support research investigations aimed at discovering the degree of waste a stream can adequately tolerate without the initiation of noisome conditions. Decisions as to what constitute a tolerable degree of pollution must be reached after considering the water's natural purification capacity and the purpose for which it is to be used.

Although I do not subscribe to a fatalistic view of pollution and certainly not to the concept of waste disposal as a legitimate water use, certain facts remain. Even if all flagrant pollution violations were eliminated tomorrow, continuous changes in water quality might be expected in Lake Erie. Public pressure may achieve enough momentum to result in truly adequate treatment of municipal sewage. Similar forces might eventually be effective in eliminating or reducing toxic industrial wastes, but we would still be faced with the continuing phenomenon of eutrophication. Surface runoff will continue to be a major contributor to the process of eutrophication. The leaching of agricultural fertilizer and siltation resulting from natural erosion are potent contributors to this process (*2*).

Eutrophication is clearly a natural process. However, the alarming rate of increase, related to man's activity in the Lake Erie watershed, has been the subject of much concern and has resulted in considerable documentation and discussion (*3*). There is still a tremendous task ahead both in identifying the cause and effect relationships of eutrophication and in developing new corrective measures. Model systems for the utilization of waste water for agricultural production have been proposed and can be expected to achieve functional status (*4*). Research and development of improved methods of waste disposal and reclamation must continue. With the elimination of the source of pollution, the answer to many other problems will fall into place. If anything can be gained by our experience with the accelerated eutrophication of Lake Erie, it is that we must expand our efforts to study the lake as a system of complex interrelationships. The lessons learned at this time can provide the informational basis for action when we face similar massive problems in the future.

The sources of municipal sewage and toxic industrial wastes have been identified, and, if given proper priority, corrective measures will be developed (*5*). Erosion, siltation, and agricultural runoff present much more diffuse targets for correction, since there are obvious difficulties in developing and enforcing effective legislation in these areas. Natural forces and agricultural