The Sound of Space Design

An invited lecture to Interior Design class at Oregon State College in 2012

The goal of this paper is to help interior designers open their eyes to the sound of the space they are designing.   We can't see sound but we can begin to hear it. Normally sound is taken as a given, something that just is, has been and always just be there. True but, sound has qualities which can be adjusted to better suit the designated use of the space being designed. Every architectural design has a voice, how sound in the space responds to the geometry and surfaces of that space.   As students of designing space, one aspect of space design is sound design, the sound of the space you and your clients will be in. What your client wants is a space that sounds as good as it looks, a sound which supports the activities of the occupants of the space.

Echoes and Sound Fusion

We have two eyes and we have two ears. With two eyes we can see and focus on things that are before our eyes, in front of us. But with two ears we can hear and focus on things that are anywhere around us. We can eavesdrop on a conversation that is out of sight, behind us. We can perceive where a sound is coming from regardless of where it is coming from and this is called echolocation.

Echo location works up to some point. If we stand outside in an open field, facing directly towards the side of a barn which is located some distance away and we clap our hands together one time we hear the clap loudly and after a short time we hear an echo off the side of the barn. If we then begin walking towards the barn, stopping every once in a while, to clap and listen we notice two things changing. The closer to the barn we get, the louder the echo becomes and the sooner it arrives. Sound travels about 1120 feet per second, or 1 $1/8^{th}$ foot per millisecond.

As we get near the barn, about 25 feet away, something else changes, we no longer hear a distinct clap and separate echo, we hear some sort of a smeared sound. One more step towards the barn wall and we lose all contact with the echo. As we step even closer, the "echo" has to be getting even louder but we still can't hear the echo. The direct sound, from the clap to our ears, and the reflection have become one sound, they have fused together.   But we also notice something new, the sound of the clap has become louder and the closer to the wall we get the louder the sound of the clap becomes.

Sound fusion occurs when two or more distinct sonic events, each of which sounds just like the other, arrive at our ears within our sonic reaction time, about 1/30 second or 35ms.   Same as for vision, where separate but otherwise very similar frames fuse together into a seemingly continuous visual event, a moving picture. Two very different separate sonic events which take place close in time to each other do not fuse together; they remain two separate sonic events, just like two very different photographs.

Sound Fusion in Small Rooms

What is the size of a room? Acoustically there are large rooms and small rooms. Large rooms are like a gymnasium and small rooms are like a classroom. In large rooms most of the reflections arrive outside the echo detection threshold, 50 ms or 1/20 sec. In small rooms most of the reflections arrive well inside the echo detection threshold, inside the sound fusion time period, 1/30 second.

For the most part, we live and work inside of acoustically small rooms. This means what we call "indoor sound" is mostly a direct sound followed by 25 or so early reflections of that same sound, which fuse into the direct sound, making it seem louder and giving it some coloration. These early reflections bounce off the surfaces of the small room, surfaces which you have just decorated. Oh oh….What if your decorations make some of these reflections sonically weird. Does that weirdness appear in our perception of the direct sound? By all means available, yes. And so now you can begin to see the connection between the materials and surfaces you use inside a room and how sounds made in the room…. sound.

Now that we know what we are going to talk about, we can begin to talk about it.

Let's explore room acoustics for a little while. Remember, the sound of my voice is a sound fusion of the direct signal that goes from me to you plus some 100 early sound fusing reflections. Since each of you is sitting in a different location, the direct and the set of early reflections are different for each of you. As I move around, the set of signals each of you get change. Your mind averages out all the different variations being delivered into one basic sound. Like we do visually. My face changes a lot when I speak. If you freeze frame it, I would look pretty stupid most of the time but let it just run freely and well, I'm just me, and not any of those stupid looking freeze frame versions of me.

I'm going to speak to you while changing positions in the room and listen to how the sound of my voice changes even though I'm doing my very best to keep speaking the same. As I back up to a wall, my voice seems to become more bass sounding. If I go to the corner, even more. If I talk to you over a desk, I add a single strong early reflection that follows the direct signal by only a few milliseconds and my voice get particularly loud compared to no desk. As I move around the direct + early reflection sound fusion package changes. If I stood still and talked while you moved around the room, the same effect will take place. I'll stay here and I need some volunteers, one for each corner and a couple against each wall. Walk slowly and keep quiet and listen carefully.

Listening to the Sound of Sound

Speaking of listening carefully, imagine someone who is intently listening. What do they look like? Not as an individual but their posture. What are they doing while listening intently. They are not dancing nor are they looking around for the sound. They are pretty still or slightly swaying. They are staring up or down or ahead but looking at nothing. Often they will touch or hold their face. They pretty much look like they are in a trance. What they are doing is trying to eliminate other sensory inputs which are usually overpowering our ability to listen. We are always hearing sound but to listen deeply, we have to shut down inputs from all other senses, in particular, the visual sense.

I had an interesting experience when I was a lot younger and in grad school for the first time, finishing up my thesis in acoustics. I woke up in the middle of the night and rubbed my eyes. Despite washing my hands the glue was still on my hands and my eyes caught no fire. Went to ER and after getting pain medicine and bandaged up the doc said that I might or might not see after the bandages come off in 2 weeks. I had put a lot of chemicals in my eye and could have scarred the lens. Only after the bandages come off would we know….prepare for the worst. With that, I was sent home.

I was led around for a while and fumbled around by myself but trying to memorize where everything was located seemed impossible. But within hours something new was happening. I began hearing where I was. I could hear when I was walking towards a wall. I could hear where the doorway was located. I could hear curbs, trees, fences and lots of things. The world was rapidly becoming clear again in a dark and murky sort of way. I had lost my visual sight but was connecting with my hearing sight. Little did I know at that time, I was peeking into what would become the body of my life's work. After 2 weeks, the bandages came off and with my sight restored I quickly forgot all about how to live in the dark. It took another 15 years before I realized I had become completely involved in helping people see sound and I've been lucky enough to have been able to continue doing so for the last 25 years, now. Let's return to the present, the sound of the space we are in.

The Sound of Space

A dark sounding space is not created by black paint. It is created when there are no early reflections. It is also a very quiet. A Victorian parlor with lots of overstuffed fabric covered chairs, layers of huge heavy curtains, Persian carpets on the floors and Polar bear heads on the walls tends to sound dark.

A bright sounding space is not created by yellow paint. It is created by lots of early reflections. It is also a very noisy space. A small enclosed kitchen with lots of glass windows, hard shiny painted surfaces, linoleum or worse marble floor and lots of hanging pots and pans. Spick and span, super cleanable, a room full of mechanical clutter and sonic clatter.

When we first walk into our prospective new apartment, there are no furnishings, no curtains, no chairs, nothing but freshly painted walls and ceiling and maybe a wall-to-wall carpet in some rooms and no carpet but wood floors in others. These are small, empty reverberant rooms, which makes for a hollow sounding space, lots of repetitive early reflections.

When we walk into an empty gym we again enter an empty space, no furnishings, nothing bur hard wall surfaces. This space has almost no early reflections but still lots of reverberation. It has an echo reverberant kind of sound.

A modern tendency in interior design leans towards the minimalistic, lint and dust free clean-ability. Wall to wall shag carpets with all those awful dust mites is out and wall to wall parquet flooring is in. This means bright and hollow sounding rooms. How do we change out the sound of a room? How do we know what the new sound of the room should sound like?

We change the sound of a small room by adding sound absorption and/or sound diffusion. Sound diffusion scatters sound and breaks up the repetitiveness quality of a rectangular room. It takes the hollowness character of the room out. It leaves a smooth sounding room that is however still too bright. Sound absorption quiets the room. Some blend of sound diffusion and sound absorption will get the room sounding right.

What diffuses or scatters sound? Sound reflecting objects, like lampshades, vinyl surfaced chairs, pictures hanging at an angle on the wall. Or, add architectural features that make the walls and ceilings irregular. Add a few wall pilasters and a coffered ceiling, a door that is usually left swung in and you have greatly removed the hollowness of the room.

What absorbs sound? Thick deep breathable fabrics or objects. You can always check out if an object is diffuse or absorptive. Hole it close to your face and say something like “check, check, testing one, two, three…”   If you hear yourself back in your face, it’s reflective. If you hear quietness instead, you have a sound absorbing surface. Go to a carpet shop and “check out” at rug samples and you’ll be surprised how reflective they all are. People like carpets that do not pass liquid through into the pad. The backs of carpets are sealed watertight with a plastic sheet. To keep the carpet costs low, the less thread used means less cost. But the thread is the sound absorbing element in the carpet. No thread, no absorption.

Add a coat rack to the corner of a room and create sound absorption. Add fabric covered thick cushioned chairs. If you have a slick vinyl or leather couch, add soft fabric faced cushions. Put louvers on a closet door, not only for ventilation but so sound can get into the fabric filled closet. Shelves loaded with books are very good sound absorbers. Sheer curtains do not absorb sound but thick, soft curtains do. You have access to a variety of fabrics, learn about how they sound. Cultivate the sound of the room as you cultivate its vision.

How do we know when the right balance has been reached between sound diffusion in the room and sound absorption? It’s when it sounds right, when the room does not seem to dominate one’s attention. People don’t like to listen to a room. If they notice the room, it’s wrong. A good sounding room takes no notice, is neither attractive nor distractive. It is taken for granted. In other words, you have to connect your ears to your feelings about the room and follow your intuitive lead.

Remember always that any form of distraction, particularly visual, pretty much disables your ability to hear the room. If you love a look, you might also be turning your ears off to the sonic impact due to the materials used in achieving that look.

The Sound of Privacy

Let’s look at one of the worst architectural/interior design fads in the last couple decades. It is the “great room” layout. This is where we have an open kitchen, breakfast nook, dining room and TV or family room area in a two-story cavern. Feeding into the great room are the upstairs and downstairs hallways that lead to various rooms and bedrooms. The great room was an intuitively appealing concept that does not pass the sonic livability test. Great rooms are too noisy. If no one lives in the house, everything works fine but put mom in the kitchen zone, some kids in front of the TV zone and some happy visiting upstairs and the sonic connection between zones is too strong. There is no sense of privacy. And mom can't get any peace of mind, can't think her own thoughts because she is constantly being distracted by being forced to receive too much sonic information.

What is privacy? There is a sound to privacy. It is two things, a sense of intimacy combined with a sense of distance. Intimacy comes from some but not lots of very, very early reflections which implies a small space with multiple nearby sound reflecting surfaces alternating with sound absorption. The concept of distance comes from the outside sound coming into the private space is muted, in that the higher frequencies are quieted down.

And so it goes. As you can imagine, we can go on and on, coordinating the sounds of spaces with the intended uses for those spaces. We don't have that option available to us and so, now that you know it's out there and truly part of your world, it's up to you to pursue. As you come into each space, pause and listen to it and see if you can read the appropriateness of its sound to the use of the room. If you are not too careful, some day you will find yourself walking into an empty room, clapping your hands a couple times and boldly saying "…check, check, testing one, two, three.." and listening to what the room is saying back to you, and interpreting what that means. You will have become a self-taught sound designer of space.

Another Version of Louder

If someone is having a hard time hearing they usually want the sound to be louder. There are two ways to make sound louder. One is to turn up the strength of the direct signal, where the person speaking speaks louder. The other way to make sound louder is to increase the number of early reflections heard along with the direct sound.

If we increase the strength or loudness of sound by +10 dB, the human listener perceives this increase in loudness as being a new sound that is twice as loud as before. There are two ways to make this happen. We can turn the volume of one speaker up by a factor of 10, meaning if a 1 watt speaker made a certain loudness of sound in our room a 10 watt speaker could make a sound 10 dB higher in our room. We could also get this same effect by adding ten 1 watt speakers into the room. We could lastly get loud sound by using the one 1 watt speaker and adding about 25 early reflections.

Let's say that we are designing a space where it is important for someone to hear someone else. It could be a student in the classroom or a table at a fine dining restaurant. The rules stay the same. We know we don't like people shouting at us so increasing the speaker's loudness is usually an unattractive option. We can cause the speaker's loudness to be louder by moving closer to the speaker. But we can only get so close to the speaker before we begin to feel cramped, too close together, which is also unattractive. What's left? We can simply increase the number of crystal-clear early reflections.

We are talking about communication, which is always dependent on the signal to noise ratio. If we make the signal to noise ratio larger we will achieve better, more clear communication. If we make the signal to noise ratio smaller we will reduce the ability to communicate.

To improve the signal to noise ratio we can either increase the signal strength or decrease the background noise floor to get a better signal to noise ratio. We could also do both, increase the signal strength and decrease the sound masking background noise and improve the communication capability of the space we are in.

Table Top Conversation

What if the owner of a good but noisy restaurant hired you to create a special table where his high end clients could visit comfortably during dinner without having to lean forward, cupping their ears and practically shouting to hear each other? You know you need to increase the number of early reflections around the table, so as to keep the sound from the table lingering around the table for a long time. And you also know you want to reduce the loudness of the intruding din of noise from the rest of the restaurant. And once you have mechanically dialed in the solution, you have to dress it up so it visually works.

We have a cloth tablecloth and decide to change it to a glass covered tablecloth. That makes the tabletop reflection stronger. But it also makes the tabletop reflection of the restaurant din of noise stronger so we didn’t change our signal to noise much. However, if our special table has a number of guests, their bodies do shield the tabletop from the restaurant din of noise and we do get a positive signal to noise improvement.

We notice a light bulb and tiny lamp shade over the table. We imagine we could replace this with a large convex shaped glass lampshade and increase the number of early reflections back down onto the tabletop. This does something else, it blocks some of the intrusion of the din of noise, that which is flooding down onto the table from overhead. We’ve reduced the noise floor and improved the number of early reflections.

This might be just enough of a change that the table begins to work the way the owner wants. So you try it and although it is better, you decide more is needed.

We don’t exactly want to build a private eating room around the table but we do have to continue to improve the signal to noise ratio. You dream about options, ways to do this. Basically, we want to add a set of panels around the table, with the back side of each panel absorbing the intruding restaurant noise and the front side of each panel backscattering the tabletop conversation. A set of custom folding privacy screens might work but it is too obvious, attracts too much attention. And suddenly you think of high back chairs, large high back chairs. Custom chairs with fabric and absorption on the back side and sound reflecting qualities on the front side. Maybe something like high wingback chairs, vinyl on the seating side and sound absorbing fabric covered on the back side. You try an experiment, rent some wingbacks and draping a wool blanket on the back side of each one. It works great, so you make arrangements with an upholsterer to do the modifications, and finally get to write up your invoice for consultation work and send it to the restaurant owner.

By knowing the rules and creatively applying them you can cultivate the sonic space you want. Sometimes the visual version of the space does not lead the design effort. In this case the client didn't ask for a new look, but asked for a new sound. You create the sound and then figure out how to decorate it so it looks great too.

Open Office Plan

Let's look at an open office plan problem. Fortunately, you didn't design the open office plan, it's another architectural design brainstorm that doesn't really work. But now you are stuck with fixing it. Each office has 7' wood stud and sheetrock walls. The open truss bare ceiling is 15' up and everyone is usually alternating between talking on the phone and typing up reports. The complaint is that people can hear their neighbors too easily. You could call an acoustic engineer to help but let's say you want to try it yourself. You know it's a signal to noise adjustment that is needed. Let's go through it in slow motion.

We don't want to hear the guy next door. We listen and determine that the sound is not coming through the walls much but mostly over the top of the wall. No one is complaining about the din of noise, the hubbub that fills the space. That's good because this is your noise floor and you want it as loud as possible as long as it doesn't interfere with doing the work, listening and talking on the phone. Someone is saying you need to put some brightly colored sound panels on the walls. Of course, they don't really know what they are talking about. They just know that sometimes sound panels are used for noise control. Whatever we do we want to reduce the signal to noise ratio over the top of the wall. It is not intuitively clear how a sound panel on the wall does that. Yes, it reduces the sound that bounces off the wall. Some of these wall bounces needs to be reduced, that part that supports the sound going over the top of the wall. But another part of the sound in that space does not want to be reduced, the reflection of the general din of noise off the office walls.

We tried an experiment and added sound panels into an office at ear level. We created a quieter office but the quieter the office, the better we can hear intruding sounds. Wall panels didn't work; we want a noisy office to keep our signal noise floor as loud as we can. We think we might try adding sound panels to the very top section of the wall, between 6 and 7', all walls and both sides. That leaves most of the office wall noisy and only the very top of the wall being sound absorptive. You try it and the neighbor noise across the top of the wall is reduced while the ambient noise level seemed unchanged. Good, we lowered the signal to noise ratio.

The not-so Great Room

Let's tackle the not-so-great Great Room. What's the problem? Mom can't get enough distance between the kids and their noise. The room is too noisy and too loud. Before we attack the huge great room problem, let's look at something else. People can endure and keep their good humor as long as they have a respite and a sip of water once in a while. A respite. What's that? A place to rest. But no one's tired of anything except the noise. A respite is a place where the noise isn't. A perfect example of this from a design perspective is the iconic Egg Chair. Just sit in it one time and you can't forget what it is like…..the world is still speeding buy outside but inside time has slowed way down, and it's so quiet and comfortable. If anything would be a respite, the egg chair defined a respite.

The egg chair envelops a person with total quiet. The normal sound of busy life still enters your listening space because the front of the sound absorptive space is open, but the rest is blocked. Well, you could order an EggChair but we also have another option, the breakfast nook. It's small and has only one opening to the din of noise. You could outfit the interior of the nook with nice looking sound panels and create a respite zone, where mom can go to take a break from the noise, or where mom can put a cranky child so their noise does not permeate the house so loudly.

Something else about very quiet rooms, they help people become quiet and peaceful, without anyone having to say or do anything. It's an autonomic response to the quiet. And it works in reverse, which is that loud noisy rooms make people loud and noisy. Finally, it doesn't solve the problem everyone thinks should be fixed, the great room, but it does address the real problem, frazzled nerves.

If they wanted to quiet the great room you need to add acoustic materials. Deep pile thick carpets, throws and runners here and there. The walls of these rooms are full of things. But the upper half of a great room is fairly empty of anything, including personality. That's where you get to add acoustic panels and the decorative features that let them integrate into the room. An interesting exercise might be to place twelve sound panels, each being 2' by 5' by 2" thick, located in the upper portion of a great room. But to do so in a way that looks like they are not an afterthought but something that was integral to the room design in the first place.

Sound Absorption and Reverberation

The unit of sound absorption is called the Sabine, named after the 19th century scientist who did a lot of groundbreaking work in this area. There are metric Sabines and English Sabines. A metric Sabine is 1 square meter of 100% sound absorption. An English Sabine is 1 square foot of 100% sound absorption. Now if we have a surface that is 100 square feet in size and it has a sound absorption coefficient of 30% then we have the equivalent of 30 square feet of 100% sound absorption of 30 Sabines.

If you make a loud noise in a gym, and then be quiet and listen, you hear the reverberation of the sound dying out. The time it takes to go from loud to inaudible is called the reverb time of the room. By loud, I mean how loud a starter pistol shot would sound in the gym. In a bare gym you'll see reverb times of about 5 seconds. And it is all due to the friction created as sound waves impact the bare walls, floor and ceiling of the gym. If the gym is 100 by 100 by 20' tall it has 200,000 cubic feet of volume. The room constant is the volume divided by 20 or in this case 10,000 Sabine Seconds. The reverb time of 5 seconds means we have 10,000/5 = 2000 Sabines of absorption in the room.

The surface of the room is 2 x 100 x 100 + 400 x 20 = 28,000 sqft. We have 2000 Sabines of acoustics in the room. We have an absorption coefficient of 2000 x 100% / 28,000 = 7%. This is due to the friction between the sound wave and the walls, floor and ceiling of the gym.

If we want a quieter gym, all we have to do is to add sound panels to the gym. If we double the amount of acoustics in the room we cut the reverb time in half. In this case we have 2000 Sabines already and if we add 2000 more Sabines worth of sound panels we have 4000 Sabines and our reverb time drops to 2.5 seconds. This is good quiet enough to coach in but not quiet enough to be a multipurpose room. For that the gym needs to have a reverb time of about 1.25 seconds. That's half of what we already have and so to get there we need to double the acoustics in the room again, from 4000 to 8000 Sabines.

Cost sometimes is a factor in acoustics. Rule of thumb is that sound panels cost about $10/sqft installed. In the gym, our first 2000 Sabines came with the gym. The second upgrade just to make a useful gym to coach required another 2000 Sabines, or $20,000 installed. The second upgrade is very costly. We have to add another 4000 Sabines and the cost is $40,000 installed. But now we have a good sounding multipurpose room.

The Octaves of Conversational Sound

A good way to think about sound is to imagine the piano keyboard. Middle C divides bass from treble. Treble sound has short wavelengths and is the kind of sound that travels around the room bouncing off surfaces the way people imagine sound does, as if it was light bouncing off mirrors. Bass sound has long wavelengths and has the ability to go around objects instead of bouncing off of them. When you think about sound panels they only absorb the treble part of sound. They do not absorb the bass part of sound. The fundamental tones of both the female and male voice are in the bass range. The parts of speech that are in the treble range are the a,e,I,o,u vowels and the Tsss or sibilant sounds .

Nearly all the acoustics you will come into contact with is in the treble range. It is said that 80% of the information contained in speech is in the treble range. When it comes to the level of acoustics you will be expected to know about you need to know the basics.

All this talk about absorption coefficients leads us to the NRC, Noise Reduction Coefficient. I mentioned before that sound panels absorb the treble but not the bass. The NRC is an architectural acoustic standard. It is the average treble range sound absorption coefficient. Officially it is the average of the absorption coefficients starting with the octave of middle C, 250Hz, 500 Hz, 1K Hz and 2k Hz. I have included a published paper on the same NRC value can create different sounding rooms. And that it is important to not only specify NRC but the octave band absorption coefficient of the products you are specifying for some project

…………………………………....**Arthur Noxon, PE, Acoustical Engineer**…………………………………………………..