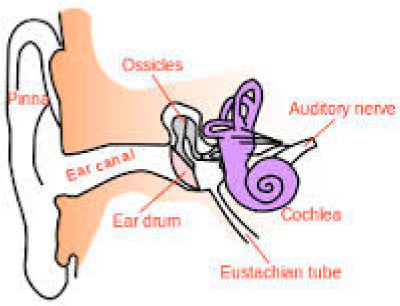
The Science of Hearing

The human hearing range is between 20 to 20,000 Hz. There is considerable variation in the hearing range between individuals. Most young people can hear up to 18,000 Hz. Our ability to hear high frequencies declines with age. By the age of 55 some men can't hear above 5,000 Hz and some women can't hear above 12,000 Hz. Women tend to have better hearing than men at high frequencies.

Check Your Hearing - http://www.youtube.com/watch?v=MMu6nPeIDOY

The speaking voice of a man has a fundamental frequency between 85 to 180 Hz, and a woman between 165 to 255 Hz.

The ear's sensitivity varies significantly with frequency. The human ear is most sensitive to frequencies in the range of 2,000-5,000 Hz. Our hearing has its peak sensitivity around 3,500-4,000 Hz. This frequency is associated with the resonance of the ear canal. At frequencies above 10,000 Hz our hearing sensitivity declines.



We hear low frequencies less well than high frequencies. Frequencies below 30 Hz are hard to distinguish. Lower frequencies produce more of sense of ‘feeling’ than a sense of sound. Low frequency sounds are heard mainly through bone conduction.

Sound intensity is quite different for different frequencies. High pitched sounds will seem louder than low pitched sounds of the same intensity. A 30 Hz sound has to be louder than 60 dB to be heard (60 dB is the sound level of normal conversation).

The Mechanics of Hearing

We hear through air conduction and bone conduction. Air conduction occurs as sound passes through the ear canal to the eardrum. The sound then vibrates the eardrum and these vibrations are transferred to the cochlea, via the three tiny bones of the middle ear called the malleus (hammer), incus (anvil), and stapes (stirrup). The cochlea is the sensory organ of the inner ear.

Inside the cochlea, there are thousands of tiny hair cells (cilia). These specialised hair cells convert the vibrations into electrical signals that are sent to the brain through the auditory nerve.

Each hair cell has a small patch of stereocilia sticking up out of the top it. Sound makes the stereocilia rock back and forth. If the sound is too loud, the stereocilia can be bent or broken. This will cause the hair cell to die, and it can no longer send sound signals to the brain. Once a hair cell dies, it will never grow back. The high frequency hair cells are most easily damaged by loud sounds.

Repeated exposure to sounds above 85 decibels can cause hearing loss. 85 dB is the noise level of busy traffic. The louder the sound, the shorter the amount of time it takes for noise-induced hearing loss to happen. People with hearing loss will often have problems hearing high pitched sounds like crickets or birds singing.

http://www.nidcd.nih.gov/health/hearing/pages/noise.aspx

Bone conduction is hearing induced by vibrations carried through bone. This is the process through which we hear ourselves as the vibrations of the vocal cords induce vibrations in the bones of the skull that stimulate the cochlea.

We hear 50 per cent of your own voice through bone conduction as a result we are often surprised when we hear our voice played back to us. It will sound different because of the change from bone conduction to air conduction hearing. Bone conduction is especially prevalent when we hear low frequencies, which vibrate all the bones of the skull.

By the end of his life the composer Beethoven was almost completely deaf. Beethoven found a way to hear the sound of the piano through his jawbone by attaching a rod to his piano and clenching it in his teeth. He heard his music by vibrations transferring from the piano to his jaw.

The Ear Canal

The ear canal conducts sound to the eardrum. The size and shape of the ear canal varies among individuals. In adults the ear canal, is between 2 cm and 3 cm long and 5-9 mm in diameter.

The amplification of sound by the ear canal is accomplished by two mechanisms. The funnel-like shape of the ear (pinna) collects the incoming sound. The fact that the opening of the ear canal is much smaller than the outer ear increases the pressure of the sound. The second part of the amplification of sound in the ear canal is due resonance.

The ear canal is similar to an organ pipe that is open at one end. When any sound enters a tube that is closed at one end and open at the other end the simplest standing wave that can form under these circumstances is one-quarter wavelength long.

The fundamental resonant frequency is the lowest frequency possible in the ear canal, only a quarter of the wavelength can occur in that length of tube.

For an explanation of how this is calculated see links below –

Quarter Wave Length Resonator
http://forensicaudiology.com/2009/11/17/quarter-wave-length-resonator

Standing Waves and Resonance
http://www.allaboutcircuits.com/vol_2/chpt_14/6.html

The ear's frequency response changes with respect to loudness. In the 1930s the researchers Fletcher and Munson were the first people to measure and publish a set of curves showing the ear's sensitivity to loudness compared to frequency. The curves show that the ear is most sensitive to sounds in the 3,000-4,000 Hz range. Frequencies above and below 3,000-4,000 Hz must be somewhat louder in order to be perceived as equally loud.

Consequently when we hear frequencies around 3,500 Hz they will be 10 to 20 dB louder than other frequencies. However, the resonance is disturbed when a hearing aid is placed in the ear. Consequently, a hearing aid needs extra amplification around 3,500 Hz to compensate for what has been lost by its insertion.

Although the ear canal resonates most strongly with sound wavelengths of 3,500-4,000 Hz male resonant frequencies are usually lower that female resonances. Men generally have larger ears than women. Smaller ear canals, like those in children, have higher resonant frequencies, usually around 4,000 Hz.

The main harmonic frequencies produced when choirboys sing are 3,000-4,000 Hz and 8,000-10,000 Hz. These frequencies produce a substantial resonance in our ear canal. This may explain why we are so moved by the singing of boy sopranos.

Why do we React to Certain Sounds?

Scientists used brain imaging to see what goes on in the brain when we are exposed to unpleasant sounds. The imaging showed that when we hear sounds we don't like, the amygdala becomes much more active.

The amygdala is an area of the brain that processes memories and creates emotional reactions. The amygdala is part of the limbic system. The limbic system supports a variety of functions, including emotion, behaviour, motivation, long-term memory, and our sense of smell.

The scientists believe that the amygdala processes sound information from the auditory nerve in such a way as to provoke a negative reaction to certain sounds.

In the study the volunteers listened to the sounds while inside a brain scanner and rated them on a scale from most unpleasant to the most pleasing. The sound of a knife scraping against a bottle was the most hated sound. The scientists studied the brain responses to each type of sound.

There appeared to be a correlation between the type of sound the participants heard and the levels of activity in the amygdala and the auditory cortex, the activity varied according to the ratings of the sounds. The higher the activity, the greater the revulsion.

The amygdala, which is the emotional part of the brain, appears to take charge and modulate the activity of the auditory part of the brain, making our perception of a very disagreeable sound feel even more upleasant.

The author of the study Dr Sukhbinder Kumar, said, "it appears that there is something very primitive kicking in. It's a possible distress signal from the amygdala to the auditory cortex”.

After analysing all the sounds the participants liked and hated, and placing them in order of unpleasantness, the researchers found that the most disagreeable sounds tend to be in the frequency range of 2,000 to 5,000 Hz.

Dr. Kumar said: "This is the frequency range where our ears are most sensitive. Although there's still much debate as to why our ears are most sensitive in this range, it does include the sounds of screams which we find intrinsically unpleasant."

The researchers believe that if we can better understand what is going on in the brain when we are exposed to sounds, we might have a greater insight into what makes some people have a low tolerance of sound. People with autism, hyperacusis (a reduction in tolerance of everyday sounds), and misophonia (a hatred of sound) all have a low sound tolerance.

Professor Griffiths said: "This might be a new inroad into emotional disorders and disorders like tinnitus and migraine in which there seems to be heightened perception of the unpleasant aspects of sounds."

Scientists have known for a long time that long-term exposure to certain sounds can affect our mental and physical health. Arab architects have for centuries designed buildings with fountains and the sounds of bubbling water. An article published in the European Heart Journal revealed that long-term exposure to the sound of traffic increases our risk of stroke (link to article below).

http://eurheartj.oxfordjournals.org/content/early/2011/01/08/eurheartj.ehq466.full

The Most Unpleasant Sounds

1. A knife scraping against a bottle.
2. A fork on a glass.
3. Chalk on a blackboard.
4. A ruler on a bottle.
5. Nails on a blackboard.
6. A female scream.
7. An anglegrinder.
8. Brakes on a cycle squealing.
9. A baby crying.
10. An electric drill.

The Most Pleasing Sounds

1. Applause.
2. A baby laughing.
3. Thunder.
4. Water flowing.

http://www.medicalnewstoday.com/articles/251489.php

How Loud Can Your Baby Cry?

The Sight & Hearing Association say that a baby's cry reaches 115 dB. This compares to a rock concert at 120 dB. Laser Mom says, "At about two months old, we measured our daughter's cry to be 122 dB at about 4″ from her mouth. Her loudest screams are above the pain threshold."

The frequency of a baby's cry is between 1,000 Hz and 5,000 Hz, centered at 3,500 Hz a very sensitive frequency range for the human ear. It seems that we are hard wired to hear the cry of our baby.

http://lasermom.wordpress.com/2012/01/08/crying/

How the Ear Responds to Different Sounds

The "loudness" button on home-audio amplifiers and the various bass-boost switches on portable compact disc players are a way of correcting the ear's non-linearity. The loudness button is designed for use at low listening levels to compensate for the ear's intrinsic loss of low and high frequency perception. The loudness of a tone can also affect the perceived pitch of the sound. If the intensity of a 100 Hz tone is increased from 40 to 100 dB, the ear will perceive a pitch decrease of about 10%.

Other effects experienced by the listener when tones interact with each other, these include – beats, combination tones and masking.

Beats
Any two sounds that are close to each other in vibration will cause a clash of vibration. Our minds interpret this close clash of vibrations as a 'beat'.

There is no outer physical beat going on, but the close relationship of the sounds coming together feels like, or is heard as, a throbbing, pulsating, beat. In acoustics, a beat is interference between two sound frequencies very close together. Beats are the result of the ear's inability to separate closely pitched notes.

Tuning two tones to unison will create a peculiar effect: when the two tones are close in pitch but not identical, the difference in frequency generates the beating. The volume varies producing a 'wah wah' effect as the sounds alternately interfere with each other constructively and destructively.

As the difference between the frequency decreases, the speed of the beats decreases. As the two tones gradually approach unison, the beating slows down and may become so slow as to be imperceptible.

For example, if we pluck the B and E strings on an electric guitar we can hear the two notes separately. If the E string is loosened more and more, to lower its frequency down to the B, for some time we will be able to hear two sounds.

When the two strings have the same frequency, only one sound will be heard; but just before unison occurs there will be a strange effect: one sound will be heard, but its volume will appear to change sometimes getting louder and sometimes getting quieter.

When two people tone vowel sounds while facing each other and try to create the same note beats will be heard as they get close to unison.

Binaural beats are sounds created in headphones when we hear two tones separated by less than 30 Hz. For example, if a 300 Hz tone is played in one ear and 310 Hz tone in the other ear, then the binaural beat would have a frequency of 10 Hz. The frequencies of the tones must be below 1,000 Hz for the beating to be noticeable.

It is claimed that listening to binaural beats can help induce relaxation, meditation, creativity and other desirable mental states. Binaural beats reportedly influence the brain in subtle ways through the entrainment of brainwaves. It has been claimed that listening to binaural beats reduces anxiety and providse other health benefits such as control over pain.

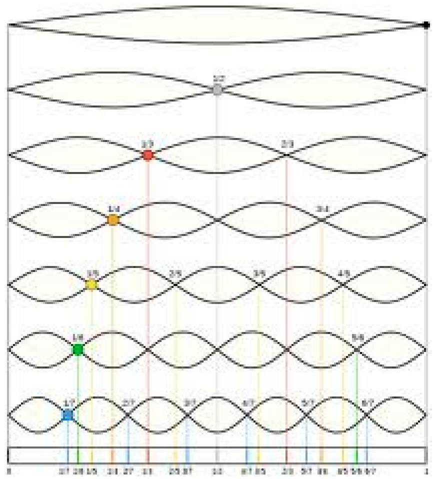
Tibetan cymbals (tingshas) are two small cymbals that are very slightly different in pitch. When you strike the cymbals together you'll get a binaural beat or binaural throbbing. Genuine Tibetan Bowls create 'beats' within themselves when they are played, due to the different metals used and the shape of the bowl.

Combination Tones
Two loud tones that differ by more than 50 Hz will be interpreted by the brain as a complex set of tones, including the two original tones and an additional set of tones that are equal to the sum and the difference of the two original tones. For example, the two tones 1,000 Hz and 1,500 Hz will produce a difference tone of 500 Hz and a sum tone of 2,500 Hz. We will hear the difference tones created by the brain more clearly than the original tones.

Masking
Masking is the phenomenon that prevents us from hearing softer sounds underneath loud tones. The effect is more pronounced when the frequencies in question are relatively close together. For example, a loud 4,000 Hz tone will mask a softer 3,500 Hz tone, but will have little effect on a soft 1,000 Hz tone.

Harmonics
Harmonics are sound frequencies that are integer multiples of the fundamental frequency and they occur simultaneously with the fundamental vibration. Harmonics contribute to the resonant quality or timbre of the sound. When you pluck a string on

a guitar it not only vibrates across the whole of its length; it also vibrates at half its length, a third, a quarter and so on.



For example, an instrument playing a note at a fundamental of 200 Hz will have a second harmonic at 400 Hz, a third harmonic at 600 Hz, a fourth harmonic at 800 Hz, etc. Even-numbered harmonics tend to make sounds ‘soft’ and ‘warm’, while odd-numbered harmonics make sounds ‘bright’ and ‘metallic’. Lower-order harmonics control the basic timbre of the sound, and higher-order harmonics control the harshness of the sound.

Every musical instrument favours certain clusters of harmonics according to its shape and size. The shape and properties of the instrument will cause the clusters of harmonics to be boosted or dampened. This creates the difference in sound quality we hear when the same pitch is played on different instruments.

The voice is like an instrument, and when we change the shape of the vocal tract, its acoustic properties are altered leading to different harmonics being boosted or dampened.

This is clearly demonstrated when the larynx is raised or lowered whilst maintaining the same pitch In the lower laryngeal position, lower frequency harmonics are boosted, whilst in the higher position higher frequency harmonics are boosted. This technique is used in Mongolian throat singing.

Formants

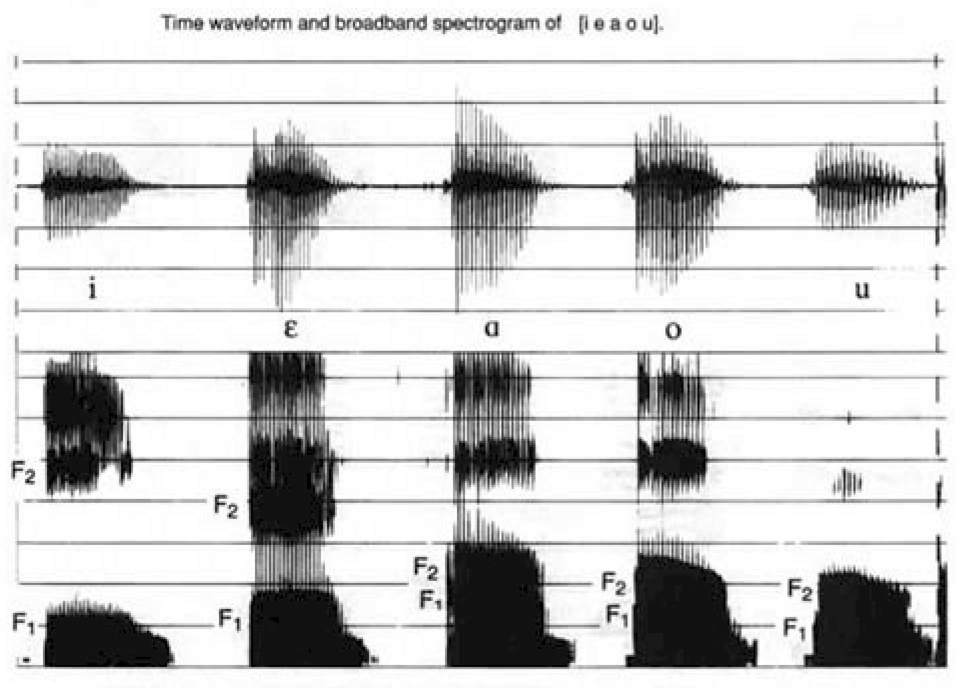
Formants are specific resonance peaks created by the vocal tract as sounds pass through it. The shape of the vocal tract causes clusters of harmonics to be boosted or dampened. When we make a sound the harmonics that are close to the resonance frequencies of the vocal tract get stronger and others will be damped. As a result a series of peaks and valleys are formed on a sound spectrum chart.

The peaks are given numbers that relate to their position in the sound spectrum. The dimensions of the vocal tract determine the relative positions of the peaks.

When we move our lips, tongue, larynx or jaw while speaking or singing, we are changing the formants. This will change the boosted harmonics, giving different tone qualities and creating different vowels. For example, moving the tongue forward in the mouth accentuates the second formant, lowering the jaw accentuates the first formant and so on.

A formant is a concentration of acoustic energy around a particular frequency in the speech wave. There are several formants, each at a different frequency, roughly one in each 1,000Hz band. Each formant corresponds to a resonance in the vocal tract.

Formants can be seen very clearly in a wide band spectrogram, where they are displayed as dark bands. The darker a formant is in the spectrogram, the stronger it is, the more energy it has and the more audible it is (see below).



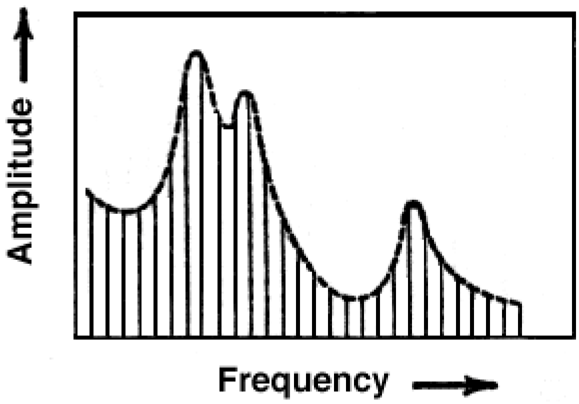
Any room can be said to have unique formants, due to the way sound may bounce across its walls and objects. Room formants reinforce themselves by emphasising specific frequencies and absorbing others. A formant is a way to measure an acoustic space. A smaller space has a higher formant value, which brings out the higher harmonics. A larger space has a lower formant value, which brings out the lower harmonics.

A guitar has formants that can't be changed. This gives the guitar a consistent sound. A musical instrument may have several formant regions dictated by the shape and resonance properties of the instrument.

The human voice is a moveable, very agile resonator that can assume different shapes. This means we can change the formants quickly, giving us a huge range of sounds. The human voice has formant regions determined by the size and shape of the nasal, oral and pharyngeal cavities that permit the production of different vowels and voiced consonants.

Formant regions are not directly related to the pitch of the fundamental frequency and may remain more or less constant as the fundamental changes. If the fundamental is well below the formant range, the quality of the sound is rich. If the fundamental is above the formant regions the sound is thin and in the case of vowels may make them impossible to produce accurately. This is the reason singers often seem to have poor diction on high notes.

Formants are always independent of the fundamental frequency of the sound. Harmonics are always integer multiples of the fundamental frequency.



The diagram above is a line spectrum chart of the vowel 'ah' showing three main formant regions. The vertical lines represent harmonics produced by vibration of the vocal cords. These harmonics are resonated by the vocal tract to create the vowel's characteristic spectral shape.

Three formants are generally required to create a vowel sound. These regions appear as dark horizontal bands on a spectrogram or amplitude peaks on a line spectrum diagram.

Sung vowels are characterised by an additional formant called the singing formant in the range of 2,500 to 3,000 Hz. It is created by the special resonance of the vocal tract when the larynx is lowered, as practised by trained singers in the Western tradition. The formant not only gives sung vowels a characteristic colour, but also allows the voice to be heard over the accompaniment of instruments or even a full orchestra.

Alfred Tomatis

Alfred A. Tomatis (1920-2001) was an internationally known specialist in ear, nose, and throat conditions. He received his Doctorate in Medicine from the Paris School of Medicine. His alternative medicine theories of hearing and listening are known as the Tomatis Method or Audio-Psycho-Phonology (APP).

Tomatis and his colleagues have tested more than 100,000 clients for 'listening disabilities', vocal and auditory handicaps in his centres throughout the world.

Tomatis found that peaks or troughs on a Listening Test using an audiogram will indicate if a person has difficulties with concentration, memory, spelling and confidence. Distortions in the lower range of frequencies reveal a lack of grounding.

The Listening Test also highlights where the emotional conflicts are located in the body. Each sound frequency pertains to the resonance of a specific organ or part of the spine.

Tomatis found that a dysfunction of the vestibular system of the ear may lead to speech impediments, poor motor co-ordination, difficulties standing, sitting or walking. Tomatis explains that it is possible to correct a listening or learning problem by stimulating the muscles of the middle ear, where the distinction between listening and hearing begins. To do this Tomatis used filtered high frequency recordings of Mozart, Gregorian Chant and the spoken voice.

The Tomatis treatment begins with normal non-filtered sounds. The listener is then gradually introduced to more highly filtered sound until all frequencies below 8,000 Hz are filtered out. In addition, the sound delivered to the listener alternates between the two ears.

Tomatis believes that bass sounds are felt throughout the body in a manner similar to the sense of touch. Low-pitched sounds stimulate the ear via the skin, the joints and the muscles. The ear translates this sound to the brain. Tomatis believed that the skin is an extension of the ear.

Tomatis found that low frequency sounds (125-750Hz) affect our physical co-ordination. Hence a drum beat will makes us want to dance. Middle frequency sounds (750-3,000hz) tend to stimulate the heart, lungs and the emotions.

Tomatis believes that the resonance of 2,000Hz stimulates the bones. Bone conduction stimulates the staples muscle of the ear, which stimulates and charges the brain.

Tomatis believes that high frequency sounds (3,000Hz and above) will literally 'charge up' the brain and affect cognitive functions such as thinking, spatial perception and memory. These high frequencies, even in small doses help to increase attentiveness and concentration.

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