D. BAUMANN & C. NIEDERSTÄTTER

Acoustic Design

The architectural acoustics of school buildings and schoolrooms are often not taken into account until late in the design phase. The following considerations should help to explain why it makes sense to include them at the earliest possible stage, and why careful acoustic design is both aesthetically and financially worthwhile.

One reason for assuming that room acoustics are a secondary design function lies in the traditional belief that they are primarily dependent upon the absorption characteristics of the internal finishing materials. The factors which govern room acoustics are more complex, however, and will already have been predetermined by the choice of construction and spatial form. Also, a condition fundamental to the psychology of perception is that the quality of an acoustic will be judged according to the personal experiences of the listener. This judgement and the auditory reception itself will ultimately be influenced by the individual's perceptual expectations. Recent neurological investigations have confirmed that perception is an active process and extends to the regulation of the sensitivity of the ear for amplitude and frequency. This can be intensified or reduced via nerve fibres which send feedback from the brain to the ear, which explains why the judgements formed of acoustic or room acoustic impressions are sometimes very different. The definition of an acoustic sound as opposed to unpleasant noise is subjective. Nevertheless, quality factors may be defined to which value ranges can be assigned that apply for certain listener groups and types of use.

Sensory perception and acoustics

Sound experiences trigger emotions and activate numerous areas of the brain. They are strongly linked to the autonomic nerve system and may effect a variety of changes, including fluctuations in blood pressure and respiratory rate. Acoustic impressions may mask other nerve signals (like Tinnitus, but also discomfort and even pain); they may have a calming effect, but may also cause fear (e.g. a sudden noise). It is known that rooms with excessive sound insulation may induce breathlessness, unease and fatigue because perceptible spatial dimensions have been lost. But it is also true that a good acoustic may have a liberating, invigorating effect and may promote concentration and communication. Seldom do we consciously perceive acoustics unless they are unpleasant. The perception of sound is a way of detecting meaningful structures in our environment, guided by our expectations. Acoustic signals assist social communication. In this sense, acoustics are an integral part of the whole design process.

Temporal resolution of the senses

Of all the sensory organs, the ear transmits the most finely attuned temporal orientation. Binaural perception from the side towards the front enables us to experience differences in direction of only 1 cm or 3°, corresponding to the unbelievably minute time differential of 0,03 ms (milliseconds). Only 3 ms are needed to perceive middle frequency pitches with a soft attack. Our sense of touch is able to detect vibrations through the fingertips with the same temporal resolution. The ear requires up to 28 ms to perceive tone colours and pitches produced with a hard attack, and up to 50 ms (1/20 secs.) to perceive low pitches. It is known that a continuous film sequence needs at least 20 images per sec., and that at least 50 ms are required for the visual perception of each individual image. Much longer, namely 160 ms, is needed to feel an object. The conscious recognition of a smell or taste takes seconds if not minutes. An important consequence of this is that the slower sensory perceptions benefit from faster auditory perception. This is a reason for the strong coordination between eye and ear, but also for the importance of room acoustics in architectural design.

Sensory experiences in preschool and school-age children

These physiological data clearly show how important the opportunity for acoustic experiences is during early childhood and school years. Investigations show that small children are very active and sensitive in exploring their acoustic environment. In teenagers, however, the emotional perspective already predominates over acoustic impressions. Nevertheless, an analytical approach to listening can be stimulated in every individual through independent acoustic events. The attention can be tuned in both to the sound source and to the quality of the sound. Generally, adults can only sustain this approach to listening for a few moments before making a comparison with the spectrum of standard sounds stored in the memory. Just as we say that snow is white even though it is a shimmering blue in evening light, so do we store stereotyped images of sound for certain situations and sound sources. We have a preconception that a gymnasium should be reverberant, a bedroom muted and a busy street noisy. These 'preconceived opinions,' which help us to orientate ourselves quickly, are essentially formed during childhood. Subsequently, they can only be corrected if we are constantly subjected to different experiences. We know that threatening or happy moments leave behind deep impressions which also stamp our acoustic perception of the world, so from the number of hours a child spends in school, we can make a direct conclusion as to the importance of the sensory experiences gained there.

Noise and silence

Noise is an invasive nuisance which masks important acoustic signals. Insulation against outside noise is therefore regarded as a great relief. Also, it is only in periods of continuous silence that our aural perception achieves its highest level of sensitivity. Building technology has made enormous progress by sealing windows and doors against penetrating airborne sound and by decoupling mechanical connections with elastic elements (footstep damping, floating floors, softening rigid wall and conduit junctions). Building standards provide clear guidelines in this respect. In the USA and the UK high levels of acoustic performance has been made a statutory requirement in all new school buildings. For example, the 2006 UK publication, Acoustic Design of Schools – Building Bulletin 93 recognises that teaching and learning are acoustically demanding activities. In particular, there is a consensus that low ambient noise levels are required particularly to integrate pupils with special needs into mainstream schools. The most serious acoustic problems are due to noise transfer between rooms and excessive reverberation in rooms. This is often the case in old Victorian buildings or in more recent open plan school design, which is particularly problematic at primary school level.

The quality of room acoustics

It is much more difficult to define the quality criteria by which the architectural acoustics of internal rooms should be designed. This is where the standards are less helpful. Often, the correction of reverberation may lead to excessive damping, even if the calculated absorption measures are exceeded only slightly. This in turn produces unpleasant acoustic discolouration in the high frequency range when conventional absorbing materials are used. A room acoustic must never be dead but should preserve a quality of spaciousness.

clockwise

Music school in Auer
South Tyrol, Italy,
Christina Niederstätter, 2005
Room for flute lessons

Music school in Auer
South Tyrol
Room for piano lessons and chamber music

Gustav Mahler Hall,
Arts Centre and School of Music
Toblach, South Tyrol,
Wachter & Partner, 1999/2006

Sports hall, Gasteiner Upper School
Bolzano, South Tyrol, O. Zoeggeler, 2001

Zoned areas offering different acoustic experiences

Of particular benefit to children, who receive essential acoustic experiences in schoolrooms, would be the conscious creation of different zones offering a variety of acoustic characteristics: places of silence and concentrated tranquillity (library); places for eating; places for speaking (classroom, lecture hall), singing and making music in small groups (music rooms); and rooms for a larger number of listeners (music hall). Children are among the first to recognise the use of acoustic signals such as the gentle splashing of a fountain to denote relative peace in the refectory, and to discover that a corridor channels sound and carries it over long distances, or that their voices and other sounds reverberate longer in the cellar. It is not always the case that children will be less aggressive in a dampened acoustic and will shout more in a reverberant one. However, as with adults, children experience a feeling of well-being if the acoustic design suits the function of the room.

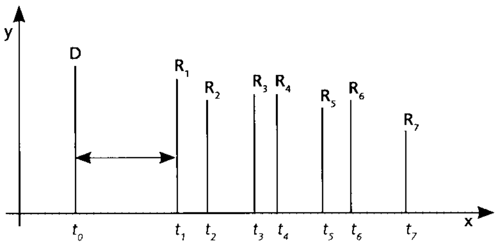
Refectory, Manzoni Elementary School
Bolzano, South Tyrol, Christina Niederstätter, 2004

Direct sound

One of the first acoustic experiences we perceive is that we hear better when we can see the sound source, but good visual contact with the sound source alone is not enough for a good acoustic. Nevertheless, direct sound improves speech intelligibility because it is ideal for transmitting high frequencies. This can be achieved by banking rows of seats, or, if the room has an adequately high ceiling, raising the sound source may be sufficient.

Indirect sound, reflection and diffraction

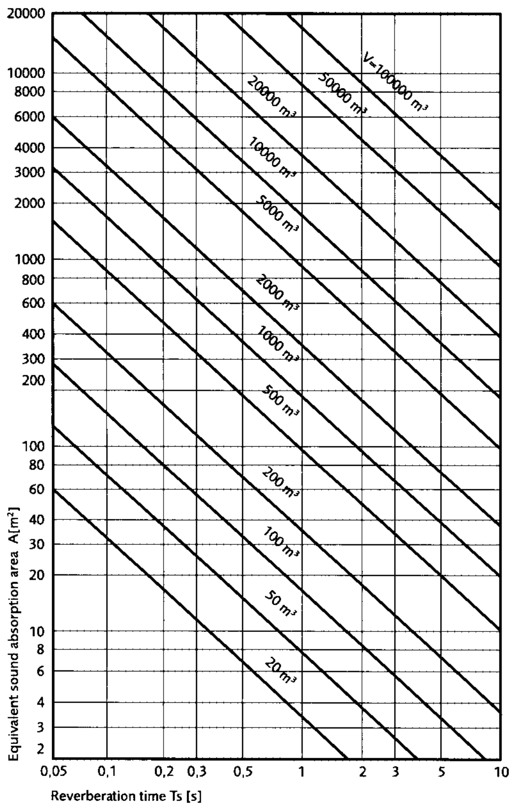
Sound is reflected off the room boundaries like light off a mirror. An effective reflector must be substantially bigger than the length of the sound waves. (Wavelengths within audible range are approximately between 17 m at 20 Hz and 17 mm at 20.000 Hz). As with light, when a sound wave encounters a barrier or surface undulation within its wavelength, it will be diffracted. By texturing the surface with raised and recessed areas, harsh reverberations are prevented, flutter echoes between parallel walls avoided, and the required amount of absorption achieved in the higher frequency range (diffuse reflection). Architecturally, these rules relating to reflector dimensions and surface texture touch upon an aesthetically sensitive design realm, which should be taken into account when designing a space. In the temporally staggered field of reflections, we talk about useful early reflections which amplify and clarify the sound, and late reflections which are heard as reverberation. They add spaciousness and fullness.



x = time (in milliseconds)
y = volume (in decibel)
D = direct sound
R_1, R_2, R_3 = reflections from walls, ceiling, rear wall and other surfaces

The reverberation formula of Wallace C. Sabine

Around 1900 Boston physicist Wallace C. Sabine successfully demonstrated that there was a relationship between room volume V, absorption A and reverberation time T (time taken for the sound pressure level to



Realtion between sound absorption and reverberation time

fall by 60 dB): $T\ (\text{sec.}) = 0.163\ V/A$, whereby $A = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 \ldots$ This equation can be used in the design phase to calculate reverberation time if the precise absorption factors α_x and joint faces S_x of the materials used are known. The coefficients of A for a planned reverberation time can thus be determined for the given room volumes. In the absence of laboratory measurements, calculations can be made using the α-values given in the technical specifications (e.g. the α-database of the PTB, Physical-Technical State Institute, Brunswick), but a reserve margin should always be planned for essential fine-tuning of the room acoustic. Measuring the reverberation of the shell of the building has proved useful for clarifying the acoustic properties of the construction. A measurement taken after essential internal elements have been completed allows the planning of final adjustments.

Absorption

The application of absorption materials reduces not only the intensity of sound reflections but may also prevent the formation of energy accumulation, which may in turn cause unpleasant late spatial responses. Modern construction now rarely uses surface textures. Vibrating floors and wall claddings are absent and mostly hard and heavy materials are preferred which absorb little acoustic energy, particularly within the 100 - 200 Hz range (this applies to concrete but also glass).

It is technically easier to dampen high and mid range frequencies. This is achieved by using porous surfaces such as mineral and organic fibre materials, but they are also absorbed by people in the room and textured surfaces. The sound absorbing effect of curtains increases from the high to the middle frequency range with increasing weight per unit area and distance from the wall covered. However, curtains may also impair the lateral acoustic so important to the perception of direction and sound amplification. Depending on the surface, carpets are effective in the mid to high frequency range. Carefully chosen upholstered seating may also compensate acoustically in a lecture room when few people are present.

Invasive low frequencies require more extensive corrective measures. Perforated and slotted absorbers are used (absorbed frequency range depends on the thickness of the panel, the size of perforation, the proportion of slotted surface, width of slot, the distance between perforations, the surface distance and the sound-absorbing infill). Panel absorbers may also be used (soft, pliable panels with an enclosed air cavity, positioned in front of acoustically hard, heavy structural components), as well as cavities lined with absorbing materials, which can be very precisely adjusted to the frequency range to be dampened. Especially suitable for schoolrooms are non-fibrous absorbers in micro-perforated plastic, metal sheeting or plywood

Details of elastic suspension of walls and ceiling in Aula Magna at Gasteiner Upper School
Bolzano, South Tyrol, V. Andrialo, 2001

(diameter of perforation: 0.5-0.7mm) which, depending on construction, can be effective in a broad frequency range. A regular distribution of sound-absorbing areas alternating with reflecting areas is acoustically advantageous.

Classroom at Middle school
Schlanders, South Tyrol, T. Simma, 2002

Acoustic standards and guidelines relevant to school buildings

For the design of room acoustics, standards specify reverberation times for the best reception of speech and music within a minimal frequency range of 60 - 4,000Hz. (The narrower frequency range of 500 - 1,000 Hz given in the German norm DIN 18041 for speech does not include the frequency band between 2,000 - 3,000 Hz, which is important for the carrying capacity of the voice and the masking effect of low frequency reverberation). The ideal average reverberation time, T, for speech is 0.7 secs., but for music lessons it is 0.4 to 1.2 secs., depending on the volume of the room and the musical instrument. In a smaller public hall the average reverberation time for music should not lie below 0.9 secs. to guarantee a pleasant sound. This time should be proportionately longer for larger room volumes.

Experiences in the construction of acoustically sensitive rooms (music schools, auditoria and concert halls, children's schoolrooms etc.) have shown that the linearisation of upper reverberation, i.e. the most even reverberation time possible within the 50 to 5,000 Hz frequency range, permits longer reverberation times because of less masking. This satisfies the requirements of multi-purpose use of rooms for speech and music. Flexible use can also be facilitated by moveable absorbers (reflecting or absorbing partition walls, moveable reflectors with different textures, upholstered seating, curtain with the correct wall coverage, etc.).

It is particularly important to consider children with impaired hearing, who require special measures, to create good hearing conditions. According to standards, to be intelligible without strain, speech in a classroom should be twice as loud as the sum of all interfering background noises (the level differential to the ambient noise should therefore be about 10 dB). For those with impaired hearing, however, the ideal level differential is 15 to 20 dB. Difficulties in perceiving sound and speech can be overcome by the position in the room of the listener with impaired hearing (proximity to, and good visibility of, the speaker). Experts will need to be consulted on this point.

Multi-purpose hall at school Vella
Graubünden, Switzerland, V. Bearth & A. Deplazes, 1997

Geometric room acoustic

The shape of the room determines the geometric diffusion of the sound. Concave surfaces concentrate the sound while convex surfaces diffuse it. Narrow angles, niches and rooms linked by openings cause so-called sound accumulations, which may produce unpleasant delayed reverberations. Asymmetrical shapes produce an uneven sound distribution, especially when reflections bounced off two or three surfaces before reaching the listener. Because the ear is more sensitive to lateral sounds, it is important that the height of the room is adequate to allow lateral reflection from above.

It is known that shoe-box shaped, rectangular rooms give the most even sound distribution. Nevertheless, parallel walls may produce standing waves and flutter echoes, which must be carefully attenuated by texturing/structuring the surfaces, or at least by absorbing specific frequencies. Even in the absence of right angles, standing waves may occur over several surfaces. In smaller rooms absorbing measures are often sufficient on only one of the interacting surfaces.

Seminar room, University of Zürich Musicology Institute
Beate Schnitter, 1997

Masking and summation

An acoustic event comprises a constant temporal overlaying of direct sound and reverberation. It therefore moves within the range of masking – too loud, delayed or discoloured reflections – and the summation of useful reflections. Depending on what is being perceived, reflections of 15 ms to 150 ms blend to form a complete impression. From this quality factors are derived such as the extent of syllabic recognition, clarity, transparency, spatial impression, level of lateral sound, sound colour of the early reflections, amplitude etc. If there are numerous reflections, temporally well-layered and converging from all directions, the sound is more transparent and the listener can tolerate a higher sound level and longer reverberation times.

Music school in Auer

South Tyrol, Christina Niederstätter, 2005

Teaching room for flute: length 5.5 m, width 3.5 m, average height 3.4 m, volume approx. 65 m^3.
Teaching room for piano: length 6.5 m, width 6.0 m, height 3.0 m, volume approx. 115 m^3.
Linear reverberation times 0.5 - 0.9 secs., depending on the instrument taught.

Absorbing resonators in the walls and in some rooms in the ceiling, covered and concealed by perforated metal sheeting. The ceilings are clad with sheets of perforated plasterboard. Tube-traps were installed in the corners of the rooms as excellent low-frequency absorbers. Flexible lining shells of plasterboard are installed in some rooms to act as low-frequency absorbers. Fine tuning for high frequencies was accomplished by applying colourful highly absorbent foam structures as necessary, particularly in sharp angles. The floor structures were produced throughout in floating Keene's cement; the doors were checked for sound transmissions and sound-insulated wherever necessary using double-sealed door panels of sufficient weight, soundproof door frames and flush rubber seals. The partition walls achieved sound insulating coefficients of Rw'= 57dB. To reduce resonance in the windows, melamine resin foam elements were installed between the panes. Some of the timber cladding in the rooms was designed as undulating panelling for low-pitch absorption. By applying precise measures and step-by-step optimisation, each room has an acoustic matched exactly to its purpose. The goal was to sound- insulate the rooms and to achieve the best possible acoustic transparency and appropriate sound volume to ensure undisturbed teaching.

Gustav Mahler Hall, Arts Centre and School of Music

Toblach, South Tyrol
Wachter & Partner, 1999/2006

Length 32 m, width 16 m, height 10 m, volume approx. 5.200 m^3. Linear reverberation time 1.8 secs. with 430 persons in the hall.

Shoe-box hall room with carefully textured wall and ceiling cladding in wood. Acoustic installations: following measurement taken in the shell, 1,000 exactly calculated absorbing cavity resonators were installed behind the wall and ceiling cladding. Seating in light-weight upholstery enables use of the hall with a small audience and for recording when the hall is empty. Outstanding acoustic for orchestral concerts, chamber music and recordings.

Sports hall, Gasteiner Upper School

Bolzano, South Tyrol, O. Zoeggeler, 2001

Length 46 m, width 34,6 m (ceiling), 28 m (floor), average width 31 m, height 8 m, volume approx. 11.400 m^3. Average reverberation time 2.3 secs. (reverberation times before non-linear correction 4 - 6.5 secs).

A fully equipped sports hall used as a venue for handball tournaments. Acoustic renovation: installation of approx. 340 m^2 absorbing cavities (approx. 162 m^2 in the ceiling, approx. 108 m^2 in the side walls, approx. 70 m^2 in the front and rear walls). The coefficients achieved conform to the standard. The absorbing resonators in the walls were deliberately designed as 'windows' in this architecturally distinctive 'urban' inner space.

Refectory, Manzoni Elementary School

Bozen, South Tyrol, Christina Niederstätter, 2004

Average length 20.5 m, width 11 m, height 2.60 m, total volume approx. 590 m^3. Linear reverberation time 0.8 secs. (before correction non-linear 2-2.5 secs. with a noise level of 86 dB(A)).

Absorbing resonators in the ceiling, additional high pitch absorption using insulating panels in mineral wool covered with fibreglass; additional absorbing wall panels as notice boards and sound-absorbing partitions. The sound absorbers are deliberately designed as playful or technical elements. The acoustics, and therefore the sense of well-being of the children, were also optimised by organisational and design measures: this long, low room was subdivided into areas for small groups of pupils; passage ways were rationalised; mealtimes in three shifts were introduced so that the room did not become overcrowded; meal waiting times were reduced; and a pleasant acoustic ambience is created by the sound of flowing water.

Aula Magna, Gasteiner Upper School

Bolzano, South Tyrol, V. Andriolo, 2001

Length 22.5 m, width 19.2 m, maximum height 9 m, average height 6.5 m, volume approx. 2.600 m^3. Linear reverberation time 1.1 secs. when the room is full (reverberation times before correction non-linear 3-6 secs.).

Acoustic renovation: installation of approx. 90 m^2 absorbing cavities (approx. 54 m^2 in the ceiling, mainly to the back and side, and approx. 32 m^2 evenly distributed on both sides of the stage).
The Aula Magna had been unused for many years because of acoustic pollution from the sports hall located immediately above it. The whole acoustic ceiling (reflectors in the ceiling with resonators) and all the timber cladding with absorbing resonators on the side walls were suspended to provide elastic decoupling. Noise transmission from the sports hall above was thus prevented. Today it is possible to use both the Aula and the gym at the same time without any problem. Light-weight upholstered seats were installed to improve the acoustic when the hall is not full. Linearisation of reverberation ensures good acoustics for speech. The clear, pleasant acoustics also make the Aula ideal for theatrical and musical events.

Middle school in Schlanders

South Tyrol, T. Simma, 2002

Room height 2.83 m; rooms of differing dimensions. Linear reverberation time of 0.7 secs. (reverberation times before renovation: 1.4 to 2.5 secs.).

Acoustic optimisation of three existing classrooms used for music lessons.The absorbing resonators were installed in the ceiling between the rows of lights. Additional high-pitch absorption was achieved by the installation of wall panels (Acoustichoc – glass wool covered with a fibreglass fabric), designed as notice boards. Two types of resonators were combined which absorb at 315 Hz and 125 Hz respectively. The timber of the resonators was stylised painted in a metallic silver-grey to give the visual effect of technical elements. The acoustics achieved are pleasant and transparent in all rooms.

Multi-purpose hall and classrooms at school Vella

Graubünden, V. Bearth & A. Deplazes, 1997

Length of hall 27 m, length of stage 7 m, width 15 m, maximum height 12.40 m, height of side walls 7 m, total volume approx. 4.350 m^3. Reverberation time in hall (stage open) with 200 persons present: from 125 to 4000 Hz, virtually linear 1.8 secs., dropping to 1.2 secs. above and below this frequency range. The reverberation time in the empty sports hall when the stage is closed off by a folding door: 3 secs. between 315 Hz and 5000 Hz, reducing to 1.5 secs. above and below this frequency range (reverberation time in shell 3.5 to 1.4 secs.).

The room is used, without changes, as a sports hall, assembly hall, theatre and concert hall. Thanks to early planning and measurements taken in the shell, an aesthetically attractive solution with good linearisation of the reverberation was achieved by optimising the ceiling (slightly convex, vaulted gable areas) and installing absorbing cavities behind the timber walls and in the stage door.

Seminar room, University of Zürich, Musicology Institute

Beate Schnitter, 1997

Length 9.85-11.50 m, width 7.40-7.90 m, height of side walls 4,80 m, total volume approx. 290 m^3 (room slightly asymmetrical without right angles). Linear reverberation time when the room is full 0.9 secs.

Teaching room with 50 seats maximum, in which music is also made. Owing to the water-tight outer walls of this room, which is barely above the ground water level, no wall mountings were possible. The convex ceiling, which curves downwards, houses the ventilation and lighting systems. The acoustics could only be corrected by using free-standing cubic hollow bodies in the room, fixed to the floor. To linearise reverberation, they absorb standing waves which form at 250 Hz and 125 Hz diagonally across the walls, although the surfaces are not parallel. Absorption with this newly developed type of resonator does not occur through the braking effect of an opening with a neck (Helmholtz principle), but by lining the cavity with absorbing rock wool (Kirchhoff principle). They are positioned at points where maximum disturbing soundwaves accummulate. Thanks to the corrective measures taken, are pleasant acoustics are now ensured for speech intelligibility and music whether the room is empty or full.

Literature

α-database: PTB Braunschweig. www.ptb.de/de/org/1/17/173/datenbank.htm

Acoustic Design of Schools – Building Bulletin 93,
Department for Education and Skills, 2006,
www.teachernet.gov.ok/schoolbuildings

Dorothea Baumann,
'Können wir unseren Ohren trauen?',
in: *Schweizer Musikzeitung* 1,1998, p. 1-9

Jens Blauert (ed.): *Communication Acoustics*
Berlin/Heidelberg: Springer, 2005.

Classroom Acoustics, A resource for creating learning environments with desirable listening conditions, Acoustical Society of America ASA 2000.
http://asa.aip.org (15. Sep. 2006)

DIN 18041: 2004 - 05, Audibility in small to medium-sized rooms.

Wolfgang Fasold and Eva Veres,
Schallschutz und Raumakustik in der Praxis
Berlin: Verlag für Bauwesen, 2003.

Guidelines of the Swiss Acoustical Society
(Schweizerische Gesellschaft für Akustik SGA)
for the acoustics of school rooms and other speech rooms, SGA, 2004.

Stephen Handel,
Listening. An Introduction to the Perception of Auditory Events,
Cambridge, MA: MIT Press, 1989.

Ludowika Huber, Joachim Kahlert, Maria Klatte
(eds.), *Die akustisch gestaltete Schule.*
Auf der Suche nach dem guten Ton.
Göttingen: Vandenhoeck & Ruprecht, 2002.

Christina Niederstätter
Studie über den Zusammenhang zwischen akustischer Qualität und Wohlbefinden der Kinder in den Grundschulmensen der Stadt Bozen / Studio sulla relazione tra qualità acustica e benessere dei bambini nelle mense delle scuole elementari del Comune di Bolzano, unpublished manuscript, Unterinn, 2002.

Rudolf Schricker, *Kreative Raum-Akustik für Architekten und Designer,*
Stuttgart: DVA, 2001.

www.uni-oldenburg.de/psychologie/mub/meis.htm#pub (Sep. 15, 2006)