Technologies **2014**, *2*, 31-53; doi:10.3390/technologies2010031

OPEN ACCESS

technologies

ISSN 2227-7080

www.mdpi.com/journal/technologies

Review

Local Control of Audio Environment: A Review of Methods and Applications

Jussi Kuutti †,*, Juhana Leiwo † and Raimo E. Sepponen

Health Factory, School of Electrical Engineering, Aalto University, Aalto FI-00076, Finland; E-Mails: juhana.leiwo@aalto.fi (J.L.); raimo.sepponen@aalto.fi (R.E.S.)

† These authors contributed equally to this work.

***** Author to whom correspondence should be addressed; E-Mail: jussi.kuutti@aalto.fi; Tel.: +358-505-124-243; Fax: +358-98-550-128.

Received: 22 December 2013; in revised form: 16 January 2014 / Accepted: 22 January 2014 / Published: 10 February 2014

Abstract: The concept of a local audio environment is to have sound playback locally restricted such that, ideally, adjacent regions of an indoor or outdoor space could exhibit their own individual audio content without interfering with each other. This would enable people to listen to their content of choice without disturbing others next to them, yet, without any headphones to block conversation. In practice, perfect sound containment in free air cannot be attained, but a local audio environment can still be satisfactorily approximated using directional speakers. Directional speakers may be based on regular audible frequencies or they may employ modulated ultrasound. Planar, parabolic, and array form factors are commonly used. The directivity of a speaker improves as its surface area and sound frequency increases, making these the main design factors for directional audio systems. Even directional speakers radiate some sound outside the main beam, and sound can also reflect from objects. Therefore, directional speaker systems perform best when there is enough ambient noise to mask the leaking sound. Possible areas of application for local audio include information and advertisement audio feed in commercial facilities, guiding and narration in museums and exhibitions, office space personalization, control room messaging, rehabilitation environments, and entertainment audio systems.

Keywords: local control of audio environment; directional speaker; parabolic speaker; flat panel speaker; ultrasonic speaker

---

1. Introduction

The ability to listen to whatever audio content you want, while others around you enjoy silence or their own program of choice is an attractive prospect—thus far, generally, achieved by wearing headphones. Listening with headphones, though, means that you cannot hear what anyone else is saying, unless the playback is paused. The ridicule of someone asking "What?" and tugging an earbud headphone out of one's ear to hear what you are saying is familiar to anyone. So is the conversation about whether it is a bigger nuisance for one to have to turn down the volume or the other to have to listen to something they do not want. Having your own music in the background, while holding a conversation with the person next to you, has not traditionally been very practical. In the near future it might become feasible, if emerging technologies that aim for an individually customizable indoor environment turn out successful.

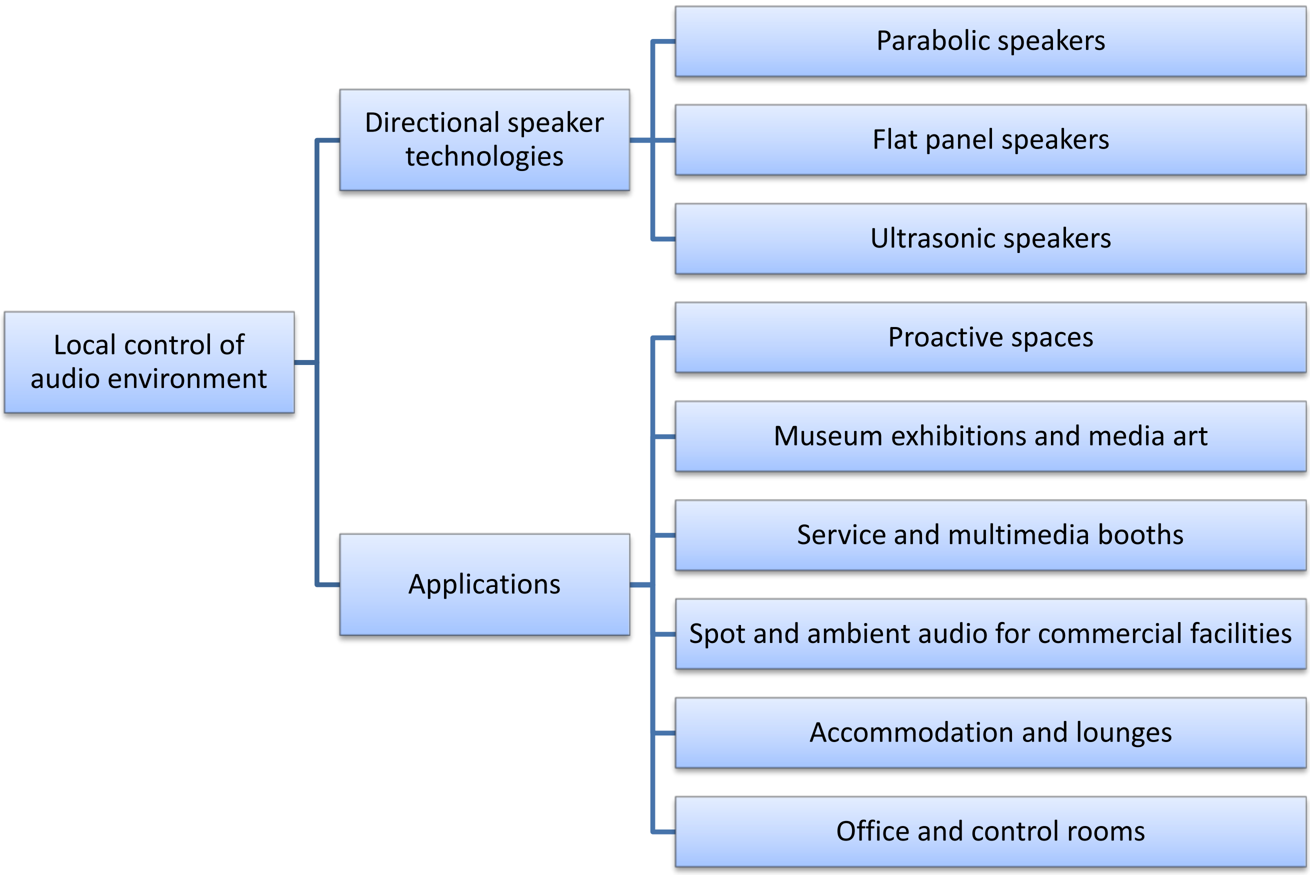
A local audio environment, as the concept is called, is a hypothetical application of computer and sensor controlled, or "smart" directional and localized audio technology, where the playback of sound can be spatially confined. That is, sound broadcast from the system would be bounded to a specific portion of a wider space, and inaudible elsewhere. With such a system it would ideally be possible to arrange completely independent listening conditions in closely adjacent positions, such as on different sides of a table or in different parts of a room. In a less idealized setting, the aim could be, for instance, to deliver focused audio to specific spots of a larger space, but to allow some sound to carry outside the intended area. Such a system could be used, for example, to create location-specific audio advertisements in a shopping mall, where background noise would efficiently mask the leaking sound.

It is important to understand the difference between the aim to direct and spatially restrict sound output, and the aim to affect how the listener experiences the sound. Creating a sound that can only be heard at a specific location and creating for a listener the perception of sound coming from a specific location are different things altogether. This study concentrates on technologies and applications of the former sort. We perceive the direction of a sound source by interpreting small differences in the sound as it arrives at each ear. The ears are separated by the width of the head, so a sound from one side arrives at one ear slightly earlier than the other. The ears point in different directions, thus, one hears the sound slightly louder than the other, depending on which side the source is located. Additionally, the shapes of the earlobe and head impose direction-dependent changes to the timbre of the sound. The brain combines these cues to a coherent perception of direction. Using a multiple-speaker system it is possible to produce sound that matches the directional cues at the listener's ears and the effect of sound coming from a chosen location can be created. The converse, however, is not possible. A surround speaker system cannot create a sound that is only heard by a listener at a chosen position—the sound will always come from the speakers and carry around the normal way [1].

On the other hand, the location where a sound is audible is determined by how sound travels within the space in question. Sound consists of vibrations, and vibrations travel as waves, which propagate readily through air, liquid, and solid objects, and can be reflected, absorbed or refracted along their path. Whether a sound can be heard at a certain location depends on whether the sound waves can reach that location at a sufficient intensity. Creating a local audio environment—that is to say, restricting sound within a bounded location—is problematic, as sound waves travel in a continuous pattern and cannot be made to stop arbitrarily. A wave will continue to travel until it gets reflected or absorbed, so there is no way to suddenly silence it in the middle of an empty room. Mostly, though, it is not necessary to completely silence the sound outside the target area, just to get it outside the human hearing range: either too quiet to be heard or so high-pitched that the ear does not react to it. This can, up to a point, be achieved with existing technology, such as directional speakers and modulated ultrasound.

This study presents a survey on the current state of the art of spatially limiting local control of audio environments. An overview of the speaker technologies and applications of local audio control handled in this survey are presented in Figure 1. This paper is organized as follows: Different directional speaker technologies are presented in Section 2, and Section 3 deals with application examples of local audio control. Section 4 discusses the results of this survey and conclusions are drawn in Section 5.

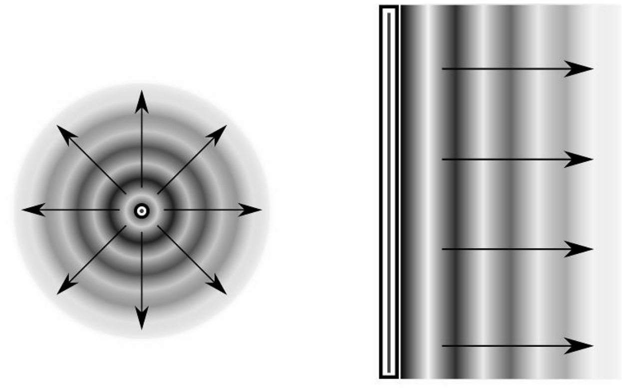
Figure 1. Overview of the directional speaker technologies and applications of local audio environment control handled in this review.



2. Directional Speaker Technologies

Generally speaking, sound waves do not travel in a straight beam, but spread from the sound source in, more-or-less, all directions. The shape of the source, however, has an effect on how much spreading will occur. If we consider theoretical sound emitters, an infinitely small point source emits sound in all directions equally, while an infinitely large plane source emits sound in one direction only without any spreading (Figure 2). Practical sources of sound, such as speakers, fit somewhere in between these two theoretical extremes [2].

Figure 2. Radiation patterns of theoretical sound emitters.



Speakers generate sound by vibrating an electrically actuated diaphragm, the motion of which produces sound waves in the surrounding air. The larger the diaphragm compared to the wavelength of the sound, the better it approximates a plane source, and the straighter a beam of sound is emitted. A speaker can therefore be made more directional by increasing the area of the diaphragm, with directionality being better for high frequencies than low frequencies [2–4]. Directionality can also be improved with parabolic reflectors, much in the same way as in spotlights. In this case, the degree of improvement in directionality again depends on sound frequency and the diameter of the reflector [5,6].

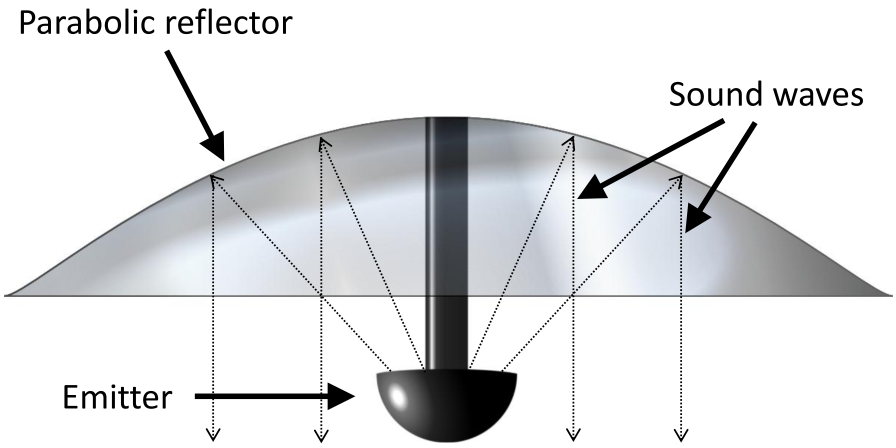
Traditional speakers have a conical diaphragm that is actuated by a magnetic coil attached to the middle of the cone. The conical shape gives the diaphragm stiffness against the forces of actuation, enabling it to maintain its shape when moving and to produce sound without distortion. If the diaphragm is made too flexible, it will bend and different parts of it will vibrate at different phases [7]. This sort of flutter adversely affects both the sound quality and the directional pattern of the speaker. Increasing the diameter and high frequency response of this kind of a speaker quickly makes it bulky and expensive, as exotic materials are needed to construct a sufficiently stiff diaphragm and the conical shape takes up space behind the speaker. Due to these limitations, other designs are better suited for directional speakers.

A highly directional speaker can transmit sound in a narrow beam, which for a listener means that the sound is loudest when standing in the center of the beam and drops off rapidly when moving to the side. Apart from this, directionality does not in itself directly translate to spatially confined sound. Regardless of how directional the source is, the sound will still be scattered and reflected around the environment when it hits an object, such as the floor, walls, furniture, or the listener’s head. In addition, a beam is confined in only two dimensions. While it can be pointed in any direction, the intensity of the sound along the length of the beam is not all that controllable. That being said, directional speakers can give good results for applications where a “sound corridor” is desired, or where the speaker is mounted on the ceiling directly above the listening spot, provided there is sufficient background noise to mask the sound leaking outside the intended area [3].

2.1. Parabolic Speakers

Perhaps the simplest approach to constructing a directional speaker would be to use a parabolic reflector. Instead of a large and flat diaphragm, the sound is generated by a small emitter which is positioned at the focal point of a much larger parabolically shaped dish made of sound-reflecting material, for example, polycarbonate plastic (Figure 3). The effect of the reflector is to steer the sound waves from the small emitter so that they reach the mouth of the paraboloid at an equal phase, creating in effect a flat emitter the size of the reflector's diameter. The design is simple and requires no special materials or components. Its main disadvantage is that the reflector dish takes up a lot of space and is not always easily integrated to an indoor environment [5,6].

Figure 3. Conceptual drawing of a directional parabolic speaker.



2.2. Flat Panel Speakers

Another approach to create a directional source of sound is to specifically aim for a flat panel speaker, which neatly fits in its surroundings (Figure 4). A flat panel speaker is more complicated than the parabolic reflector type, since the sound must be produced in phase over a broad area, placing more demands on the emitter. Large planar emitters are generally constructed in one of two alternative ways: either one large continuous diaphragm that is actuated over its entire area (for example, electrostatically), or an array of several closely spaced independently actuated emitters that are synchronized electronically [4,8].

A property of panel speakers that is worth noting is the ability to use beam-forming techniques to steer or focus the sound output without moving the speaker itself. If instead of maintaining a uniform phase over the whole emitter assembly a controlled phase difference is introduced between parts of the emitter, the strongest part of the resulting wavefront can be made to be emitted at an angle instead of perpendicular to the emitter plane. The amount of deflection can be controlled by varying the amount of phase difference. The phase difference itself can be achieved by introducing a delay between the actuation of adjacent emitter elements. In case of arrayed emitters this is trivial, but in a speaker with a continuous diaphragm the actuator system must be specifically adapted to the task, for example by providing independent control voltages to different parts of an electrostatically actuated diaphragm [4].

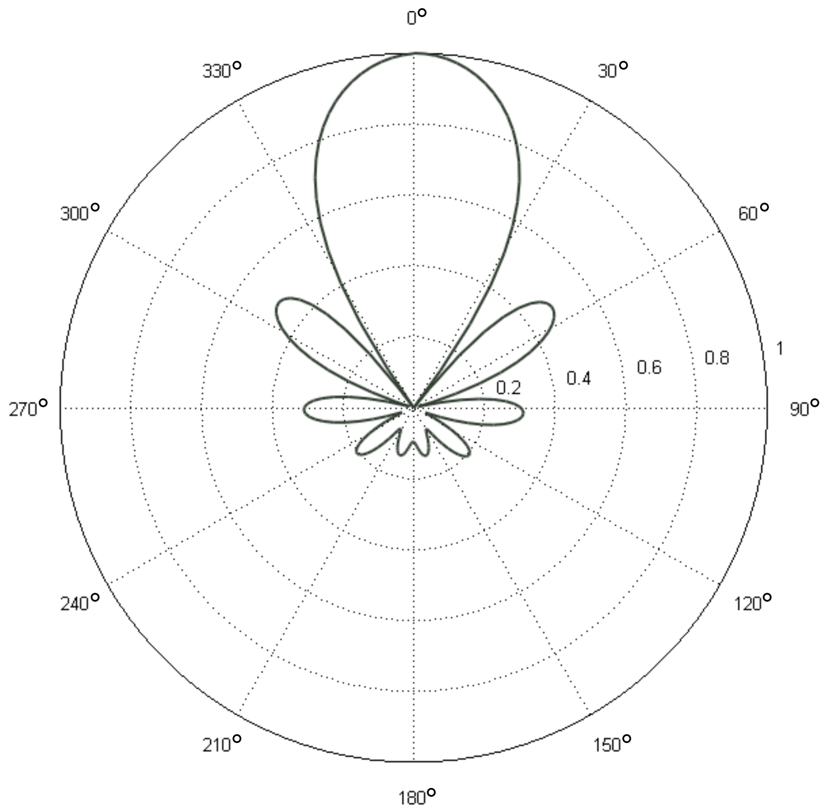
Figure 4. Examples of directional panel speakers (Panphonics Sound Shower).

Beam forming allows the so-called main lobe, or most intense part of the sound beam, to be pointed to a direction other than straight ahead within limits of some specified sector in front of the speaker. It also enables some adjustment to the directionality of the speaker, namely allowing it to be made less directional. The highest attainable directionality is limited by the physical size of the speaker, and cannot be exceeded even with beam forming techniques. Directionality also suffers the more the beam is steered off-center [9].

2.3. Ultrasonic Speakers

The directionality of a speaker can also be improved by increasing the frequency of the sound being transmitted. At first glance, this might not seem like a very useful observation, because the audio signal we want to broadcast is fixed to a very specific range of frequencies, namely the human hearing range. The signal would lose its meaning if we were to, for example, increase its speed to broadcast it at a higher frequency. It is, however, possible to use high-frequency ultrasound as a carrier for an audio-frequency signal. If a somewhat high-powered ultrasound source is amplitude-modulated with an audio signal, the non-linear properties of air as a transmitting medium cause the signal to be self-demodulated so that the modulating signal becomes audible [10,11]. The acoustic sound beam produced by the self-demodulation follows the radiation pattern of the ultrasound carrier, so the scheme can be utilized to create a speaker that is far more directional than a similar-sized speaker transmitting normally at audio frequencies. The method is quite promising and a subject of active research. It does have certain shortcomings, namely distortion due to sidebands created by the modulation, somewhat poor performance at low frequencies and relatively high power consumption from the perspective of mobile devices [11,12]. It seems likely that these aspects will improve as research advances. The principle of the directivity pattern of an ultrasonic speaker element is presented in Figure 5.

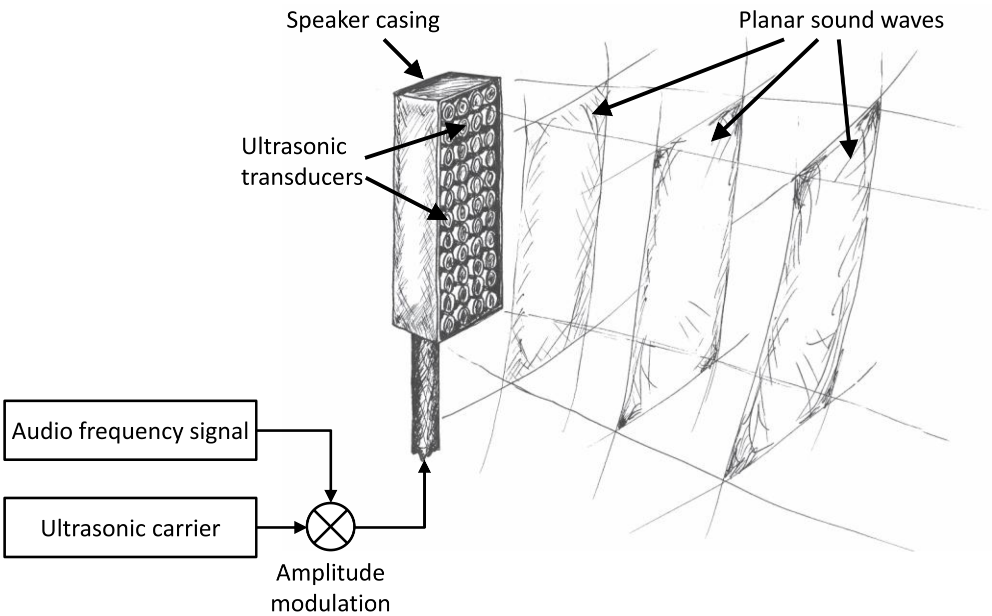
Figure 5. Rough conceptual drawing of the directivity pattern of an ultrasonic speaker element. The beam sizes present the proportion of sound emitted in different directions.



Westervelt *et al.* [10] presented the theory of scattering sound by another sound or the self-demodulation of a modulated ultrasound carrier in air. Air attenuates ultrasound frequencies more than audible frequencies and, hence, forms, in effect, a semi-permeable screen capable of extracting as audible sound an audio-frequency amplitude modulation carried by a high-frequency ultrasound. The process is analogous to the formation of a beat frequency in the superposition of two waveforms of slightly different frequencies. When the two waveforms are superimposed, two new waveforms are created, one with a frequency, which is the sum of the original two, and another with a frequency equal to their difference. If the original two waveforms are of ultrasonic frequencies and differ by an amount that corresponds to an audible frequency, the difference frequency resulting from their superposition can be heard as sound. In addition, it turns out that the compound waveform created by such a superposition is analogous to the waveform that results from amplitude modulating an ultrasound carrier with a frequency equal to the difference frequency of the superposition case. Thus, audible sound can be broadcast from an ultrasonic speaker by amplitude modulating the ultrasonic output [10].

Yoneyama *et al.* [11] presented an experimental setup for producing audible sound from modulated ultrasound by exploiting the nonlinear sound transmission properties of air described by Westervelt *et al.* [10]. An array of piezoceramic transducers is used to emit an ultrasound carrier, which is amplitude-modulated with an audio signal (Figure 6). The speaker is very sharply directional, because its radiation pattern is defined by the high frequency of the carrier wave rather than the lower audio frequencies of the modulation. [11].

Figure 6. Conceptual drawing and block diagram of an ultrasonic speaker.



The sound quality of the experimental speaker by Yoneyama *et al.* is not very high. The frequency response of the piezoceramic transducers used in the prototype is narrowly centered on their resonant frequency of 40 kHz, which limits the usable bandwidth of the modulating signal. This leads to uneven spectral characteristics of the output sound, thus, equalization of the input audio is needed for the speaker to sound acceptable. The linear modulation method used also causes harmonic distortion, which is inversely proportional to the square of the frequency. This limits the ultrasonic speaker's performance at low frequencies [11].

Kamakura *et al.* [13] presented a method to reduce the ultrasonic speaker distortion due to the signal squared, using a square root modulation scheme. Kamakura *et al.* [14] also proposed a further improvement to this. The power consumption of the speaker system is reduced by adjusting the power of the carrier wave according to the power envelope of the modulating audio signal. In previous systems, the carrier was always turned on and driven at constant average amplitude irrespective of whether any sound was being transmitted at the moment. In the new modulation scheme, the carrier is turned on only when sound is transmitted, and its power is adapted to the average loudness of the audio signal. The amplitude modulation now consists of two terms, one for the actual audio frequency modulation, and another term of much lower frequency for the carrier power modulation. The new modulation scheme reduces the power consumption to approximately a third of that of the basic amplitude modulation method [14].

Olszewski *et al.* [8] proposed a steerable beam ultrasonic speaker. The speaker is constructed from an array of generic commercially available 40 kHz ultrasonic transducers. Due to the high directionality of these transducers, conventional beam forming techniques are inefficient in steering the emitted sound field. In general, beam steering with a phased array is achieved by introducing a phase difference between elements in the array in such a manner that constructive interference of the radiated waves forms a high-intensity main lobe in the desired direction, while destructive interference mostly cancels out the waves traveling in other directions. For the interference pattern to occur, it is required that the emitters forming the array radiate somewhat equally in all directions. With directional emitters, the forward-radiated components are so strong that interference in the side lobes has little effect on the overall beam shape, and the main lobe remains pointing ahead in spite of the phase modulation. In the proposed system the emitters in the array are mechanically turned to steer the beam. Conventional phase-difference beam forming is used in addition to the mechanical steering to maintain phase coherence of the output wave [8].

Olszewski and Linhard [15] presented an ultrasonic speaker emitting multiple sound beams simultaneously in different directions. The speaker consists of several sub-arrays of ultrasound emitters, each of which points in a fixed direction so that the sub-arrays together cover all directions. Each sub-array can emit a separate beam of sound. The beams themselves are not steerable, so the directional resolution of the device depends on the number of sub-arrays built into it. The authors presented an experimental device with 13 sub-arrays arranged in sectored concentric rings. They report that finer directional resolution would not be useful, since the neighboring beams would overlap and become mixed together. On the other hand, what effect increased resolution would have on accurately orienting a single beam is not discussed [15].

A directional ultrasonic speaker was used in the Honda Asimo humanoid robot for spoken communication by Nakadai and Tsujino [16]. The benefits are that when speaking the robot's hearing is not affected by its own voice and the sound output (the robot's speech) can more easily be directed at a specific conversation partner (the person interacting with the robot). The gain of the ultrasound carrier wave is adjusted to control how far the broadcast carries. The adjusting is done to minimize the amount of sound that reflects back from the conversation partner into the robot's hearing microphones. Adjusting the carrier intensity is different from adjusting the apparent volume of the audio playback, that is, the modulation depth. The attenuation of the sound beam depends on the attenuation of the ultrasonic carrier, not the volume of the modulating signal. A strong carrier can be used to transport a quiet sound a long way. If only the modulation depth was decreased, the sound would appear quieter but it would still carry as far as before [16].

Nakashima *et al.* [12] presented an ultrasonic directional speaker that could be integrated with a handheld mobile device, such as a smartphone or a tablet computer. Their experimental setup consists of two separate speaker units that are installed into a mobile phone casing. The speaker units are located at each end of the phone, and the authors mention that they produce a good stereo channel separation even with such a small distance between them. Each of the speaker units is constructed of 16 commercially available piezoelectric transducers arranged in a cluster. It is noted that the system will need to be further miniaturized and the demodulation characteristics of especially lower audio frequencies need to be improved before the system is commercially viable. The authors also propose a system where the mobile device would identify its position to a computer controlling the surrounding smart indoor environment. The smart controller would then channel the audio output of the mobile device to the nearest one of several directional speakers. That speaker would then broadcast the audio for the person using the mobile device. This could help to overcome the small size of mobile devices, which makes it difficult to build speakers on them [12].

Pueo *et al.* [9] described how the theory of beamforming established in the field of radio transmission for antenna arrays could be applied in acoustics to model sonic beamforming with loudspeaker arrays. Beamforming is based on the principle of superposition, which states that the in-phase portions of two coincident waveforms will strengthen each other in constructive interference, while the out-of-phase portions will cancel each other out in destructive interference. The superposition principle can be applied equally well to acoustic and electromagnetic waves. The authors derive expressions, which describe a sound field generated by an array of loudspeakers. The field depends on certain factors, such as the relative positioning of the individual speakers and the amplitudes, phases and frequencies of the waveforms emitted at each one of them. The theorized behavior of the sound field is demonstrated experimentally with two computer-controlled speaker arrays, one with five and another with seven speaker elements. The results from the experiments correspond accurately with predictions from numerical simulations. An array of several speakers can produce a steerable beam of sound that is markedly more directional than the beam of a single speaker [9].

2.4. Commercial Examples of Directional Speakers

Panphonics Ltd. (Tampere, Finland) manufactures planar Sound Shower directional speakers exploiting plane wave technology. The available standard sizes are 60 cm × 60 cm and 120 cm × 20 cm. All units include a built-in amplifier, a power supply, and an assembly kit. The available connectors include a 3.5 mm standard audio plug and a USB socket for powering an external sound source. The amplifier includes a microphone for automatic volume adjustment based on ambient noise. The power rating of the speakers is 30 W. Panphonics Audio Elements are also available in custom sizes and they can be integrated with other products and building structures [17].

Audio Spotlight directional planar speakers by Holosonic Research Labs, Inc. (Watertown, MA, USA) exploit ultrasonic technology. The speakers are available in standard 40 cm and 60 cm square shapes, as well as in custom sizes and shapes. All systems include the speaker panel, a combined processor-amplifier and connection cables. The power rating can be chosen from 30 W or 65 W options [18].

Dakota Audio Inc. (Bismarck, ND, USA) manufactures planar overhead speakers with built-in amplifiers and a power rating of 15 W. They are available in sizes of 609 mm × 609 mm and 915 mm × 915 mm. The connectors include screw terminals and a 3.5 mm mini jack. Mini array speakers are available in sizes of 50 mm × 457–965 mm and 83 mm × 558–965 mm with a 3.5 mm mini jack input, and they are suitable for use with for example a flat screen television. All the models include power supplies [19].

Brown Innovations, Inc. (Boston, MA, USA) manufactures directional speakers available with both mono and stereo sound. The Maestro focusing speaker carries a built-in amplifier and has an automatic volume control based on the ambient sound level. Sound Dome parabolic speakers are available in diameters of 510 mm, 800 mm and 810 mm. The Double Sound Dome is a parabolic speaker with two emitters, designed to provide stereo sound for two listeners at the same time (its maximum power is 50 W per channel). The SonicBeam focused speakers are available in sizes of 51 mm × 305/610/915 mm and are intended to be used with a flat screen television. Their power limit is 25 W per channel [20].

The Secret Sound by MSE Audio SoundTube Entertainment (Overland Park, KS, USA) is a museum quality parabolic speaker with a molded composite housing. The diameter of the speaker is 762 mm and its height is 305 mm. An additional amplifier is needed for operation. The optimal assembly height of the speaker is 2.5–3 m. Greater installation heights are also possible; however, a slight increase in the sound beam coverage will occur above the recommended installation height range [21].

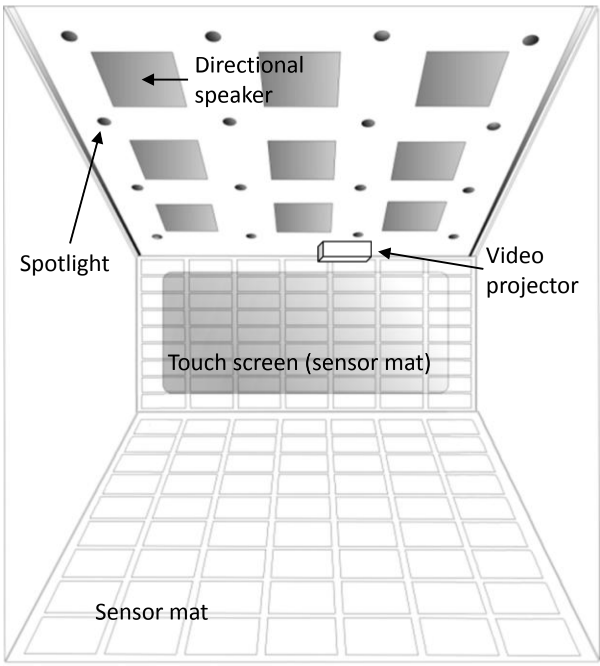
LRAD Corporation (San Diego, CA, USA) provides directional speaker devices for breakthrough hailing and warning for military and authoritative purposes of use. As their operational range is from hundreds of meters to even some kilometers, they are not suitable for indoor local audio environment applications [22].

3. Applications of Local Control of Audio Environment

3.1. Proactive Spaces

Linnavuo *et al.* [23,24] designed a proactive space for stroke and neurological disease rehabilitation. Previous research results show that enhanced therapy for stroke recovery is associated with improvements in a patient's gait. The proactive space provides a training environment for recovery purpose. The space gives the user stimuli from multiple sources: nine directional speakers and twelve spotlights mounted to the ceiling, and a large touch screen display created by a video projector on the sensor mat covered wall (Figure 7). The room's audio content, illumination, and visualizations can be controlled based on predefined cycles and the user location revealed by near field imaging. The floor and one wall of the room are covered with capacitive sensor mats that can be used to discover a person's feet or hand. In addition to neurological rehabilitation other possible applications of the proactive space are in computer game control techniques and in the area of multimodal interaction for educational learning environments [23].

Figure 7. Proactive space with various sources of stimuli (figure made for this review by Matti Linnavuo).

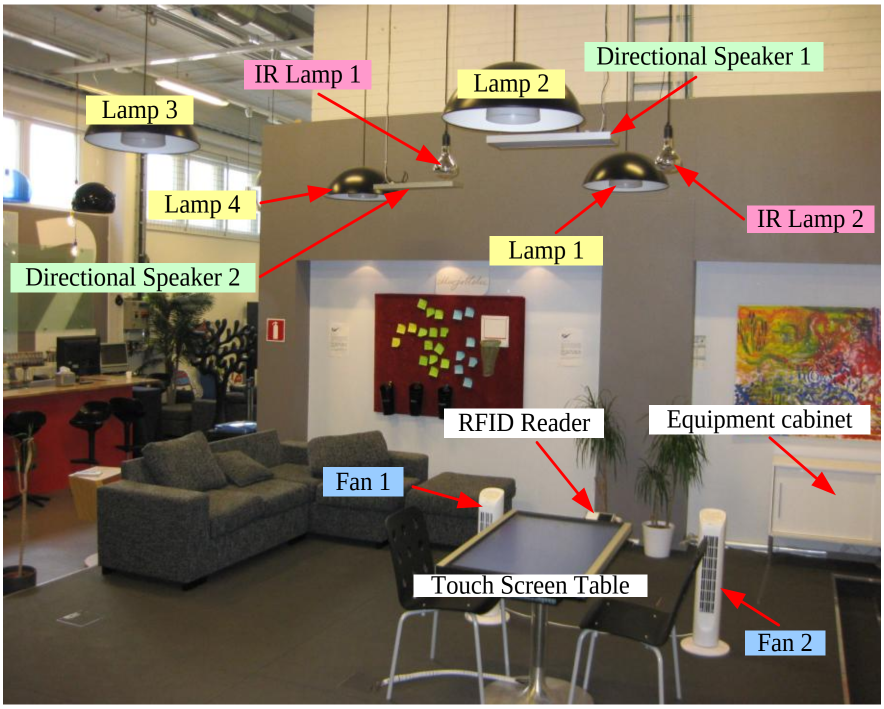


A pilot version of the proactive space with dimensions of 3 m × 4 m was constructed at the Aalto University School of Art and Design in Helsinki, Finland. The ELSI (Electric Sensors with Intelligence) research monitoring system by Marimils Ltd. (Tuusula, Finland), based on capacitive sensing, was used for movement detection. The system is capable of simultaneously detecting the location and movement of multiple people and needs no wearable tags on the subjects. Identification tags can be used with the system if needed, though. As one of the room's walls is covered with the ELSI mat, it is possible to use the video projector image as a variable function touch screen. The directional speakers assembled to the ceiling can be used to give location specific instructions and spatial cue sounds, or to play music. The area of audible sound under a speaker is about 50 cm in diameter for a standing person. Additionally, the spotlights can be controlled by a computer to produce light stimuli at selected locations of the space. To motivate a recovering patient, the programs used for rehabilitation are game-like and are automatized to be used without trained personnel. The games, the user interface and the collection of data are realized in LabView-code and run on a PC with the Windows operating system [24].

Feasibility of the pilot stage of the proactive space for rehabilitation purposes will be evaluated by professionals in neuropsychology. Preliminary tests with healthy subjects show that the space can be used even for slow paced gaming and especially the directional speakers are found to be useful in multi-person applications. In another realization of the proactive space similar features are exploited in simulating selected smart house functions [24].

The smart 4D-Space presented by Sormanen [25] is an indoor environment control scheme, which involves local control of lighting, audio content, heating and cooling (Figure 8). Some of the spatial conditions—ceiling lighting and a directional speaker above the couch—are controlled automatically based on user location. The user is detected using a similar capacitive ELSI monitoring system as Linnavuo *et al.* used [23,24]. The space occupants can use a touch screen table to adjust the illumination, the thermal IR lamps and the cooling fans above and next to the table. The content and volume of the music played from the directional speakers can also be chosen. The environmental functions of the touch screen table are only active if a user is detected next to it [25].

Figure 8. 4D-Space smart environment with individual environmental conditions (figure adapted with permission from Aleksi Sormanen) [25].



3.2. Museum Exhibitions and Media Art

At museum exhibitions, local audio can be combined with other forms of information, usually video content, without impractical and unhygienic earphones. Several separate museum installations can also be set in close proximity without disturbing overlap in the separate audio tracks being played. In media art, local audio forms an essential part of the artwork instead of just providing additional information about the installation or the artist.

Kortbek and Grønbæk [26,27] conducted a study about involving communicating art through interactive technology and spatial multimedia in the ARoS art museum in Aarhus, Denmark. The idea was to achieve holistic and social experiences with seamless transitions between the art itself and related information. Techniques used include spatially bounded audio, floor-based multimedia and multimedia interiors. Traditional audio guides were abandoned as the museum found them isolating and detached from the actual art experience [27]. Japanese artist Mariko Mori's exhibition was chosen as a target as her art already has built-in high tech elements. The design includes gentle audio augmentation of artworks and interactive installations in separate locations, but with conceptual connection to the original artwork. The interactive installations were intended as separate supplements revealing knowledge about the artworks and avoiding disturbance to the true art experience. The installations provide audio-visual cues for the possibilities of interaction [26].

The Sound of Art initiative includes 25 audio spots located near the artworks at the exhibition. Each of them comprises a visual circle on the floor and four meters above it a directional speaker equipped with a passive infrared (PIR) sensor. The type of audio material to be played is divided in three categories by using circle signs of different sizes on the floor. When a user steps on the circle's area the PIR sensor is triggered and an audio recording containing the artist's supplementation to the artwork is played. The audio clip being played can be changed by making small movements under the sensor. With directional speakers the audio experience can be made personal to the listener and undisturbing to others without shutting out the outside environment. Visitors can hear the playback at the same time with ambient sounds and each other's voices and even hold a conversation, which would be not possible while wearing traditional headphones. Two visitors can also share the same listening spot by bringing their heads together. The project includes a part called *The Contemplation of Art* containing interactive installations that communicate the inspirational sources behind the art, but are spatially detached from the corresponding exhibition pieces [26]. In addition, in contemplation room called *The Sprit from the Past* spatial audio is utilized. Visitors can walk through a maze and at separate listening posts hear about inspirational things behind the artwork. In this piece the audio is played continuously and an increase in volume can be experienced when the audio spot is approached. However, a close proximity is needed to properly distinguish the audio content [27].

The value of the technical installations at the museum was quantitatively evaluated using questionnaires and qualitatively through video shadowing and interviewing the visitors to the exhibition. During the three-and-a-half month period approximately 70,000 people visited the exhibition. Filled-in questionnaires were received from 91 visitors and four groups of two to three people were interviewed and videotaped as they explored the exhibition. Directional speakers were found to be pleasant as they did not bind visitors and reading text was not necessary. Visitors found the silver circles marking the audio spots attractive and interesting and the local sound environment personal. The augmentation of the artworks with the artist’s own voice was also found pleasing and creating closeness. Some couples liked to share audio spots, but other visitors thought on the contrary, that the spots prevented sharing the art experience properly and would be better suited for people visiting the museum alone. Larger audio spots for groups were also proposed. For the elderly it was occasionally difficult to properly hear the voice clips. Descriptions about the audio content to be heard were also occasionally missed. Over 80% of the respondents understood that the silver circles indicated interaction opportunities. About 67% of the respondents said that they would be more likely to visit art exhibitions with interactive communication, and about 17% would prefer traditional museum signs as sources of information. The authors conclude that the distinction between the descriptive content and the artwork itself should be clearer. The informative content could be further customized, for example to include an ability to select the spoken language and sound volume level. This could be realized by using computer interfaces or “smart” tickets containing visitor information [26].

The German automotive manufacturer BMW Plc. utilizes directional audio systems as part of the exhibits at its recently renovated museum in Munich, Bavaria, Germany. The close proximity of the exhibits with each other ruled out the use of traditional speakers, as this would have led to a cluttered and noisy sound environment [28].

The Japanese automotive manufacturer Toyota combines visual and directional audio information in its visitor and education center in San Antonio, TX, USA. The center provides visitors information about the car building processes in the company, and the audio content can be continuously played without disturbing the surrounding areas [29].

Local audio environments are also exploited in a museum context at Schirn Kunsthalle in Frankfurt am Main, Hesse, Germany and at the Chicago Cultural Center in Illinois, USA. The museums wanted to connect sound to certain exhibitions without adding any ambient noise to other spaces. The Perkin’s School for the Blind in Watertown, MA, USA uses directional audio in their museum to ensure that no distraction is caused to the auditorily sensitive students attending classes close by [30]. The setup additionally enables placing audio-equipped video installations in libraries, which are among the environments most sensitive to background noise. One example is a set of multiple displays and speakers providing news and information at the New York Public Library, USA [31].

At the Museum of Modern Art (MoMA) in New York, NY, USA, directional speakers have a role as a source of audio content that is part of the works made by artist Bruce Nauman [32]. The *Restaurant Symposium* installation by artist Markus Kåhre is another example of such media art, involving picture, sound and environment. The work creates an illusion of a restaurant space full of contemporary cultural people engaged in conversation. The artist Susan Philipsz also uses hidden directional speakers in her voice installation at the Helsinki Central Railway Station, Finland [33].

3.3. Service and Multimedia Booths

Local audio systems exploited in commercial service booths include user-operated systems for browsing and purchasing products and searching information about store facilities and non-interactive multimedia displays that are utilized to provide clients audio-video advertisements and possibly essential security information.

The German retail company Metro Plc. has launched a pilot hypermarket utilizing novel customer service applications in 2006. The store is located in Tönisvorst, North Rhine-Westphalia, Germany and it is part of the company's Real (stylized *real,-*) chain. One of the market's innovative services is an interactive media booth providing audio and video samples and information about the CD, DVD and Blu-ray products available at the store. Customers may search desired content manually from the database using the touch screen interface or just pick a disc they are interested in from the shelf and read its bar code at the booth. The system displays the cover art and contents of the disc on the screen, and the customer has a possibility to browse sample tracks (Figure 9, left). Audio tracks can be listened either by using traditional headphones or through the directional speaker element hanging on the ceiling in front of the media booth (Figure 9, right). With the overhead speaker, the music track or video clip is audible straight under it but the sound cuts off sharply already about half a meter aside. Ambient noise in the store helps cover the sound unavoidably leaking from the speaker [34].

Figure 9. Interactive media booth for customer use at the Metro Future Store: (**Left**) The user interface with a touch screen and a bar code scanner, and (**Right**) the overhead-installed directional speaker (figure adapted with permission from Petri Saarikko) [34].

The Estonian mobile operator Tele2 Estonia utilizes multimedia information kiosks with touch screen interfaces and directional sound in their stores. The kiosks can be used to browse, listen, and purchase E-books and music. Using directional speakers instead of traditional headphones increases the customer—and personnel—comfort and the level of hygiene. Maintenance costs are also reduced as there is no need to frequently replace the worn-out headphones [35].

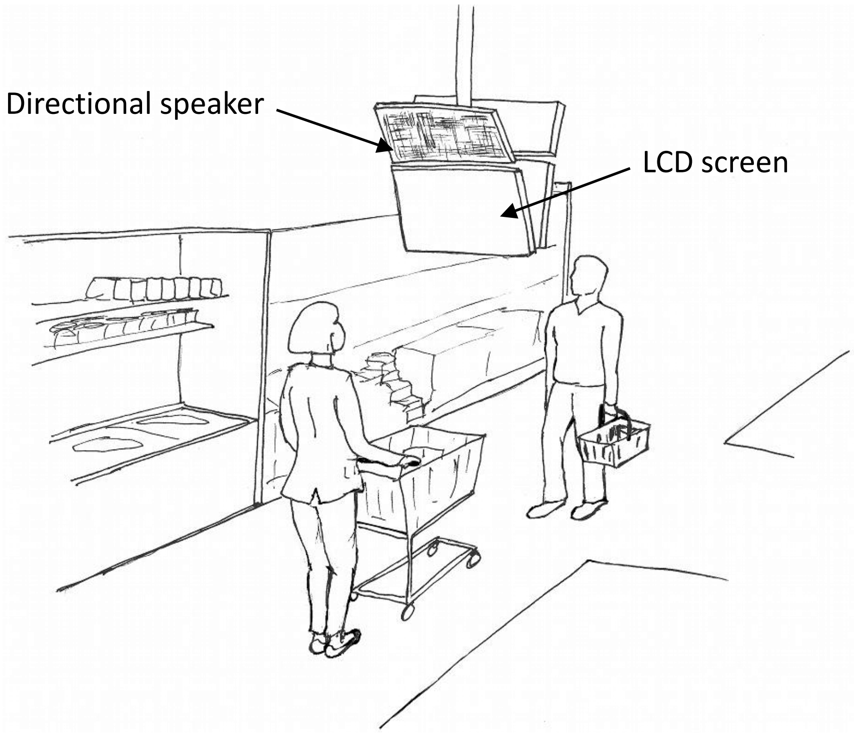
The American car rental agency AVIS exploits local audio environment in its Face2Face virtual service booths. By utilizing the booths at airports it is possible to cover large geographical areas and optimize back-office resources and thus better provide service also to customers arriving on the late-night flights. The virtual booth enables car key pick-up and processing the rental documents, and possible personal conversations remain private as a directional speaker is used [36].

A digital signage kiosk from American Becker Communications, Inc., has been installed at the Central Wisconsin Airport, USA. The kiosk combines LCD (liquid-crystal display) screens and directional audio to deliver information and advertisements to the airport customers. Each kiosk has three screens and speakers, enabling multiple advertisements at the same footprint, or alternatively displaying the same content to separate directions [37].

Combinations of LCD screens and directional speakers are also used in the visitor center of American Cisco Systems. With this setup, only those interested in interacting with the display will hear the related sound track, and the rest of the space will remain quiet and free of speaker noise [38].

Directional speakers connected to LCD screens are used to provide information and entertainment for the customers at K-Supermarket Mankkaa in Espoo, Finland (Figure 10). Plain LCD screens without audio content usually remain unnoticed by the customers, and using normal speakers would raise the overall noise level too high. The store has, altogether, 50 display-speaker systems above its main aisles, thus, targeting the sound only to the people currently on a certain aisle. The sound remains constant along the aisle despite the distance to the speaker, and it is decreased to almost a non-existent level elsewhere. Particularly the service counters are left free of the speaker sound [39].

Figure 10. Conceptual drawing of an information screen with directional audio content.



A similar combination of LCD screens and directional speakers is used in the Kamppi shopping mall, Helsinki, Finland. The information stations enable local advertisement without overlapping sound and a marked rise in the noise level. The constant sound strength is used to for example cover escalators with an even sound field over their whole length [40].

Multimedia displays of ALOOHA Ltd. (Mataró, Spain) and Media-TV Ltd. (Jyväskylä, Finland) combine video images and local audio content created with directional speakers. The systems can be used to show for example advertisements, news and weather or safety information at public locations. Media-TV displays are used, for example, at Finavia-maintained airports in Finland [41,42].

3.4. Spot and Ambient Audio for Commercial Facilities

Local ambient audio can be used to create the desired atmosphere to a public space, or to just provide the customers entertainment, for example in the form of popular music. Local audio can also be utilized to feed commercial content to clients waiting in a queue without disturbing the nearby employees. Directional audio can also be used to provide information at self-service counters [43]. Trade shows and fairs are often filled with general noise and competing advertisements. In this kind of environments directional speakers can be used to target the messages to a specific area and to effectively deliver the desired message to passers-by, or to highlight certain products. This additionally helps meet possible sound level regulations of the public event [44].

Directional speakers are exploited at the sports department of the German Metro Future Store mentioned above in creating an outdoor atmosphere by playing audio tracks containing birdsong [34].

At the fruit and vegetable department of K-Supermarket Mankkaa in Espoo, Finland directional sound is used to create a jungle atmosphere, and at the check-out area displays and directional speakers are utilized to offer entertainment to the customers in the queues. The sound is, however, cut off at the check-out counters [39].

Local audio realized with directional speakers also suits waiting room areas, where some customers may like to watch and listen to entertainment, while others prefer silence. Local audio is currently utilized for example in the customer facilities of an American eye care company Eyemaginations [45].

At Swisscom shops, across Switzerland, directional speakers are used at strategic points to divide the space to audio zones, and provide information related to things that customers are currently looking at [46].

The Danish Jyske Bank decided to abandon traditional bank counters and create a more open customer environment. For interested customers, information about the services of the bank is available on screens equipped with directional audio signs. Sound curtains created by using directional speakers are used to provide entertainment music and information notices at the bank's coffee shop [47].

The global oil and gas company, Shell, utilizes combined information displays and directional audio at its service stations in New Zealand to provide audio messages to people queuing to the counter. The messages are heard clearly by the customers in the queue, but do not disturb the store clerk or the person being served [48].

3.5. Accommodation and Lounges

In accommodation and lounge rooms local audio can be utilized to provide customers a convenient way for example to enjoy music of their choice as other clients that are sharing the same facilities are not disturbed.

The Best Western Hotel Haaga, in Helsinki, Finland, serves as a pilot location for the *Tomorrow's Hotel* project of the Haaga Helia University of Applied Sciences. *Tomorrow's Hotel* is a living laboratory for innovation and testing of new technologies that enable the modification of a hotel room's environment according to the preferences of each guest. The nature concept room connects customers with virtual outdoor environment, and the technology concept room provides technological innovations for the visitors' entertainment. In both rooms, directional speakers are utilized. In the nature concept room the speakers are installed above the bed to wake up the visitor with the sound of singing birds and the speaker can be also used when watching television. In the technology concept room two directional speakers are exploited to create adjacent sound fields—for watching television and relaxation on bed—without any interference [49].

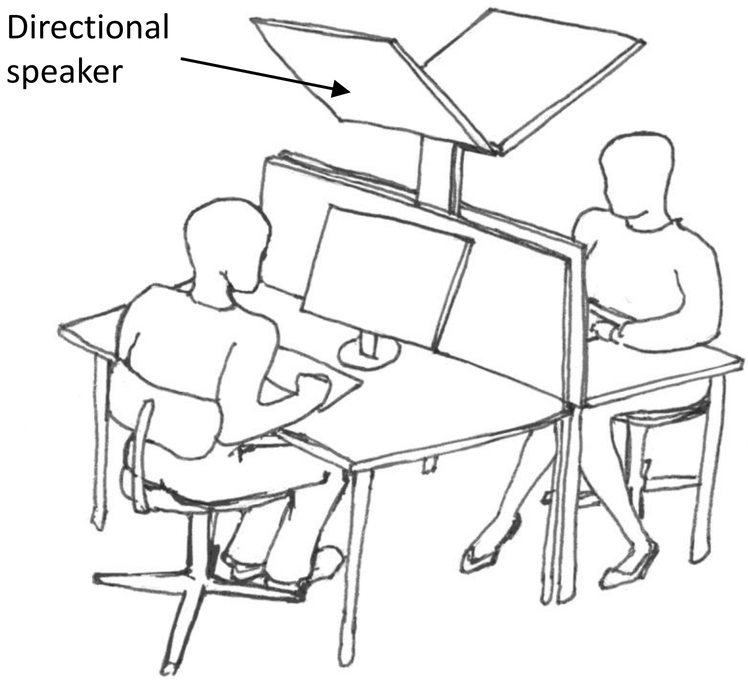
The Kontula center for the elderly in Helsinki, Finland, has quieted down their reception hall by creating relaxation spots with armchairs and directional audio above them. Thus, it is possible to sit and listen to music or audio books, while simultaneously being in the company of other people. Additionally, to cheer up the residents, one hallway is equipped with artwork and a directional speaker at the end of the corridor playing birdsong [50].

The PASEOT lounge concept of the Finnish-Estonian company Thorandson Ltd. enables personal and private audio content to be provided to exclusive customer spaces, such as airport business lounges and congress centers. With local directional audio no headphones are needed and users can connect their own audio sources to the system with the provided cords. Power sockets for charging the customers' mobile devices are also available [51].

3.6. Office and Control Rooms

Local audio can be used in offices and control rooms to create individual sound environments for communication and entertainment that cause no disturbance to others working in the same space (Figure 11). Local audio also removes the mechanical stress of headphones pressing the ears and makes simultaneous discussion with colleagues possible.

Figure 11. Conceptual drawing of creating individual audio environments at offices using directional speakers.



The Acu personal sound system for office use by the furniture manufacturer Martela Ltd. (Helsinki, Finland) creates individual audio zones for employees. The zone created by using a directional speaker gives a shield from possible ambient noise or disturbing speech without the need for isolating and uncomfortable earphones, and it also avoids disturbing other people. The system includes a radio receiver, connection sockets for audio players and a Bluetooth connection that enables the use of a mobile phone through the system [52].

The Maritime Rescue Sub-Center (MRSC) in Helsinki, Finland, is part of the Finnish Border Guard being in charge of the surveillance of the Gulf of Finland. The MRSC receives about 800 search and rescue calls annually. Each MRSC operator has a set of displays with different information content and a set of loudspeakers for monitoring multiple radio channels. Altogether 18 voice channels are simultaneously monitored at the sub-center and a clear hearing of each of them by the appropriate operator—without confusion created by mutual sound overlapping—is of great importance. For this purpose, three directional speakers have been installed above each operator desk behind the ceiling tiles and according to their geographical positions on map—for example the western surveillance areas are heard from the left speaker. Previously, traditional omnidirectional speakers were used [53].

The operations center developed by the Swiss ABB Ltd. and Swedish CGM Ltd. combines the ABB's 800xA automation platform and the CGM's EOW-x control environment. It involves directional audio, large monitors, remote graphical units, multi-client keyboards, and live video systems. The operations center can be utilized for example in factories and power plants. The system provides one sound system for public sounds like alarms and another for example for communications between operators, or for personal audio entertainment. Using directional audio the overall noise level is decreased, and up to 20 operators using different communication systems can simultaneously work in the same open space. These features increase the job satisfaction, safety, and collaboration between the operators [54].

4. Discussion

In this study a review on the current state of the art of the local control of audio environment was performed. Localized audio, realized with directional speakers, can be used to create individual and private sound environments for communication and entertainment, without causing disturbance to other people present in the same space. If needed, also holding a conversation while listening to the audio content is possible. The features of local audio control can help add new services to public facilities and improve well-being in work environments. The latter is a timely issue everywhere—even in western industrialized countries, where there is an increasing need for extending work careers. Currently, however, limited awareness of the technologies and the comparatively high price of the equipment will probably limit the adaptation of the local audio applications.

While preparing this review, the available scientific research on different directional speaker technologies was focused on ultrasonic technology and the range of studies on the technical background of parabolic and flat panel speakers could have been more comprehensive. Most of the application examples were of commercial origin. The case studies of the manufacturers of directional speakers were, however, presented here as areas of application only. There is, thus, still a need for more scientific research on the applications of local audio environment in order to get unbiased information about their practical performance and utility. Especially interesting would be evaluations of exploiting directional speakers in office environments, where the background noise is usually much lower than in public facilities, and thus provides less masking for leaking sound. In the area of development of directional speaker technologies, future focus should be in improving the directivity, compactness and power consumption of the speaker systems.

5. Conclusions

Directional speakers can be used to create spatially limited local audio environments without the acoustic isolation and mechanical stress pressing the ears caused by the traditional headphones. Currently directional speakers are planar or parabolic-shaped or they are based on modulated ultrasound. However, as even highly directional speakers radiate some sound outside the desired area, they are most suitable for environments with enough ambient noise masking the leaking sound. The directivity of speakers based on audible sound improves as the diameter of the speaker is increased. Thus, either the directivity or the compact size of the speaker has to be prioritized. Ultrasonic speakers enable improving the speaker's directivity while maintaining a compact size by increasing frequency of the signal transmitted. Currently, the main obstacles in effectively adapting ultrasonic speaker technology are the speakers' distortion due to sidebands created in the modulation, poor low-frequency performance and high power consumption. Possible areas of application for local audio include information and advertisement audio in commercial spaces, guiding and narration in museums and exhibitions, office space personalization, control room messaging, proactive rehabilitation environments, and entertainment audio systems. However, more research and product development is still needed to further improve the sound quality and directivity of the speakers as well as their compactness and adaptability to various installation environments.

Acknowledgments

This study was funded by the RYM Indoor Environment research program and the Aalto University Health Factory. Petri Saarikko and Aleksi Sormanen kindly permitted the use of their artwork and photographs as illustration in this review. Laboratory manager of the Health Factory Matti Linnavuo helped the authors by drawing a custom figure for this paper.

Author Contributions

Jussi Kuutti and Juhana Leiwo designed and carried out the literature survey, drew the original artwork and drafted the manuscript. Raimo E. Sepponen participated in the design of the survey and revised the manuscript critically. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Vilkamo, J. Spatial Sound Reproduction with Frequency Band Processing of B-Format Audio Signals. M.Sc. Thesis, Helsinki University of Technology, Espoo, Finland, 28 May 2008.
2. Plane Wave Technology. Available online: http://www.panphonics.com/how-it-works/plane-wave-technology (accessed on 30 October 2013).
3. Audio Element Manual. Available online: http://www.panphonics.com/sites/default/files/AudioElementManualv1–1.pdf (accessed on 5 November 2013).

4. Kelloniemi, A. Panphonics Audio Transducer Technology. Available online: http://www.panphonics.com/sites/default/files/audio_transducer_technology.pdf (accessed on 30 October 2013).
5. SB-1 Q&A. Available online: http://www.meyersound.com/pdf/products/industrial_series/sb-1_qa.pdf (accessed on 6 November 2013).
6. Technology Showcase: Focused Loudspeaker Systems. Available online: http://digitalcontentproducer.com/mag/avinstall_focused_loudspeaker_systems (accessed on 6 November 2013).
7. Rossing, T.D.; Moore, F.R.; Wheeler, P.A. *The Science of Sound*, 3rd ed.; Addison Wesley: San Francisco, CA, USA, 2002.
8. Olszewski, D.; Prasetyo, F.; Linhard, K. Steerable Highly Directional Audio Beam Loudspeaker. In Proceedings of the 9th European Conference on Speech Communication and Technology, Lisbon, Portugal, 4–8 September 2005.
9. Pueo, B.; Escolano, J.; Roma, M. Precise Control of Beam Direction and Beamwidth of Linear Loudspeaker Arrays. In Proceedings of the 2004 IEEE Sensor Array and Multichannel Signal Processing Workshop, Barcelona, Spain, 18–21 July 2004.
10. Westervelt. P.J. Parametric acoustic array. *J. Acoust. Soc. Am.* **1963**, *35*, 535–537.
11. Yoneyama, M.; Fujimoto, J.-I.; Kawamo, Y.; Sasabe, S. The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design. *J. Acoust. Soc. Am.* **1983**, *73*, 1532–1536.
12. Nakashima, Y.; Yoshimura, T.; Naka, N.; Ohya, T. Prototype of mobile super directional loudspeaker. *NTT DoCoMo Tech. J.* **2006**, *8*, 25–32.
13. Kamakura, T.; Yoneyama, M.; Ikegaya, K. Development of a Parametric Loudspeaker for Practical Use. In Proceedings of the 10th International Symposium on Nonlinear Acoustics, Kobe, Japan, 24–28 July 1984.
14. Kamakura, T.; Aoki, K.; Shinichi, S. A Highly Directional Audio System Using a Parametric Array in Air. In Proceedings of the 9th Western Pacific Acoustic Conference, Seoul, Korea, 26–28 June 2006.
15. Olszewski, D.; Linhard, K. Highly Directional Multi-Beam Audio Loudspeaker. In Proceedings of the 9th International Conference on Spoken Language Processing, Pittsburgh, PA, USA, 17–21 September 2006.
16. Nakadai, K.; Tsujino, H. Towards New Human-Humanoid Communication: Listening During Speaking by Using Ultrasonic Directional Speaker. In Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, 18–20 April 2005.
17. Panphonics—The Global Provider of Directional Audio Solutions. Available online: http://www. panphonics.com (accessed on 6 November 2013).
18. Audio Spotlight—Add Sound and Preserve the Quiet. Available online: http://www.holosonics. com (accessed on 6 November 2013).
19. Dakota Audio. Available online: http://dakotaaudio.com (accessed on 6 November 2013).
20. Brown Innovations. Available online: http://www.browninnovations.com (accessed on 6 November 2013).

21. SoundTube Entertainment. Available online: http://www.soundtube.com (accessed on 14 January 2014).
22. LRAD Corporation. Available online: http://www.lradx.com (accessed on 6 November 2013).
23. Linnavuo, M.; Ojapelto, A.; Sepponen, R. A Proactive Space for Rehabilitation, Gaming and Multimodal Interaction—A Poster Presentation. In Proceedings of the 13th International MindTrek Conference: Everyday Life in the Ubiquitous Era, Tampere, Finland, 30 September–2 October 2009.
24. Linnavuo, M.; Kovalev, O.; Sepponen, R. Proactive Space—A Novel Post Stroke Mobility Rehabilitation Tool. In Proceedings of the 2nd Circuits and Systems for Medical and Environmental Applications Workshop, Mérida, Mexico, 13–15 December 2010.
25. Sormanen, A. Individual Conditions in a Smart Environment. M.Sc. Thesis, Aalto University, Espoo, Finland, 7 November 2010.
26. Kortbek, K.J.; Grønbæk, K. Communicating Art through Interactive Technology: New Approaches for Interaction Design in Art Museums. In Proceedings of the 5th Nordic Conference on Human-Computer Interaction: Building Bridges, Lund, Sweden, 18–22 October 2008.
27. Kortbek, K.J.; Grønbæk, K. Interactive Spatial Multimedia for Communication of Art in the Physical Museum Space. In Proceedings of the 16th ACM International Conference on Multimedia, Vancouver, BC, Canada, 26–31 October 2008.
28. BMW Revs up its Munich Museum with Panphonics. Directional Speakers. Available online: http://www.panphonics.com/sites/default/files/Case3BMW_0.pdf (accessed on 30 October 2013).
29. Toyota Turns to Panphonics to Deliver Targeted Audio Content. Available online: http://www.panphonics.com/sites/default/files/Case2Toyota.pdf (accessed on 30 October 2013).
30. Audio Spotlight—Museums and Galleries. Available online: http://www.holosonics.com/brochure/Audio_Spotlight-Museums.pdf (accessed on 30 October 2013).
31. Audio Spotlight—Libraries. Available online: http://www.holosonics.com/brochure/Audio_Spotlight-Libraries.pdf (accessed on 30 October 2013).
32. Bruce Nauman's Award Winning Art Debuts at MOMA Museum of Modern Art, NYC. Available online: http://www.panphonics.com/sites/default/files/Case11BruceNauman.pdf (accessed on 30 October 2013).
33. Praised and Awarded Media Art with Sound Shower. Available online: http://www.panphonics.com/sites/default/files/Case16Pro-AV.pdf (accessed on 30 October 2013).
34. Saarikko, P.; Kuutti, J. Metro Group Future Store Initiative. Available online: http://www.slideshare.net/FourDee/metro-group-future-store-initiative-real-future-store-4744317 (accessed on 5 November 2013).
35. Direct Hits with Panphonics. Sound Shower. Available online: http://www.panphonics.com/sites/default/files/Case14Tele2.pdf (accessed on 30 October 2013).
36. AVIS Takes Advantage of Panphonics Directional Audio in Its New Virtual Service Desk Concept. Available online: http://www.panphonics.com/sites/default/files/Case8AVIS.pdf (accessed on 30 October 2013).
37. Digital Signage in the Central Wisconsin Airport Helps Advertising Take Flight. Available online: http://www.panphonics.com/sites/default/files/Case4CWAairport.pdf (accessed on 30 October 2013).

38. Audio Spotlight—Offices and Showrooms. Available online: http://www.holosonics.com/brochure/Audio_Spotlight-Office-showrooms.pdf (accessed on 30 October 2013).
39. Audio Allure in a Supermarket with Panphonics Speakers. Available online: http://www.panphonics.com/sites/default/files/Case23Ksupermarket_Mankkaa.pdf (accessed on 30 October 2013).
40. Helsinki's Newest Shopping Centre Utilises Panphonics Audio Technology. Available online: http://www.panphonics.com/sites/default/files/Case25Kamppi.pdf (accessed on 30 October 2013).
41. Boosting up the Digital Out-of-Home Advertisement. Available online: http://www.panphonics.com/sites/default/files/Case7ALOOHA.pdf (accessed on 30 October 2013).
42. Media-TV Succeeds Offering Quality Digital Signage with Panphonics Speakers. Available online: http://www.panphonics.com/sites/default/files/Case10MediaTV.pdf (accessed on 30 October 2013).
43. Audio Spotlight—Directional Sound for In-Store Advertising. Available online: http://www.holosonics.com/brochure/Audio_Spotlight-In-Store_Advertising.pdf (accessed on 30 October 2013).
44. Audio Spotlight—Trade Shows and Events. Available online: http://www.holosonics.com/brochure/Audio_Spotlight-Trade_Shows.pdf (accessed on 30 October 2013).
45. Audio Spotlight—Waiting Rooms. Available online: http://www.holosonics.com/brochure/Audio_Spotlight-Waiting_Rooms.pdf (accessed on 30 October 2013).
46. Panphonics Directs Audio to Switzerland. Available online: http://www.panphonics.com/sites/default/files/Case21SwissCom.pdf (accessed on 30 October 2013).
47. Panphonics Oy Co-Operates with Denmarks Most Modern Bank. Available online: http://www.panphonics.com/sites/default/files/Case26Jyskbank.pdf (accessed on 30 October 2013).
48. Panphonics Powers Energy Giant's Communication. Available online: http://www.panphonics.com/sites/default/files/Case22Shell.pdf (accessed on 30 October 2013).
49. Creating the Future with Panphonics Sound Shower. Available online: http://www.panphonics.com/sites/default/files/Case9Tomorrows_Hotels.pdf (accessed on 30 October 2013).
50. Panphonics Sound Shower Lightens up the Atmosphere for the Seniors. Available online: http://www.panphonics.com/sites/default/files/Case20ElderlyHome_Kontula.pdf (accessed on 30 October 2013).
51. PASEOT Delivers Personal Audio Environments with Help from Panphonics. Available online: http://www.panphonics.com/sites/default/files/Case5Paseot.pdf (accessed on 30 October 2013).
52. Directional Audio Heads to the Office. Available online: http://www.panphonics.com/sites/default/files/Case28Martela.pdf (accessed on 30 October 2013).
53. Maritime Rescue Command Center, Helsinki. Available online: http://www.panphonics.com/sites/default/files/Case27Maritime.pdf (accessed on 30 October 2013).
54. Panphonics Boosts Operator Focus in ABB's and CGM's Control Environments. Available online: http://www.panphonics.com/sites/default/files/Case12ABB.pdf (accessed on 30 October 2013).