An electro-acoustic implementation of Tibetan bowls: Acoustics and perception

Ronald M. Aarts*, Okke Ouweltjes and Murtaza Bulut
Smart Sensing and Analysis Group, Philips Research, Eindhoven, 5656 AE, The Netherlands *Also with Technical University Eindhoven, Department EE, Den Dolech 2, PT3.23, P.O. Box 513, NL-5600MB, Eindhoven, The Netherlands
{ronald.m.aarts, okke.ouweltjes, murtaza.bulut}@philips.com

Abstract
Tibetan singing bowls are employed worldwide for meditation, music, relaxation, personal wellbeing, and religious practices. Each Tibetan bowl can produce a limited number of sounds, defined by the size and material of the bowl, and the actuator device used. Usually, there is a need for a second person to actuate the bowl. Addressing these limitations, we built an electronic device, named eBowl, which can mimic the acoustics of Tibetan bowls, and beyond that, can produce a wide range of other sounds. Furthermore, it can be used for relaxation and sound massage without the need for a second person. The eBowl generates auditory beats that are in EEG alpha frequency range, which can cause brainwave entrainment and lead to relaxation. User tests measuring physiological parameters revealed the eBowl's effectiveness for relaxation, showing that eBowl influences skin conductance, heart rate, and respiration rate and induces relaxation.

1. Introduction

Singing bowls (also known as Tibetan singing bowls, Tibetan bowls, rin gongs, medicine bowls, suzu gongs in Japan, or qing (also shun or ching) in China) are a type of bell, specifically classified as a standing bell. An example is shown in Figure 1.

Singing bowls were historically made throughout Asia. Today they are made in Nepal, India, Japan, China, and Korea. The best known types are from the Himalayan region and are sometimes referred to as Himalayan singing bowls [1, 2].

Singing bowls have been traditionally used throughout Asia and the tradition of making sound with bronze bowls goes back 3,000 years to the bronze age. Today they are employed worldwide both inside and outside of spiritual traditions, for meditation, music, relaxation, personal well-being and religious practice. Singing bowls are used in healthcare by psychotherapists; massage therapists; and recovery, stress and meditation specialists. They are popular in classrooms to help facilitate group activities and focus students' attention [1].

Figure 1. Upper right: a Tibetan bowl (19 cm diameter, 10 cm height); Left: the eBowl, the electro-acoustic implementation of Tibetan bowls; In front: a puja, an actuator device for Tibetan bowls.

Rather than hanging inverted or attached to a handle, singing bowls sit standing with the bottom surface resting, and it is the sides and rim of the singing bowls that vibrate to produce the sound. The bowls can be made to ring by striking. The sound of the bowl when struck is related to bell sounds [3]. The sound mainly depends on the shape, material and size of the bowl and the hardness of the striker. However, the more characteristic usage type is based on a rubbing interaction, which is performed as follows. The bowl is rubbed with a wooden stick called "puja" (see Figure 1), which may or may not be wrapped in a thin sheet of leather. The performer rubs with the stick around the outer rim of the bowl at various speeds and tangential forces. If performed correctly, the rubbing movement creates a sustained ringing sound [4].

The bowl can be placed on users' hands or abdomens for body massage, but different usages are possible as well. For example, even when feet or body are not touching the bowl, one clearly perceives the sound as well as the vibration due to the acoustic coupling.

A drawback of the known Tibetan singing bowls is that there are a limited number of sounds that can be produced. The number of sounds that can be generated depends on the number of available singing bowls. The sounds are determined by the size, material, and method of actuation. One bowl can produce only a limited range of sounds. Another limitation is that during massage with a Tibetan bowl, there is a need for a second person to be present to operate the bowl. It is not preferred that the bowl is operated by the person being massaged, as this can be disturbing for relaxation, prevent proper use of the bowls, and be very difficult depending on where the bowl is placed.

In today's fast paced lifestyle and society, there is a need for people to relax. Preliminary investigations have shown that there is a need to have solutions that enable people to relax by themselves. For that purpose, an electro-acoustic version, called eBowl (shown in Figure 1), of a Tibetan bowl was built. The eBowl mimics the acoustic properties of the Tibetan bowl, is able to produce wide range of sounds, but can be operated by the person receiving the massage. Note that the eBowl is designed as a relaxation device, and it is not intended to be an exact electronic copy of Tibetan bowls.

The focus of the present paper is the design of the eBowl and its influence on listeners. Acoustic characteristics of the Tibetan bowl are analyzed, and the eBowl is designed so that similar characteristics – including sound, radiation behavior, and vibrations – as real bowls are reproduced. Effectiveness of the eBowl on relaxation is validated with user tests where both objective and subjective measurements were conducted. There is no formal psychophysiological definition of relaxation, however in the following we assume that the intuitive meaning one has is sufficient to make a connection to psychophysiological measures.

We hypothesized that the relaxation effect of listening to the Tibetan bowl sounds (and therefore of the eBowl) occurs because they can cause brainwave entrainment due to the generation of auditory beats with a frequency corresponding to the listener's EEG alpha range.

The paper is organized as follows. A brief summary of monaural and binaural beats and the brainwave entrainment concept are discussed in Sec. 1.1 and Sec. 1.2, respectively. The acoustics and design of the eBowl are discussed in Sec. 2. The user test results are presented in Sec. 3. Discussion of the paper is done in Sec. 4 and conclusions are given in Sec. 5.

1.1 Introduction to monaural and binaural beats

In [5] methods of reproducing low-pitched signals through small loudspeakers are discussed. Figure 2 shows one of these methods.

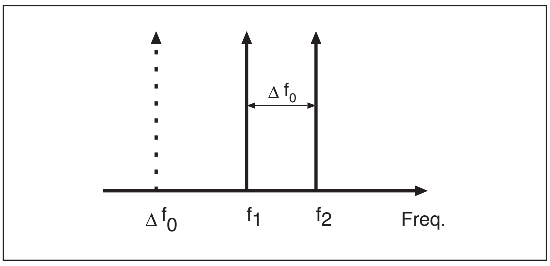


Figure 2. Difference tone, also known as third tone, tartini tone, terzi suoni, grave harmonics, combination tone, or acoustic bass. (From [5] Figure 2-c.)

Figure 2 shows two tones at frequencies f_1 and f_2. If f_1 and f_2 are presented to one ear or both ears at the same time, a tone at $\Delta f_0 = f_2 - f_1$ is perceived, known as an acoustical beat, monaural beat, or the alternative names shown in Figure 2. If f_1 is presented to one ear and f_2 to the other ear, the tone at $\Delta f_0 = f_2 - f_1$ is also perceived, referred to as a binaural beat.

It is important to note that (in both cases) Δf_0 is not present in the spectrum, therefore it is dotted in Figure 2. The origin of Δf_0 in both cases is different. Acoustical beats occur because the two frequencies are alternating in phase and out of phase and thus cancel and reinforce each other; the intensity fluctuates at a rate Δf_0 [6]. In the binaural beat case Δf_0 originates in higher nuclei in the brain.

While not as long as monaural beats, binaural beats have attracted attention for a long time as well. According to Stewart [7] the first recorded experiments with binaural beats were made by Dove in 1839, and a topic review including the year 1896 was given by Rostosky in 1905. While discussed in more specialized journals, it was brought to a broader audience by Oster in 1973 [8]. Nowadays one can buy CDs with binaural beats and there are smart phones with apps using them.

Although the origin is different, Schwarz and Taylor [9], and Pratt et al. [10] have shown that acoustical beats can have similar brain entrainment properties as binaural beats. A second commonality is that in both cases, binaural and monaural – as pointed out in [5] – only small loudspeakers are required which are capable of radiating the relatively high frequencies f_1 and f_2, say 539 and 549 Hz, respectively. While a Δf_0 of 10 Hz may be perceived, a small loudspeaker would not be capable to radiate this frequency at a sufficient sound pressure level (SPL). It is shown in Sec. 2 that the Tibetan bowl indeed generates such beats.

In the literature, it is suggested that listening to binaural auditory beats can affect psychomotor performance, mood [11, 12], and relaxation [13]. This may have applications for the control of attention and arousal and the enhancement of human performance [12]. Several papers report a visible change in the EEG spectrum, a so called brain entrainment. By exposing a participant to light, flashing at a certain rate [14, 15] or sound with specific frequency components [9, 10] the brain adapts to the frequency of these stimuli. The frequency range of these sound stimuli are in the range of the low frequency beats generated by Tibetan bowls (1-13 Hz). The eBowl can produce similar sound stimuli. Therefore, we hypothesized that the relaxation effect of listening to Tibetan bowls occurs because they will cause brainwave entrainment due to the generation of auditory beats of a frequency corresponding to the listener's EEG alpha range.

1.2 Introduction to brainwave entrainment

An early publication on brainwave entrainment by sensory stimulation is [16] and a large stream of publications have followed since. The present paper does not intend to give an exhaustive literature review on brainwave entrainment, but its scope is mainly limited to the effect on health and wellbeing, for example by alleviating stress by inducing relaxation.

The chapter "Audio-visual entrainment" in David Vernon's book [11] is on enhancing human performance using brainwave entrainment, and a comprehensive review paper on the psychological effects of brainwave entrainment is given by Huang [17]. The term 'entrainment' is used for the effect that two oscillating systems interacting with each other tend to approach each other in terms of frequency. A simple example of this is the self-synchronizing clocks on the wall, an effect which was noticed by the Dutch mathematician and physicist Christiaan Huygens (see e.g. Wikipedia's entries 'Entrainment' and 'Odd sympathy'). The term 'brainwave entrainment' (also called 'audio-visual entrainment' (AVE), 'brain entrainment', 'audio-visual stimulation', 'auditory entrainment' and 'photic stimulation') refers to the use of rhythmic sensory stimuli to stimulate targeted frequencies in the brain. Such sensory stimuli can be auditory, visual or a combination of the two. Research has repeatedly confirmed that stimuli with frequencies between about 8 and 12 Hz, which corresponds with the alpha range of the electroencephalogram (EEG), induce a frequency-following response in the brain as visible in EEG recordings. There is also entrainment possible beyond this frequency range, but for wellbeing applications the range is usually restricted to the EEG-alpha range. We hypothesize that brainwave entrainment occurs during listening to Tibetan bowls and their electronic version, the eBowl.

One of the very few formal listening tests to singing bowls is done by Thies [18], he suggested but did not perform any physiological measurements. He carried out an experiment involving 60 subjects, each of whom was exposed individually to sounds produced live on a medium-sized Tibetan singing bowl. Verbal statements were collected. Most listeners regarded the sounds as pleasant due to their long decay, beating, and softness. The primary effect was an increased feeling of relaxation. Another reported effect was improved concentration.

In the following sections we will discuss the acoustics and design of Tibetan bowls (Sec. 2) and support our hypothesis for relaxation by user tests (Sec. 3).

2. Design of an electro-acoustic version of a Tibetan Bowl

The generation of the sound of Tibetan bowls is associated with that of partly filled wine glasses [19, 20, 21, 22] or the Glass harmonica [23]. Mozart, Berlioz, et al. wrote music for this harmonica [24]. Glasses have been in contemporary use as well, e.g. by the famous rock band Pink Floyd during the recording of "Shine On You Crazy Diamond" on their Wish You Were Here album, recorded and released in 1975 [19]. In fact, there is a very active organization called Glass Music International [25], and individuals, see e.g. [26, 27], engaged with glass music.

Most of the basic elements of the theory are to be found in Rayleigh's classic *Theory of Sound* [28] and in particular for the Tibetan

Bowls in [29, 30, 31].

The acoustics of the real Tibetan bowl are mimicked by the designed electro-acoustic version. Three aspects were considered. (i) The sound is synthesized using modal synthesis. (ii) The sound radiation is mimicked using a small circular array of three loudspeakers that generate sound in a way that the listener gets a spatial impression which is similar to that of a real Tibetan bowl. (iii) The vibrations are simulated using an additional actuator at the bottom of the electro-acoustic bowl which vibrates the bottom part of the enclosure. The circular array of three loudspeakers is placed on the top, as it can be seen in Figure 1. The additional vibrator (not shown) is placed at the bottom.

2.1 Analysis and synthesis of Tibetan bowl sounds

When a Tibetan bowl is struck on the rim by a hammer, usually fitted with a felt tip, called the puja, the bowl starts to vibrate and radiate sound. Figure 3 shows an anechoic chamber sound recording of the Tibetan bowl shown in

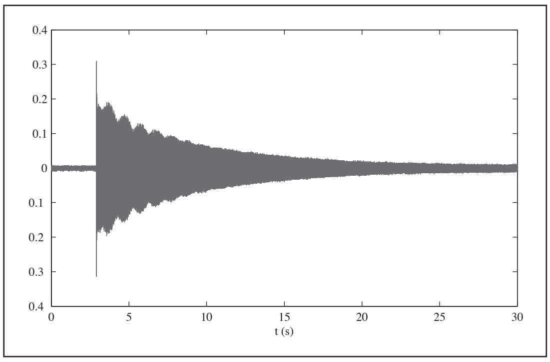


Figure 3. Acoustic response of the Tibetan bowl shown in Figure 1 being hit with a hammer with a felt tip.

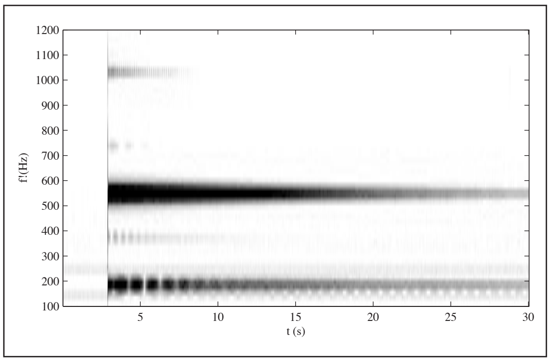


Figure 4. Spectrogram of the acoustic response shown in Figure 3. Especially at the fundamental frequency of around 188 Hz a beating phenomenon can be observed. Note that, for higher order modes this beating also occurs, but cannot be seen because of a time resolution of the spectrogram.

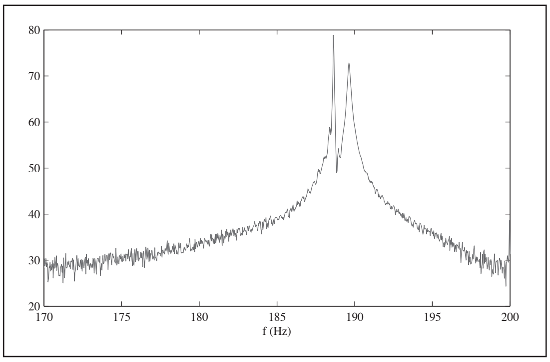


Figure 5: Part of the spectrum showing that the beating phenomenon in Figure 4 is caused by a modal pair.

Figure 1. From the envelope of the decaying signal it can be seen that a beating phenomenon occurs, this is more clearly visible in the spectrogram in Figure 4, where the beating phenomenon is shown at the fundamental frequency of around 188 Hz. When zoomed in to the spectrum of this particular mode, see Figure 5, it can be seen that the beating is caused by the existence of two modes with a slight difference in frequency, which is called a modal pair.

In [29] it is shown that the modal pairs are caused due to slight imperfections in the symmetry of the Tibetan bowl which lead to two orthogonal modes with slightly different natural frequencies, and that these pairs may occur in every mode. The sound synthesis of these kind of systems can be done with a physically motivated model, called modal synthesis [32, 33]. This model consists of N modes where each mode has a modal frequency f_n, an amplitude coefficient A_n and a decay rate d_n. Using these, the impulse response $y(t)$ as a function of time t, is the output of a sum of damped harmonic oscillators

$$y(t) = \sum_{n=1}^{N} A_n e^{-d_n t} \sin 2\pi f_n t. \quad (1)$$

To extract the modal parameters from the Tibetan bowl recording, a spectrogram based algorithm [32] is performed on the decaying part of the impulse response. The time domain recording is split into half-overlapping windows, which are transformed to the frequency domain using a fast Fourier transform. The window length is chosen such that the duration is 1.5 s, this is in order to give sufficient resolution in the frequency domain such that the modal parameters of a modal pair as shown in Figure 5 can be analyzed separately. By taking the logarithmic amplitude of each spectrum, the parameters of

Eq. 1 are effectively linearized to a simple linear regression problem given by $\ln|Y_n(t)| = \beta_n t - d_n$, where $|Y_n(t)|$ is the logarithmic amplitude of the n^{th} frequency bin at time t and $\beta_n = \ln A_n$ the regression coefficient of the n^{th} frequency bin.

Besides the modal parameters a correlation coefficient is also calculated for each frequency bin. Finally, the modes are detected by using a peak finding algorithm for finding the local maxima in both the correlations and the fitted amplitudes. The results of the modal analysis of the recording shown in Figure 3 are given in Table 1.

An efficient way of implementing the synthesis algorithm given by Eq. 1 on a DSP or other computer based audio platform is to implement it as a parallel filter bank of N second order recursive filters [32], [34] of the form

$$y[m] = y[m-1]a_1 - y[m-2]a_2 + b_1 x[m], \quad (2)$$

where $y[m]$ is the discrete output signal and $x[m]$ the discrete input signal, the coefficients are $a_1 = -2R\cos\frac{w_n}{f_s}$, $a_2 = R^2$, $b_1 = A_n R \sin\frac{w_n}{f_s}$, and where f_s is the sample rate, $\omega = 2\pi f_n$ and $R = \frac{\exp d_n}{f_s}$. The input signal $x[m]$ can be an impulse or a cosine window with length T

$$x[m] = (1 - \cos(\frac{2\pi t}{T}))/2, \quad (3)$$

for $0 <= t < T$, $x[m]$=0 for $t > T$.

Table 1. Results of the modal analysis, note some modes do not form a modal pair because one of their amplitudes was below the noise floor of the recording

f_n(Hz)	A_n(dB)	d_n
189.09	-19	0.0753
191.11	-28	0.258
378.18	-40	0.144
539.68	-23	0.237
551.12	0	0.157
740.2	-51	0.185
1031.6	-40	0.277
1039.0	-45	0.217
1101.6	-54	0.188
1633.2	-88	0.194

2.2 Design of the eBowl: Synthesis of sound field

The sound field of a vibrating bowl is in principle a multipole source with regions of positive and negative pressure[35]. The radiation of a single loudspeaker [36,37,38,39] is not similar as that one of a bowl. An accurate reconstruction of the required sound field is possible using the Huygens principle [40] but it would require an array with a large number of loudspeakers which is impractical for our purpose. Another possibility would be to use the theory of phantom sources [41], but due to the lower efficiency of this method the loudness [42,43] may decrease unacceptably in particular for small loudspeakers. Therefore we applied a different method.

In order to mimic the sound radiation of the Tibetan bowl a small three element circular loudspeaker array is used. In [44] it is shown that with a circular array of three microphones a super-directional response can be realized that can be steered with its main-lobe to any desired azimuthal angle. Also the radiation pattern can be adjusted to have any first-order pattern, like for example a cardioid.

The patterns are constructed from a monopole $S_m^0(\omega)$ and an orthogonal dipole pair $S_d^0(\omega)$ and $S_d^{\frac{\pi}{2}}(\omega)$. This principle is reciprocal and is used here for the sound reproduction of the electro-acoustic version of the Tibetan bowl. When three omni-directional loudspeakers, $L_1(\omega)$, $L_2(\omega)$ and $L_3(\omega)$ are placed in a trigonal planar geometry the linear combination weights are

$$\begin{bmatrix} L_1(\omega) \\ L_2(\omega) \\ L_3(\omega) \end{bmatrix} = \begin{bmatrix} 1 & 2 & 0 \\ 1 & -1 & -\sqrt{3} \\ 1 & -1 & \sqrt{3} \end{bmatrix} \begin{bmatrix} S_m^0(\omega) \\ S_d^0(\omega) \\ S_d^{\frac{\pi}{2}}(\omega) \end{bmatrix}, \quad (4)$$

for frequencies with wavelengths larger than the size of the array, otherwise aliasing will occur. The monopole and orthogonal dipole pair are dependent on the shape of the radiation pattern α (α=0 dipole, α=0.5 cardioid, α=1 omni-directional), and the input signal $X(\omega)$

$$S_m^0(\omega) = \frac{\alpha}{3}X(\omega), \quad (5)$$

$$S_d^0(\omega, \phi) = \frac{2c}{d}\cos(\phi)\frac{1-\alpha}{3i\omega}X(\omega), \quad (6)$$

$$S_d^{\frac{\pi}{2}}(\omega, \phi) = \frac{2c}{d}\sin(\phi)\frac{1-\alpha}{3i\omega}X(\omega), \quad (7)$$

where c is the speed of sound, d the diameter of the array and ϕ is the angle of the main lobe of the pattern. Varying the angle ϕ over time gives the user a spatial impression. The complete processing scheme is given in Fig. 6.

2.3 Design of the eBowl: Synthesis of the vibration signal

When a Tibetan bowl is placed on the belly of

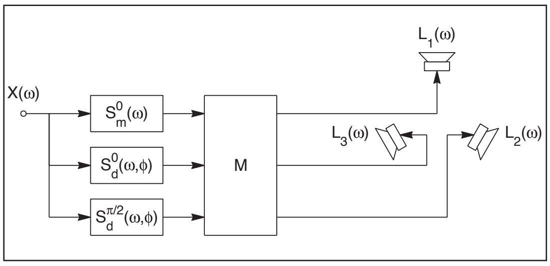


Figure 6. Processing scheme for the circular loudspeaker array, where M denotes the linear combination as given by Eq. 4.

a person lying down, the vibrations of the bowl can be also felt. This is not the case for the electro-acoustic bowl where reaction forces of the movement of the loudspeaker membranes are just too small to be felt, therefore the bottom plate of the electro-acoustic bowl is facilitated with an extra electrodynamic actuator that is used to mimic the vibrations of the bowl. When the electro-acoustic bowl is used as a playback device with relaxing sounds a frequency mapping algorithm [45] can be used to extract an actuator signal from playback sounds. Otherwise, when a synthesized sound as described in Section 2.1 is used, simply the fundamental can be fed to the actuator, creating the vibrating effect on body, similar to the Tibetan bowl.

3. User tests

The eBowl is designed as a relaxation device that can be used by users themselves in the comfort of their environment. In order to evaluate the effectiveness of the eBowl for relaxation a small scale user test is conducted. The hypothesis is that sounds and vibrations generated by the eBowl device can relax people. To test the hypothesis, users experienced both self relaxation (SR) and eBowl relaxation (EB) during which both objective and subjective measurements were taken. In these tests, instead of synthesizing the sounds, recorded sounds of the real Tibetan bowl were played using the eBowl.

During self relaxation users were asked to relax while lying on a bed, on their back, with their eyes closed. Similarly, during eBowl relaxation users lay on their back with their eyes closed, and the eBowl device was placed on their stomach. Both of the relaxation sessions lasted for 8 minutes and at all times one test coordinator was present in the test room.

As objective measurements electrodermal activity (skin conductance and skin temperature), cardiovascular activity (heart rate and heart rate variability) and respiration (breathing rate, breath depth, inhalation and exhalation time) were measured. All physiological signals were measured using a Nexus 10 (version year 2009) device and sensors from Mind Media [46].

As subjective measurements the Stress Arousal Checklist (SACL) [47] and Visual Analogue Scale (VAS) for Global Vigor (GV) and Global Affect (GA) [48] questionnaires were used. In the SACL test participants are asked to rate 20 emotions on a 5 point scale (from strongly agree to strongly disagree), ten emotions related to stress, and ten emotions related to arousal are included. These emotions are: calm, contented, active, vigorous, comfortable, lively, uneasy, tired, sleepy, worried, distressed, uptight, drowsy, tense, relaxed, passive, energetic, alert, bothered, and aroused. In the GVA, participants are asked to rate emotions on a continuous scale. Ten emotional labels are included: alert, sad, tense, effort to do something, happy, weary, calm, and sleepy.

The complete test protocol can be described as follows. (i) Upon arrival, the test is described and necessary documents are signed. (ii) Nexus 10 sensors are connected. (iii) Baseline data is collected, the participant is asked to sit still and silently in a comfortable chair for 4 minutes, while their physiological data is recorded. (iv) The participant is asked to move in front of the computer to play a memory game. In the game numbers from one to nine are presented in a random order in ten seconds. The task is to memorize the numbers in the order they are presented. After the digits have been presented the user is asked to enter the numbers (in their own pace, with no time limit) in the displayed order on the keypad (showing the numbers as a 3 by 3 matrix, but in random order) shown on the computer screen. The same procedure is repeated 10 times. The total duration of the memory game is approximately 5 minutes with small variations from participant to participant. The purpose of this game is to alert and stress the participant, so that the effect of relaxation is clearer. (v) Upon completion of the memory game the user fills in the SACL and GVA questionnaires. (vi) Relaxation session starts. The lights are dimmed. Users are asked to lay on a bed, on their back, with their eyes closed. They experience one of the relaxation methods in one session (and the other method in the next session). The relaxation lasts for 8 minutes. (vii) Sensors are disconnected. (viii) Users fill the SACL and GVA questionnaires and are asked to provide additional comments if any.

The order of Self Relaxation (SR) and eBowl (EB) was randomized and each test was performed on the same day and time, but in a different week. In total 12 participants were measured. Six of them experienced SR (and others EB) in their first session. The participants included 8 women and 4 men, with an average age above 43 years (11 people were above 35 years). All participants were Philips employees.

All tests were conducted in our labs at Philips Research, Eindhoven. A comfortable and quiet environment was created by surrounding the test bed with high panels. The temperature and light conditions of the room were set to comfortable levels, temperature was around 23°C. The lights were dimmed to create a darker (but still visible) environment.

3.1 Data processing and analysis

Processing of the physiological data is done using the Biosignal toolbox developed in Philips Research. After artifact removal, the data is averaged in 15 s. intervals, that is for 8 minutes of recording there are 32 data points. For analysis, collected physiological data is normalized for each subject. The normalization for skin conductance and skin temperature data is done by z-normalization, i.e., by subtracting the mean and dividing by the standard deviation of the relaxation data. Normalization of other parameters is done by subtracting the mean of the last 2 minutes of the baseline measurements from the relaxation data.

After normalization, SR and EB data is analyzed for each subject. Analysis is performed using an ANOVA as implemented in Matlab. In addition, averages over all subjects are computed and similar statistical analyses are performed.

These statistical analysis results are summarized in Table 2. Results of test 2 show that eBowl (EB) performs significantly better than self relaxation (SR) in terms of the following physiological measures: Heart Rate, Heart Rate Variability, Exhalation Time, Inhalation to Exhalation Ratio, Breathing Rate, and Skin Temperature.

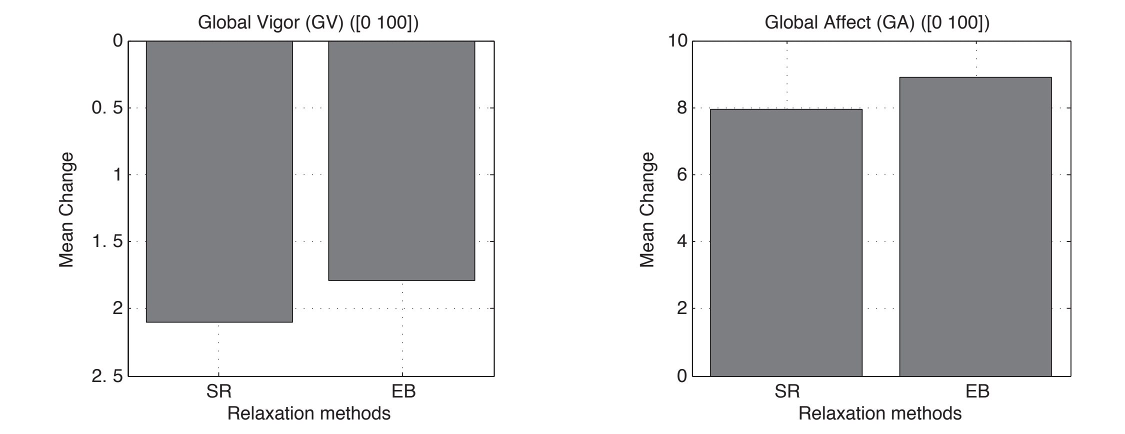
SACL and GVA questionnaires are used to subjectively assess the effects of EB and SR. The questionnaires are filled in before and after the relaxation sessions. Normalization is done by subtracting the pre-relaxation values. The results (see Figs. 7 and 8) show that both EB and SR produce relaxing effects, i.e., arousal, global vigor, and stress decreases, while global affect increases. In terms of questionnaire responses the differences between the eBowl and self relaxation were not significant.

3.2 Discussion of the user test results

Before going deeper into interpretation of the results, it is useful to make some remarks about what relaxation is and how it can be quantified. Despite the large and continuously growing amount of literature on relaxation, its definition is still not well established. It relates to both the body and mind, and due to its subjective nature, it is very difficult, if not impossible, to quantify or define what relaxation is. Nevertheless, for analysis and comparison purposes some definition is necessary. In this paper, we assume that a person is relaxing if the following physiological parameter changes are simultaneously observed: Skin conductance level decreases; skin temperature increases;

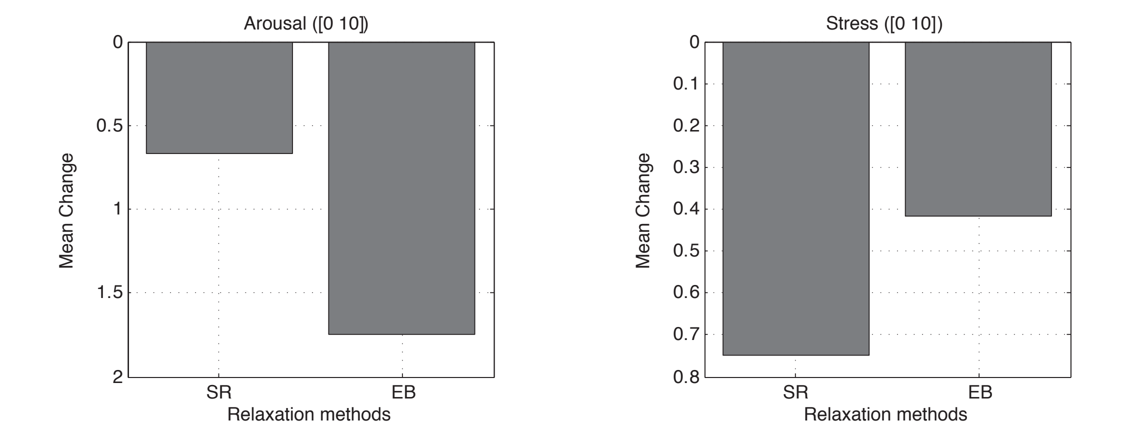
Table 2. Statistical analysis results. (Parameter is the measured physiological parameter, F(1,58) is the F value calculated for ANOVA, p is the p value indicating the significance, Observed relation is the relation observed between EB and SR measurements, Desired relation is desired relation that will show that EB is more relaxing than SR, shows statistically significant differences in the desired direction)*

Parameter	F(1,58) value	p value	Observed relation	Desired relation
GSL	0.23	0.6345	EB=SR	EB<SR
Skin Temperature*	4.43	0.0397	EB>SR	EB>SR
Heart Rate*	131.08	<0.001	EB<SR	EB<SR
HRV - EBI std	1.28	0.2627	EB=SR	EB>SR
HRV - LH*	33.79	<0.001	EB<SR	EB<SR
HRV - LF*	31.24	<0.001	EB<SR	EB<SR
HRV - HF*	15.2	<0.001	EB>SR	EB>SR
Breathing Rate*	5.38	0.0238	EB<SR	EB<SR
Breath Depth	129.65	<0.001	EB<SR	EB>SR
Inhalation Time	2.46	0.122	EB=SR	EB>SR
Exhalation Time*	51.23	<0.001	EB>SR	EB>SR
Inhalation to Exhalation ratio*	58.00	<0.001	EB<SR	EB<SR



(a) *Global vigor* (b) *Global affect*

Figure 7. Test 2: Global Vigor (a measure of alertness) and Global Affect (a measure of happiness and calmness) from GVA (VAS) questionnaire. Alertness decreases, happiness, and calmness increase.



(a) *Arousal* (b) *Stress*

Figure 8. Test 2: Arousal and stress measures calculated from SACL questionnaire. Arousal and stress decrease.

heart rate decreases; heart rate variability increases; breathing rate decreases; inhalation and exhalation time increases; and inhalation to exhalation ratio decreases. In terms of subjective data we assume relaxation if stress and arousal decrease.

Using the aforementioned relaxation definition, the results of current tests show that the eBowl can relax users.The relaxing effects are observable from both physiological measurements and questionnaire responses. The data show that users are also relaxing without any devices, i.e., by themselves just by lying on a bed with their eyes closed and in silence. However, relaxing with the eBowl is measured to be better than self relaxation. Statistical analysis of physiological data shows that eBowl performs significantly better than self relaxation in terms of heart rate, heart rate variability, exhalation time, inhalation to exhalation ratio, breathing rate, and skin temperature. Both methods perform comparable in terms of subjective questionnaire data.

If we take a closer look at the results presented in Table 2, in terms of skin conductance level (SCL) both methods perform comparably. SCL decreased with time, as is expected during relaxation. For all subjects, differences between EB and SR are not statistically significant. Skin temperature slowly increased during relaxation. For two people, the increase of skin temperature was significantly larger during EB, and for one person during SR. The mean of average skin temperature over all subjects is significantly higher for EB. Heart rate measurements show that during EB heart rates are significantly lower than during SR. Analysis of individual results show that for six people HR is significantly lower during EB, and for two people during SR. Different HRV measures that are calculated (see Table 2 for the list), in general, show that EB increases HRV significantly more than SR. Analysis of the respiration patterns show that during EB, breathing rate decreases (significantly different in seven people in favor of EB), breath depth decreases, and inhalation and exhalation times increase. Overall, the respiration parameter differences indicate that EB is more relaxing than SR.

These results are in line with physiological responses reported for subjects practicing transcendental meditation, reported in [49]. During meditation, heart rate slowed, skin conductance level decreased and EEG alpha activity increased.

Questionnaires were used to measure stress and arousal and global affect and global vigor before and after relaxation. Differences (between before and after) are shown in Figs. 7 and 8. The results show that stress, arousal, and global vigor decrease while global affect increases. This is what one can expect during relaxation. It is important to note however that the changes are small: for arousal less than 18%, for stress less than 8%, for global vigor less than 3%, and for global affect less than 9%. This means that participants perceived their state to be different before and after relaxation, but they indicated this difference to be small. Analysis of data showed that there were no statistically significant differences between responses for EB and SR.

4. Discussion

The paper does not contain a direct comparison of the eBowl with an existing bowl, therefore we can not show scientific evidence that they sound the same, but this was not our purpose. However, our aim was to make this plausible rather than to provide proof. It is important to understand why the eBowl has a relaxing effect on people. As stated in the introduction, our hypothesis is that the eBowl generates monaural beats in the alpha range, which influences the users' brainwaves, causing relaxation.

In another setting, new preliminary user tests measuring electroencephalograms (EEGs) were conducted [50]. Instead of playing the recorded sound of the real Tibetan bowl as in the previous user test, a synthesized mono signal consisting of three frequencies (188 Hz, 539 Hz, 549 Hz) was played through the eBowl. Note that the combination of these frequencies generates a monaural beat of 10 Hz and sounds similar to the original sound of the Tibetan bowl (but slightly less rich). Twenty participants experienced two sessions of the eBowl, with monaural beats and without monaural beats (frequencies: 188 Hz, 544 Hz). Two participants fell asleep during the tests, therefore they were excluded from analysis. The frequency power and event related potentials (ERPs) of these two EEG data sets were analyzed. Preliminary results show that when monaural beats are present the alpha power is larger. During the relaxation session it is observed that the percentages of delta and theta power increased, while percentages of alpha and beta power decreased. These results suggest that users go from a wakefulness state to a very relaxed and possibly sleepy stage [50].

Sound massage has been popular in Eastern cultures for centuries, it is now gaining popularity in the Western world. In the beginning sound massage was more or less seen as an exotic relaxation technique or as an instrument to increase self-awareness. Nowadays with its popular applications in healthcare centers and in social facilities it is viewed as a tool and method that can be helpful in various areas such as relaxation and depression. On the Internet there are many claims regarding the healing power of sound massages. Note however that most of these claims are not scientifically validated. We believe that there is a big opportunity in studying effects of sounds for maintaining and improving health and wellbeing. This paper is a step in this direction.

5. Conclusions

Tibetan bowls radiate sounds leading to the perception of acoustical beats. An electroacoustic version (eBowl) of an Tibetan bowl is made. Laboratory measurements and informal listening test show that the eBowl produces similar sound characteristics, and is perceived similarly to the Tibetan bowl. Controlled user tests show that listening to the eBowl leads to relaxation, validating its effectiveness and acceptability by users. Statistical analysis of physiological data collected from users show that the eBowl performs significantly better than self relaxation in terms of heart rate, heart rate variability, exhalation time, inhalation to exhalation ratio, breathing rate, and skin temperature. Both methods indicate comparable relaxation in terms of subjective questionnaire data. Preliminary analysis show that this relaxation effect can possibly be attributed to brainwave entrainment caused by the acoustical beats.

6. Acknowledgments

The authors like to thank Dr. Karin Klabunde who suggested the idea of making an electroacoustic version of a Tibetan bowl. Furthermore, we like to thank, former student Sven Plasier, and again Dr. Klabunde for many discussions and hard work for the perception tests. In addition, we are especially grateful to volunteers that participated in our experiments. Without their support this research would not be possible.

References

[1] http://en.wikipedia.org/wiki/Singing_bowl, retrieved Sep. 14, 2011.

[2] E. R. Jansen, and D. de Ruiter. *Singing Bowl Handbook: Singing Bowls - Tingshaws - Bell - Dorje*, ISBN-13: 978-9078302162, Binkey Kok, April 2008.

[3] T. D. Rossing. *Science of Percussion Instruments, volume 3 of Series In Popular Science*. World Scientific Publishing, 2000.

[4] D. Young and G. Essl. HyperPuja: A Tibetan Singing Bowl Controller, *Proceedings of the 2003 Conference on New Interfaces for Musical Expression (NIME-03)*, Montreal, Canada, pp. 9-14, 2003.

[5] E. Larsen and R.M. Aarts. Reproducing low-pitched signals through small loudspeakers, *J. Audio Eng. Soc.*, Vol. 50, No. 3, pp. 147-164, March 2002.

[6] B.C.J. Moore. *An introduction to the psychology of hearing*, Academic Press Inc., London New York, 4th Edition, 1997.

[7] G. W. Stewart. Binaural Beats, *Phys. Rev.*, Vol. 9 (2nd series), pp. 502-508, June 1917.

[8] G. Oster. Auditory Beats in the Brain, *Scientific American*, Vol. 229(4), pp. 94-102, Oct. 1973.

[9] D. W. F. Schwarz and P. Taylor. Human auditory steady state responses to binaural and monaural beats, *Clin. Neurophysiol.*, Vol. 116, No. 3, pp. 658-668, 2005.

[10] H. Pratt, A. Starr, H. J. Michalewski, A. Dimitrijevic, N. Bleich, and N. Mittelman. A comparison of auditory evoked potentials to acoustic beats and to binaural beats. *Hear. Res.*, Vol. 262, No. 1-2, pp. 34-44, 2010.

[11] D. Vernon. *Human Potential: Exploring Techniques Used to Enhance Human Performance.* Routledge, ISBN978-0415457705, 2009.

[12] J.D. Lane, S.J. Kasian, J.E. Owens, and G.R. Marsh. Binaural Auditory Beats Affect Vigilance Performance and Mood, *Physiology & Behavior*, Vol. 63, No. 2, pp. 249-252, 1998.

[13] B. Brady and L. Stevens. Binaural-beat induced theta EEG activity and hypnotic susceptibility, *American Journal of Clinical Hypnosis*, Vol. 43, No. 1, pp. 53-69, July 2000.

[14] D. Zhu, J. Bieger, G. G. Molina, and R.M. Aarts. A survey of stimulation methods used in SSVEP-based BCIs, doi:10.1155/2010/702357, *Computational Intelligence and Neuroscience*, pp. 1-12, 2010.

[15] D. Zhu, G. Garcia Molina, V. Mihajlović, and R.M. Aarts. Phase synchrony analysis for SSVEP-based BCIs, ICCET 2010; *2nd Int. Conf. Computer Eng. & Technology*, Cengdu, China, April 16-18, 2010.

[16] V.J. Walter and W.G. Walter. The central effects of rhythmic sensory stimulation. *Clinical Neurophysiology*, Vol. 1, No. 1, pp. 57-86, 1949.

[17] T.L. Huang and C. Charyton. A comprehensive review of the psychological effects of brainwave entrainment, *Journal of alternative therapies*, Vol. 14, No. 5, Sep./Oct., pp. 38-50, 2008.

[18] W. Thies. Reactions to listening to a singing bowl (in German: Reaktionen auf das Hören einer Klangschale), *Journal Musik-, Tanz und Kunsttherapie*, Vol. 19, No. 2, pp. 83-92, 2008.

[19] http://en.wikipedia.org/wiki/Glass_harp, retrieved Aug. 9 2011.

[20] A.P. French. In Vino Veritas: A study of wineglass acoustics, *Am. J. Physics*, Vol. 51, No. 8, pp. 688-694, August 1983.

[21] G. Jundt, A. Radu, E. Fort, J. Duda, and H. Vach, and N. Fletcher. Vibrational modes of partly filled wine glasses, *J. Acoust. Soc. Am.*, Vol. 119, No. 6, pp. 3793-3798, 2006.

[22] T.D. Rossing. Wine glasses, bell modes, and Lord Rayleigh, *The Physics Teacher*, Vol. 28, No. 9, pp. 582-585, Dec. 1990.

[23] http://en.wikipedia.org/wiki/Glass_harmonica, retrieved Aug. 9 2011.

[24] http://www.youtube.com/watch?v=2UpLYuSVgoQ&feature=related, retrieved Aug. 9 2011.

[25] http://glassmusicintl.org/, retrieved Aug. 12, 2011.

[26] http://glassharp.org/index.html, retrieved Aug. 12, 2011.

[27] http://www.youtube.com/watch?v=3rmFleYqNxw, retrieved Aug. 12 2011.

[28] J.W.S. Rayleigh. *The theory of sound* Vol. 1, Secs. 165 and 173-4 (pp. 383-389), 1877, Dover, (reprinted 1945).

[29] O. Inácio, L. Henrique, and J. Antunes. The dynamics of Tibetan singing bowls, *Acta Acust. United Acust.*, Vol. 92(4), pp. 637-653, July/Aug. 2006.

[30] O. Inácio. A Modal Method for the Simulation of Nonlinear Dynamical Systems with Application to Bowed Musical Instruments, Thesis for the degree of PhD in Sound & Vibration, University of Southampton, July 2008.

[31] D. Terwagne, and J.W.M. Bush. Tibetan singing bowls, *Nonlinearity*, Vol. 24, pp. R51-R66, 2011.

[32] K. van den Doel. Sound Synthesis for Virtual Reality and Computer Games, Ph. D. Thesis, University of British Columbia, 1998.

[33] K. van den Doel, and D. K. Pai. Modal synthesis for vibrating objects, Audio Anecdotes III: Tools, Tips, and Techniques for Digital Audio, chapter Modal Synthesis for Vibrating Objects, pp. 99-120, A. K. Peter, 3 edition, 2006, Source code available at http://www.cs.ubc.ca/kvdoel/publications/srcmodalpaper.zip

[34] K. Steiglitz. A Note on Constant-Gain Digital Resonators, *Computer Music Journal*, Vol. 18, No. 4, pp. 8-10, The MIT Press, 1994.

[35] T.D. Rossing, and H.J. Satthoff. Modes of vibration and sound radiation from tuned handbells, *J. Acoust. Soc. Am.*, Vol. 86, No. 6, pp. 1600-1607, 1980.

[36] R.M. Aarts and A.J.E.M. Janssen. On-axis and far-field sound radiation from resilient at and dome-shaped radiators. *J. Acoust. Soc. Am.*, Vol. 125, No. 3, pp. 1444-1455, March 2009.

[37] R.M. Aarts and A.J.E.M. Janssen. Sound radiation from a resilient spherical cap on a rigid sphere. *J. Acoust. Soc. Am.*, Vol. 127, No.4, pp. 2262-2273, April 2010.

[38] R.M. Aarts and A.J.E.M. Janssen. Spatial impulse responses from a flexible baffled circular piston. *J. Acoust. Soc. Am.*, Vol.

Hospital building work stopped because of risk to baby unit

Doctors have stopped building work at a Scottish hospital amid concern the noise and vibrations were harming premature babies. The £1.7 million refurbishment of the birthing unit at St John's Hospital in Livingston, West Lothian, has been delayed by almost three months after the project was found to be having a negative affect on the tiny patients. The health board came under fire from campaigners, who accused it of failing to properly plan for the renovation, which was taking place adjacent to the hospital's special care baby unit, where some of the region's most poorly infants are treated. The opening of the modernised facility, which had been scheduled for the Spring, has now been pushed back to June. One staff member, who did not wish to be named, said the vibration caused by building work were "echoing through the room", resulting in the babies becoming distressed. The staff member added: "Noise for pre-term infants causes irritability. Their sleep patterns are very sensitive to external stimulus, which is why when they're pre-term and in incubators we keep the lights low and the areas as calm as possible. The renovations were disturbing that. Noise can cause their oxygen saturation levels to drop as it affects their breathing and also their feeding in particular, which again is all linked to irritability. If the baby is irritable they won't eat properly, sleep properly and it all has a knock-on effect. I think they hadn't anticipated the vibration. The refurbishment had been delayed for some time so when it did get the go-ahead, it was maybe rushed." NHS Lothian insisted it had planned for the impact of noise and carried out testing, but believed adequate measures had been put in place. However, it has since been admitted that "the reality was that the prolonged nature of the noise had not been able to be tolerated".

129, No. 5, pp. 2952-2959, May 2011.

[39] R.M. Aarts and A.J.E.M. Janssen. Sound radiation from a loudspeaker, from a spherical pole cap, and from a piston in an infinite baffle. *Noise & Vibration Worldwide*, Vol. 43, No. 4, pp. 12-19, April 2012.

[40] A.J. Berkhout. A Holographic Approach to Acoustic Control, *J.Audio Eng.Soc.*, Vol. 36, pp. 977-995, December 1988.

[41] R.M. Aarts. Phantom sources applied to stereo-base widening, *J. Audio Eng. Soc.*, 48(3), pp. 181-189, March 2000.

[42] R.M. Aarts. Calculation of the loudness of loudspeakers during listening tests, *J. Audio Eng. Soc.*, 39(1/2), pp. 27-38, January/February 1991.

[43] R.M. Aarts. A comparison of some loudness measures for loudspeaker listening tests, *J. Audio Eng. Soc.*, 40(3), pp. 142-146, March 1992.

[44] R.M.M. Derkx. First-Order Adaptive Azimuthal Null-Steering for the Suppression of Two Directional Interferers, *EURASIP Journal on Advances in Signal Processing*, 2010, Article ID 230864.

[45] R. M. Aarts. Optimally Sensitive and Efficient Compact Loudspeakers, *J. Acoust. Soc. Am.*, Vol. 119, pp. 890-896, Feb. 2006.

[46] http://www.mindmedia.info/, retrieved Dec. 16, 2013.

[47] C.J. Mackay, T. Cox, G.C. Burrows, and A.J. Lazzarini. An inventory for the measurement of self-reported stress and arousal, *British Journal of Social and Clinical Psychology*, Vol. 17, pp. 283-284, 1978.

[48] T.H. Monk. A visual analogue scale technique to measure global vigor and affect, *Psychiatry Research*, Vol. 27, No. 1, pp. 89-99, Jan. 1989.

[49] R.K. Wallace and H. Benson. The physiology of meditation, *Scientific American*, 226, pp. 84-90, 1972.

[50] S.A.J. Plasier, M. Bulut, and R.M. Aarts. A study of monaural beat effects on brain activity using an electronic singing bowl (extended abstract), *Annual Symposium IEEE EMBS*, Louvain, Brussels, Belgium, Dec. 2011.

Real time mining noise monitoring

Mount Thorley Warkworth open-cut mine (NSW, Australia) will be the first Hunter mine to trial the latest noise monitoring technology. A new directional noise monitoring system will be installed in the southern area of Bulga village to assist with monitoring and managing noise from the mine. The environmental noise compass will enhance Coal & Allied's existing noise monitoring system, which currently involves eight monitoring devices surrounding the mine. The compass uses an array of 26 microphones and advanced acoustic signal processing methods to detect and assess multiple noise sources in real time with greater accuracy. Coal & Allied NSW environmental services manager Andrew Speechly said the new system would allow Mount Thorley Warkworth to be more effective in its real-time management of noise by measuring the sound energy of mining activities as they happen and responding accordingly.

Protestors want promise on Luton Airport noise limits

Campaigners protesting against the expansion of Luton Airport have accused the airport of a 'broken promise' over noise limits. In December Luton council approved recommendations to allow the airport to increase its capacity so it can cater for up to 18 million passengers a year - an increase of six million. During the ten-hour meeting on December 20 more than 30 individual representations against the plans were heard. One of the protest groups, Hertfordshire Against Luton Expansion (HALE), has said they will write to the authority to seek assurances that the airport will reduce its noise levels. Andrew Lambourne, a spokesman for the group, said: "This is an absolute scandal. We highlighted clearly in the planning meeting that a key promise to reduce night noise limits was not reflected in the planning conditions put forward by Luton Borough Council. The point was not answered, so we have written to the council insisting that the public commitments made by Luton Airport to reduce the night noise limit by 1 January 2015 to 80dB, with a five-yearly review to bring it down to 77dB, are both enshrined in the planning conditions."