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MEASUREMENT AND SUBJECTIVE ASSESSMENT OF WATER GENERATED SOUNDS

by Greg Watts, Rob Pheasant, Kirill Horoshenkov and Laura Ragonesi

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ABSTRACT

There is increasing concern with protecting quiet and tranquil areas from intrusive noise. Noise reduction at source and barriers to transmission are mitigation measures often considered. An alternative is to attempt to mask or distract attention away from the noise source. The masking or distracting sound source should be pleasant so that it does not add to any irritation caused by the noise source alone. The laboratory measurements described in this paper consisted of capturing under controlled conditions the third octave band spectra of water falling onto water, gravel, bricks and small boulders and various combinations. These spectra were then matched with typical traffic noise spectra to assess the degree of masking that could be expected for each option. Recordings were also taken during each measurement and these were used later to enable the subjective assessment of the tranquillity of the sounds. It was found that there were differences between water sounds both in terms of masking and their subjective impact on tranquillity

1. INTRODUCTION

The sounds that water makes as it falls and impacts water or rigid surfaces is complex and not well understood in all cases. It is known in the simple case of a water drop falling onto a water surface, that there is a low level impact sound, followed by tonal sounds caused by the vibration of bubbles in the water. The impact sounds are thought to be generated by supersonic shockwaves. It appears that there is a brief period after initial contact during which the contact region moves with supersonic speed creating a small shock wave [1]. However, it is the sound caused by the vibrating bubbles that appear to produce the dominant sound. Bubbles are formed when the water surface causes air to be trapped in the water, or when air is injected in the liquid by a nozzle. Cavitation is another source of bubbles, which are produced for example by a ships propeller. Air entrapment can occur, for example, when a surface wave breaks and when a cavity created by a falling droplet collapses. Large bubbles can break up into smaller bubbles causing numerous individual sound sources. After formation, the bubble emits a tonal sound, which decays exponentially as energy is dissipated.

The frequencies emitted depend critically on the size of the bubble and the resonant frequency f of a bubble in an infinite volume of water is given by Minneart's formula [2], which, under normal atmospheric conditions, takes the approximate form:

$f = 3/r$ with r the bubble radius in metres.

Since the audible range is 20 – 20,000 Hz it is bubble size from 1.5 to 150 mm that are critical for perception. As bubbles rise from below the surface the pressure decreases and frequency rises. The submerged oscillating bubble will thus create a sound, which propagates to the surface of the liquid where it is transmitted to air. In reality, a droplet impact is a very complicated phenomenon and often a jet of water is emitted, which breaks up into secondary droplets creating bubbles of their own. Water impacting solid surfaces will cause shock waves at the contact patch and turbulence which will entrap air producing bubble sounds. More complex phenomena, such as, streams, pouring water, rivers, rain, and breaking waves generate huge quantities of bubbles and a statistical approach is required to model the sounds produced. For these sounds, the individual characteristics of the bubble sounds themselves combine to produce a continuous sound. It is possible to collect statistics on the bubble population, in for example rivers and streams, in order to assist the modeling process [3]. It has also been possible to develop a bubble generator to simulate the effects of different water sounds [4]. A wide variety of water sounds can be created with the simulator, ranging from intimate dripping sounds to torrential rains or waterfalls. The resulting sounds are “quite realistic”, especially the more dense sounds.

However what is clear is that water attracts people and fountains in particular have long been used in parks and city squares to provide not only a pleasant features but also to improve the soundscape where traffic noise is present. Research by Yang at Sheffield University [5] concluded that water, in the form of fountains, has a wide ranging effect in “colouring” the soundscape in urban public open spaces. They found that high frequency components tended to be produced by water splashing onto hard surfaces. Lower frequency components were associated with a large flow of water dropping into water or hard surfaces especially if the drop height was large. For simple weir arrangements it appears that the detailed design of the water impact conditions and flow rates are important [6]

Previous work has shown the importance of water as a natural feature in the landscape to improved perceived tranquillity. In a recent test which sought to identify how tranquil 100 subjects rated 100 rural and urban images taken from across the UK during the summer of 2005, water was an important factor [7]. Of the 100 images used in the test half of the scenes that contained water, i.e. 17, were included within the top 20 ranked images. Of these 7 contained views of the ocean, 4 contained views of streams or rivers, 5 views of lakes or tarns and 1 a view of an ornamental waterway. The result is highly significant ($\chi^2 = 29.0$, $p < 0.001$). These results support Wilson's biophilia hypothesis, which suggests that modern day adults and children evidence strong preferences for scenes containing areas of water [8].

The aim of this study was to investigate the masking effects of a range of water sounds and to evaluate their impact on the assessment of tranquillity under varying background noise conditions. The sounds were generated in the laboratory under controlled conditions using a simple weir with modest drop heights and flow rates. Assessments by experimental subjects were carried out in an anechoic chamber that had previously been adapted for audio-visual studies of perceived tranquillity [7]. It was considered the findings would lead to the development of initial guidelines on the design of small water features to improve the soundscape of open spaces such as gardens and parks blighted by traffic noise. The results could also be used for the design of atria which are affected by office noise and air conditioning.

2. LABORATORY MEASUREMENT AND RECORDING OF WATER SOUNDS

2.1 Test apparatus

The test apparatus for producing the water sounds consisted of three separate chambers: a water reservoir, a measurement chamber where the water fell over a weir onto various options and a receiving chamber for the water. Each was a 1m cube in dimension. A sound level analyser (B&K type 2250) was placed above the falling water in the second chamber. The microphone was positioned 110cm above the floor of the chamber and 9 cm from the rear wall. Figure 1 shows a view of the set up. Water was pumped into this first chamber at a rate of either 1.11 and 0.55 litre/sec (4m^3/hr and 2 m^3/hr respectively). The inlet tube was secured below the reservoir water levels to prevent extraneous water sounds. Holes at the bottom of the second chamber allowed the water to flow into the third chamber. The height of water above the bottom of the chamber was kept constant at approximately 10cm. The height of the weir above the bottom of the chamber could be varied. For these tests the height above the floor of the chamber was either 30 or 40cm. The width of the weir was kept constant at 10cm. The third chamber was positioned over a drain into which the water emptied via a pipe.

[Figure 1: View of weir and microphone position in test apparatus]

2.2 Test options

The options tested included water falling onto:

- Water
- Gravel (largest dimension 20 -30 mm for coarse gravel and 5 – 10 mm for fine gravel)
- Bricks (dimensions: 220 x 105 x 65mm)
- Small boulders (largest dimensions 150 – 200mm)
- Combinations of the above

After experimentation with different options and at two weir heights it was decided to concentrate analysis on 14 sounds produced at a weir height of 30cm. It was considered that these 14 sounds covered the range of options previously examined and that the weir height of 30 cm was not significantly different in terms of sound production than the 40cm weir height. The 14 options labelled A to N are water falling onto:

A. Water

B. Coarse gravel

C. Small boulder

D. Same as C except ½ water stream striking small boulder and half onto water

E. Flight of three brick steps

F. Same as E except ½ water stream striking brick steps and half onto water

G. A heap of small boulders closely packed

H. Small boulders with more cavities

I. Boulder heap with one flatter boulder forming a "bridge" over a large cavity

J. An open cavity

K. As J but water striking top edge of cavity

L. As J but water more fully deflected by edge of cavity

M. A cavity formed by bricks with slot at top

N. A cavity with brick sides and two flat boulder forming the top (see Figure 1)

The aim of forming cavities was to increase the low frequency content of the resulting spectra by exciting resonances in the enclosed spaces. This was considered important for masking the background traffic noise that was included in the experimental design.

2.3 Measurements

For each option a short term measurement of L_{Aeq} in third octave bands and sound recording was taken over a period of 10 to 20 s. Calibrations were taken throughout and background noise was measured without the water falling over the weir but with the pump operating at the two rates.

2.4 Typical traffic noise

To compare the ability of these water sounds to mask typical traffic noise, two spectra were calculated using the Harmonoise traffic noise source prediction model and the corresponding propagation model [9]. The model is based on a large number of recent data for vehicles in three categories: light vehicles –category 1, medium heavy vehicles – category 2 (2 axles and 6 wheels) and heavy vehicles – category 3 (3 or more axles). The predictions are therefore representative of an average mix of vehicles in each of the three categories. The prediction model has been validated with field measurements [9].

Predictions for a motorway were based on the receiver at a distance of 110m from the middle of the nearside lane. It was assumed that the flow resistivity of the road surface was 2,000 KPa and the intervening ground 400 KPa. The road surface was a 11mm stone mastic asphalt. Based on typical traffic compositions the percentage of category 2 vehicles was 4.5% and category 3 vehicles 9.1%. Light vehicle speeds were 112 km/hr and that for the heavy vehicles was 96 km/h. The flow was 1150 vehicles per hours which gave a predicted A-weighted level at the receiver of 65.4 dB(A).

Predictions for a city street were based on a receiver distance of 7.5m and a flow of 1000 vehicles/hr. The percentage of category 2 vehicles was 3% and that for category 3 vehicles was 0.6%. The intervening ground was assumed to be acoustically rigid. The predicted A-weighted level was 70.3 dB(A).

3. RESULTS AND ANALYSIS OF WATER SOUND MEAUREMENTS

3.1 Results from water sound measurements

For simplicity and clarity the third octave band spectra from 25 Hz to 10 kHz were combined into octave levels. Due to background noise the use of the 31.5 Hz octave band was considered unreliable. This yielded 8 octave band spectra (from 63 Hz to 8 kHz) instead of 27 third octave bands which were considered too many for comparison and presentational purposes. Results were obtained for 2 flow rates 1.11 litre/sec and 0.55 litre/sec. With the pump operating at a lower level of 0.55 litre/sec it was found that levels were on average 6 dB(A) lower. The additional valve noise produced by this flow restriction produced background noise levels which were similar or greater than water sounds up to and including the 1 kHz octave band. For this reason the data for this flow rate was not used in the analysis.

In order to compare the spectra with typical traffic noise it was considered worthwhile to:

(a) Normalise all levels to 67.4 dB(A) which is close to the average of the water sounds and traffic noise

(b) Order the spectra in the bar chart from left to right so that those options on the left have a closer match to traffic noise than those on the right

To obtain the ranking, the sum of the deviations between band levels from 63 to 1000Hz for each option and the traffic noise level were computed. Those options with the smallest deviation were placed on the left of the chart as can be seen in Figure 2. This figure shows the octave band spectra of the 14 sounds A to N produced by the test equipment. The sounds are ordered in their ability to match the traffic noise spectrum and hence their expected effectiveness in masking this noise source.

[Figure 2: Spectra of 14 water sounds adjusted to an overall level of 67.4 dB(A)]

It is clear that from the figure that the normalised traffic noise spectra from city traffic and motorway have quite similar characteristics. The largest difference being at 500 Hz band where due to soft ground absorption the motorway noise is at a significantly lower level than the city street where propagation is assumed to take place entirely over a rigid surface.

It can be seen that generally the traffic noises have spectra which peak at a lower frequency than water sounds. Consequently at frequencies of 1kHz and below traffic sounds are similar to or above water sounds whereas the converse applies above 1 kHz. Attempting to mask low frequency traffic noise with water sounds without making the water sounds much louder overall than the traffic noise (i.e. a much higher dB(A) level) is therefore a challenge whereas at mid and high frequencies there appears to be little difficulty in arranging effective masking. However, it can be seen that options differ significantly in their ability to mask the lower frequencies. For example option M (water falling into a brick cavity) produced the highest level at 250Hz which were very similar to the levels in the 2 traffic spectra. In contrast option C (water falling onto a single small boulder) produced levels approximately 20 dB below traffic spectral. At the lowest frequency bands of 63 and 125 Hz even the most effective options were approximately 10 dB below traffic levels. Note that in all cases water sounds were similar to the traffic spectra in the 1 and 2 kHz bands but significantly greater in the 4 and 8 kHz bands.

3.2 Conclusions from water sound measurements

It is clear that attempts to produce enhanced lower frequency water noises using cavities were only partially successful. It is likely that significantly larger cavities of the order of a metre or so would be required with this weir arrangement to produce the levels at 63 Hz and 125 Hz necessary to mask background traffic noise. It is also evident that water falling onto hard surfaces rather than into cavities or onto water produced the highest frequencies. This is perceived as a light splashing or tinkling sound. This is in line with earlier work where the sounds made by various water features were analysed [5,6].

Another important consideration is the perception of the water sounds produced. There is little point in producing water sounds of the correct spectral shape for masking low frequency sound if they do not improve perceived tranquillity. This issue is addressed in the following section.

4. ASSESSMENT OF WATER SOUNDS

The aim of this part of the research was to evaluate the 14 sounds described in the previous sections. The perceived tranquillity was assessed during playback in a controlled environment with traffic noise as the background sound. The following procedures were used.

4.1 Experimental setup

The sounds were replayed in an anechoic chamber which had been modified to resemble a small balcony garden at sunset. The floor was covered with wooden decking and a patio table and chair were provided. A sun umbrella was arranged close to the table and a flood light was mounted behind the chair to simulate the effects of the setting sun. The walls of the chamber were covered with bamboo garden screens. A pile of small rounded boulders indicated the position of a water feature and two potted 1m high conifers added to the realism of the simulation. Figure 3 shows a view of the setup. The subject (S) was seated in the chair when he or she made assessments.

[Figure 3: Experimental setup in the anechoic chamber]

The sounds were replayed through two loudspeakers mounted on the floor of the chamber directly in front of the Ss. The water sounds were reproduced at the nearest speaker (0.5m behind the water feature and out of sight behind a bamboo garden screen) which was positioned 1.8m from S’s ear position. Motorway traffic noise in the form of shaped broadband noise was (see Figure 2) played at constant level from a speaker 3.2m in front of S. The levels were set at approximately 40 and 50 dB(A) which represent a realistic range in many suburban gardens where there is a motorway within 1 to 2 km which can be clearly heard in otherwise quiet background conditions and is potentially a source of annoyance. There were 4 separate experiments i.e.

[Table 1: Sound levels of water and traffic noise]

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Experiment	Traffic noise dB(A)	Water sound dB(A)	Difference in level	Traffic + water sound dB(A)
1	49.6	59.4	+9.8	59.8
2	40.8	51.2	+10.4	51.6
3	40.8	51.2	+10.4	51.6
4	50.1	42.8	-7.3	50.9

Experiment 3 was similar to experiment 2 except that a video of a water feature was shown on a wide screen (see Figure 4) when the water sound was played. The sound was reproduced from the speaker used in the other experimental conditions and the position was not changed. The screen was blank when the traffic noise only was played.

[Figure 4: Views of video of water feature]

The sequence of the 14 sounds was ordered in a randomized Latin Square design with 14 Ss. Each S heard the sequence in 3 different orders. The first was considered as a practice and results were taken from the following 2 sequences. The sound sequences were recorded on a CD and replayed using a DVD which was placed out of sight behind the bamboo screen.

Each sequence started with 8 sec of traffic noise followed by a water sound of length 8 sec. The traffic noise continued during the replay of the water sound. After the completion of each water sound Ss made an assessment of tranquillity by checking the most appropriate descriptor on a response sheet.

Ten males and 4 females took part the average age being 29.6 years.

4.2 Instructions to experimental subjects

The following information was provided to the Ss at the start of the session. Ss had to imagine that they were relaxing in a balcony garden where they could hear the sound off a nearby motorway. They also had to imagine that there was a water feature in the garden which could be altered to make different sounds. Assuming the motorway noise was always present in the background, they were asked to listen to a number of water feature sounds and to indicate the changes, if any, in overall tranquillity that the water feature made. The Ss were told verbally that for the purpose of this research a tranquil environment is a place that they consider to be quiet and peaceful i.e. a place to get away from everyday life (as described by Herzog et al. [10]).

The scale used by the Ss to make their evaluations of how the overall tranquillity of the environment changed once water sounds were introduced was:

much worse   *a bit worse*   *no change*   *a bit better*   *much better*

The Ss circled one of these descriptors for each of the 14 different water sounds presented in each of three sessions. The first session was a practice session. After which the subjects were asked if they were happy with the procedure. Presentations 2 and 3 were then used to provide the raw data.

4.3 Results of assessments

Numerical integer values were attached to each label running from -2 for “much worse” to +2 for “much better”. For each experiment the results from the 2nd and 3rd sessions were used to test for statistical significance using 2-way analysis of variance with replication (ANOVA). The differences between sounds were highly statistically significant at the 0.1% level in all experiments ($p<0.001$). Apart from experiment 1 there were no significant interactions ($p<0.05$) between the responses of Ss and their assessments. The significant interaction that was noted indicates that individual differences may be important under certain listening conditions. It is planned to examine such differences in further phases of the research.

Figure 5 plots for each experiment the overall arithmetic average values for each sound across 14 Ss. It can be seen that there is reasonable agreement concerning the worst and best sounds for improving tranquillity across the experimental conditions.

[Figure 5: Average rating of water sounds by experiment]

Figure 6 gives the values averaged over all experiments arranged in order of effectiveness in improving tranquillity. It is clear that the most effective sounds were C, G, H and I and the least effective were sounds A, J, K, M and N which on average appeared to worsen perceived tranquillity. Feedback on the water sounds was obtained from the Ss. One S thought the sounds were too fast flowing and sounded in some cases like water flowing into a sewer. Another thought the sounds could be softer which would be more relaxing.

[Figure 6: Average ratings based on all 4 experiments]

In experiment 1 the sounds were often considered too loud but about right in experiment 2 and 3. The video in experiment 3 assisted in concentration and categorisation and was generally preferred to the other experimental conditions. For some the lower level of water sounds in experiment 4 were a positive feature while for others the sounds were not loud enough. It is appears that the low levels of water sound in experiment 4 tended to improve the performance of the sounds that were given relatively poor assessments under other experimental conditions. It is possible that the quality of the sounds were harder to assess under such circumstances such that the negative features could not be fully taken into account.

The most preferred sounds C, H and I could be likened to natural sounds such as rainfall and flowing water in a stream while a sound such as J was thought to originate from water entering into a sewer. “Hollowness” was considered to be a negative feature while a light temporal variation was considered positive.

4.4 Supplementary assessments

In order to check on whether natural sounding water sounds were responsible for the positive effects on tranquillity rating a small supplementary experiment was conducted using the same experimental set up as before except traffic noise was not played. However, this time 8 additional subjects were recruited to assess the sounds. The average age of the Ss was 36.8 years. 5 males and 3 females took part. The sounds were replayed through headphones at a level of 60 dB(A). In this case no background traffic noise was present. In preliminary trials the subjects were asked to rate on a number of scales including man-made v natural, rough v smooth, hollow v full, slow v fast and constant v varying. Two variables were highly statistically significant at at least the 1% level i.e. slow v fast ($r = 0.85$, $p<0.001$) and constant v varying ($r = 0.77$, $p<0.01$). Sounds which appeared fast and varying were significantly linked to improvements in tranquillity.

The subjects were then required to categorise the water sounds. The instructions were as follows: “Listen to each of the water sounds and indicate by ticking the appropriate box the description that best fits the character of the sound”. The categories were:

Water falling into a drain	Water pouring into a container	Water falling into a pool	Water falling as rain	Water flowing over boulders in a stream	Other – please briefly describe

The distribution of categories over the 14 water sounds was highly variable. The last category (”other”) was unused. For each sound the fraction of subjects who categorised the sound as clearly natural e.g. “water falling as rain” and “water flowing over boulders in a stream” was calculated. In addition the fraction that was clearly man-made e.g. “water falling into a drain” and “water pouring into a container” was calculated and considered as a measure of a man-made sound.

If these fractions are plotted again the change in tranquillity it is clear that the sounds which are natural are well correlated with increases in tranquillity and conversely those which were considered man-made are inversely correlated. In fact the correlation between tranquillity scores and fraction “natural” was highly significant $r = 0.86$ ($p<0.001$) and similarly between “man-made” and tranquillity scores $r = -0.80$ ($p<0.001$).

[Figure 7: Average ratings based on all 4 experiments together with fraction categorised as natural and man-made]

5. COMPARISON OF RESULTS FROM MEASUREMENTS AND ASSESSMENTS

5.1 Octave measures

To compare the results on efficiency at masking lower frequency sounds with performance at improving tranquillity the rankings on these two metrics were compared. It was found that there is a strong and statistically significant inverse relationship between a measure of noise masking and assessment of tranquillity (Pearson correlation coefficient $r = 0.91$, $p<0.001$). Applying non-parametric statistics yields similar conclusions i.e. Spearman's rho $\rho = 0.90$, $p<0.001$.

The sound interference level (SIL) was also computed as it is a measure of the degree to which background noise interferes with speech and may possibly have an influence on tranquillity assessments. This measure is the arithmetic average of sound pressure levels at the 500, 1000 and 2000 Hz centre frequencies. It was found to be strongly correlated with changes in tranquillity rating ($r = 0.890$, $p<0.001$). This can be readily explained as the sounds with relatively high levels of low frequency noise would have corresponding lower levels at these mid frequencies.

It would seem that the presence of low frequency noise in water sounds although of some assistance in masking the lower frequencies in traffic noise does not appear to improve tranquillity. It is likely that this is due to the fact that such low frequencies are associated with water being poured into drains or containers whereas the sounds that are helpful are higher frequency sounds associated with natural sounds made by a stream flowing over stones or rainfall.

Sounds that improve tranquillity may not mask traffic noise but perhaps assist by providing a pleasant sound which diverts attention from the more unpleasant traffic noise [11].

5.2 Loudness based measures

The sound signals were also analysed using AtemiS Psychoacoustics Module ATP02 (supplied by Head Acoustics) to obtain Zwicker loudness (soneGF), sharpness (acum), roughness (asper) and fluctuation strength (vacil) [12]. For each water sound a time history was generated from which average values of these quantities were estimated.

It was found that sharpness was the measure most closely associated with changes in tranquillity rating ($r = 0.891$, $p<0.001$). Again this reflects the higher frequency content of the sounds which were rated more highly. Loudness was less well correlated ($r = 0.790$, $p<0.01$) but as expected the coefficient is negative reflecting greater levels of low frequency noise in sounds that were not highly rated. However, measures of roughness and fluctuating strength were not significantly related to changes in tranquillity rating.

6. SUMMARY OF FINDINGS

The results were somewhat unexpected as it appears that the masking effects of the sounds are not critical to improving the tranquillity. Improvements were possible even when the water sounds were some 7 dB(A) below the level of background traffic noise. It is considered that it is the distracting effect of natural sounding water sounds which is chiefly responsible for the perceived improvements in tranquillity. This is in line with results from recent attempts at modelling the beneficial affects of natural sounds in reducing attention given to transportation noises [11]. The visual aspect should not be overlooked as the greatest improvements in tranquillity occurred when a video clip of a water feature was shown. It has been found that increasing the percentage of natural features in a scene has a positive effect on ratings of tranquillity when transportation noise is present [7].

It appears that it is the higher frequency variable water sounds that were most highly rated and these were produced by water falling onto small boulders so that there was considerable splashing due to the random nature of falling water and the uneven surface of the boulders. Water falling into water or into cavities produced significantly higher levels of low frequency noise but this was not generally rated highly.

The research suggests that to improve perceived tranquillity with background noise present water features should generate natural sounds rather than sounds that appear more artificial or man-made. The sounds should have relatively small levels of low frequency noise and be variable in nature so that it appears likely that water splashing onto rocks or a relatively fine water spray falling on pebbles or gravel would generally be preferred to a constant stream of water falling into cavities or onto flat water which might give an impression of water being channelled into a drain or culvert or a utilitarian weir with associated negative connotations.

Further work is required to optimize the design of water features for various environments both exterior and interior spaces. Clearly individual differences in response to water sounds and the context in which the sounds are heard needs consideration. This initial work examined only a relatively small number of the many different possible water sounds and the background noise was limited to constant traffic noise levels at two levels. Further work is required to provide a fuller understanding of the effects of a greater range of water sounds under a wider range of background noise conditions in order to provide a firmer basis for optimising designs. However, these findings provide evidence of the potential benefits of water features in improving environments affected by noise.

6. ACKNOWLEDGEMENTS

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FIGURES

Figure 1: Experimental set up

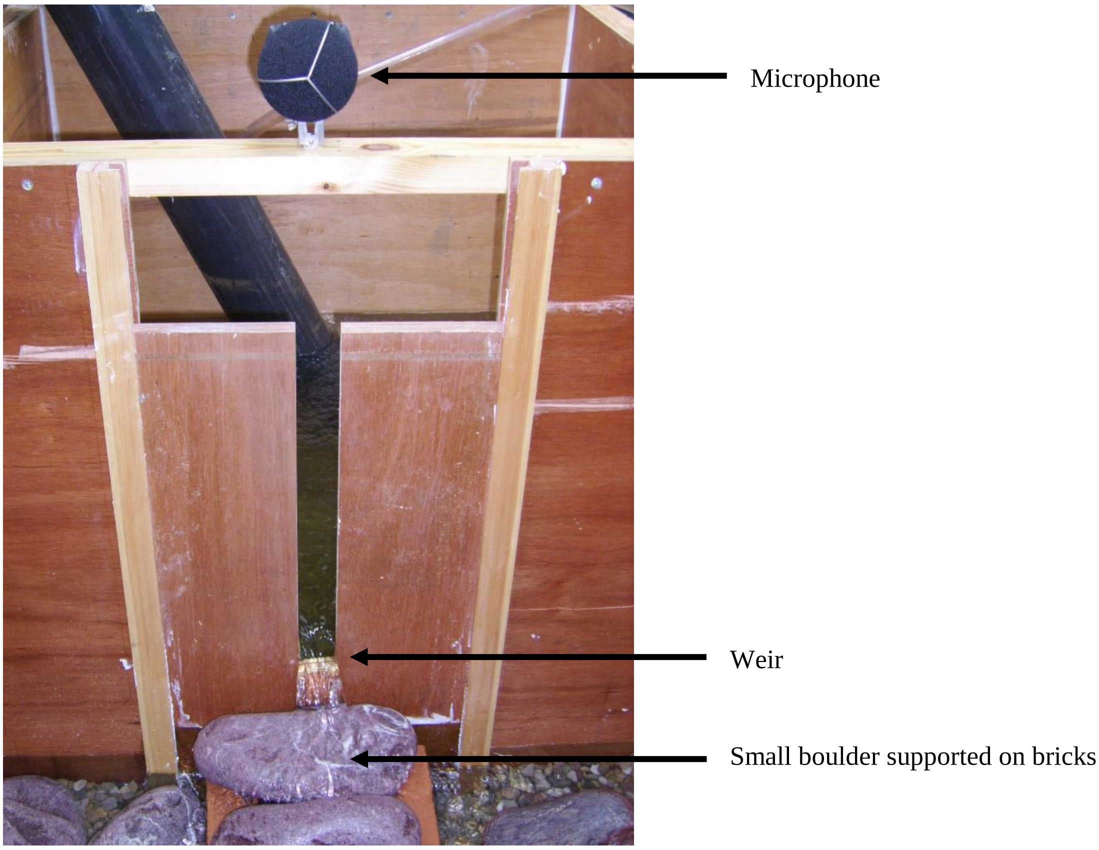

Microphone
Weir
Small boulder supported on bricks

Figure 2: Spectra of 14 water sounds adjusted to an overall A-weighted level of 67.4 dB(A)

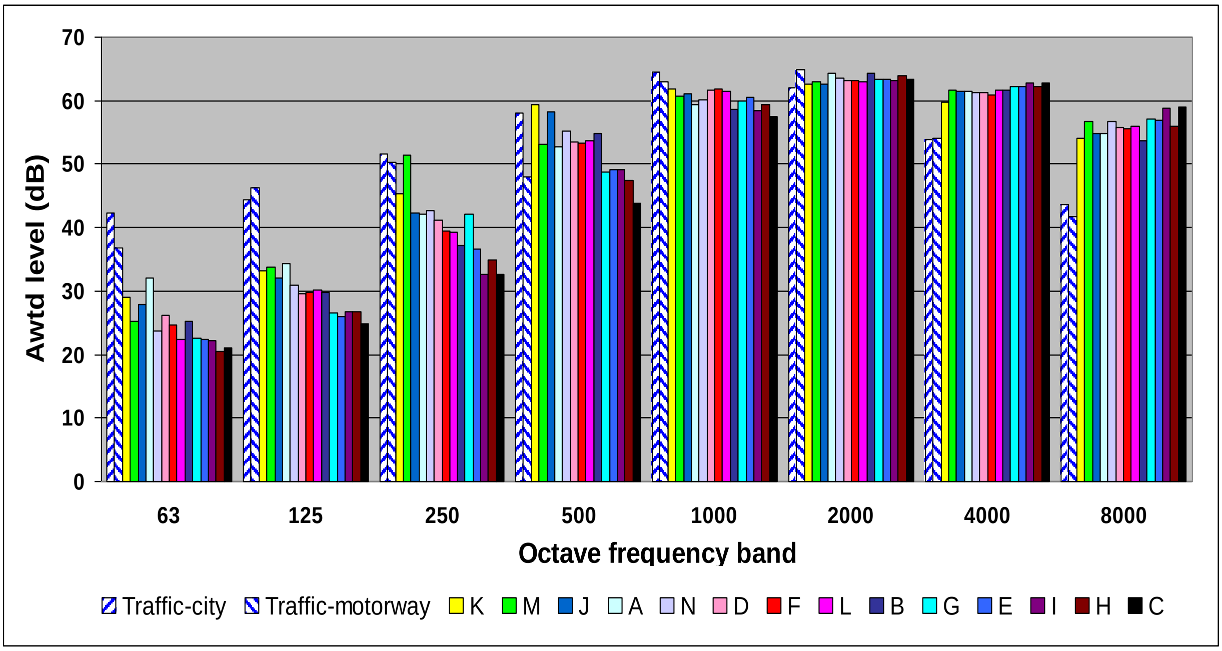


Figure 3: Experimental setup in the anechoic chamber

Figure 4: views of video of water feature

(a) View near S's position

(b) Close-up of video image frame

Figure 5: Average change in tranquility rating by experiment

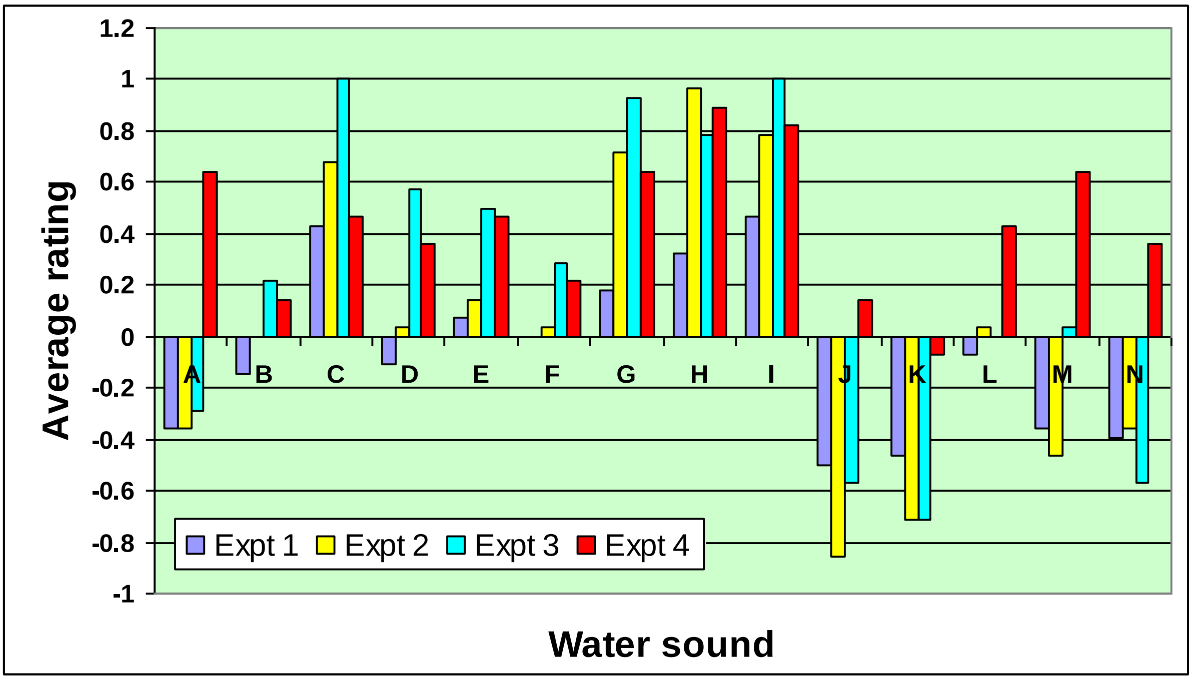


Figure 6: Average ratings based on all 4 experiments

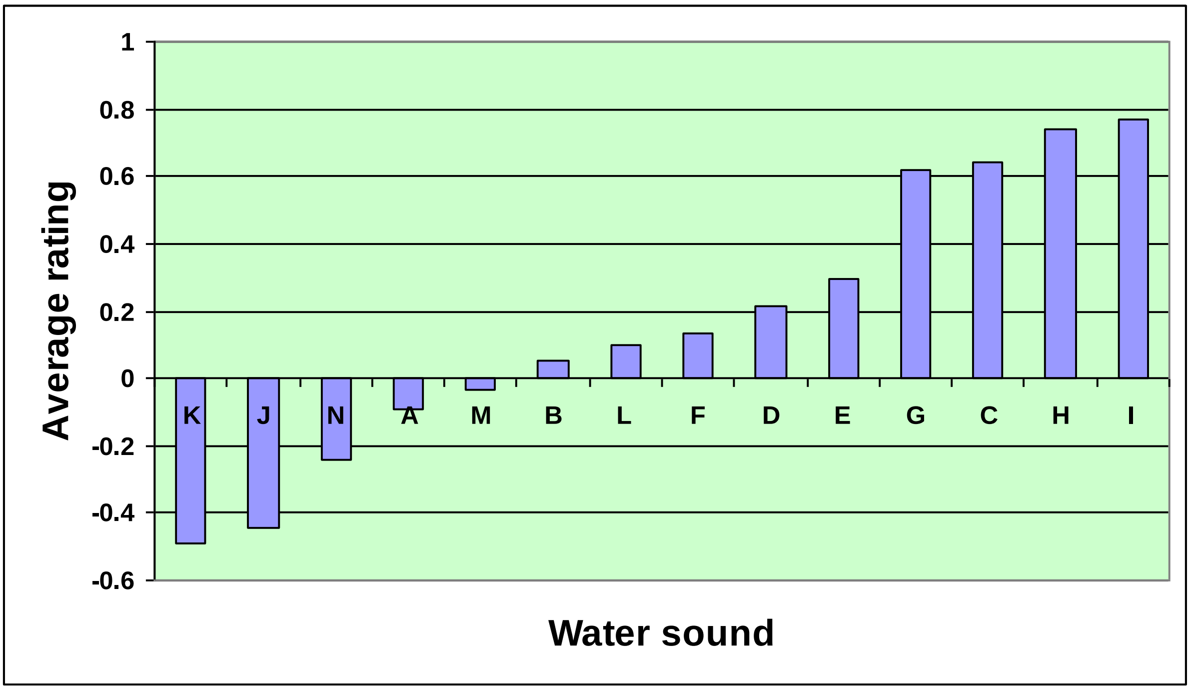
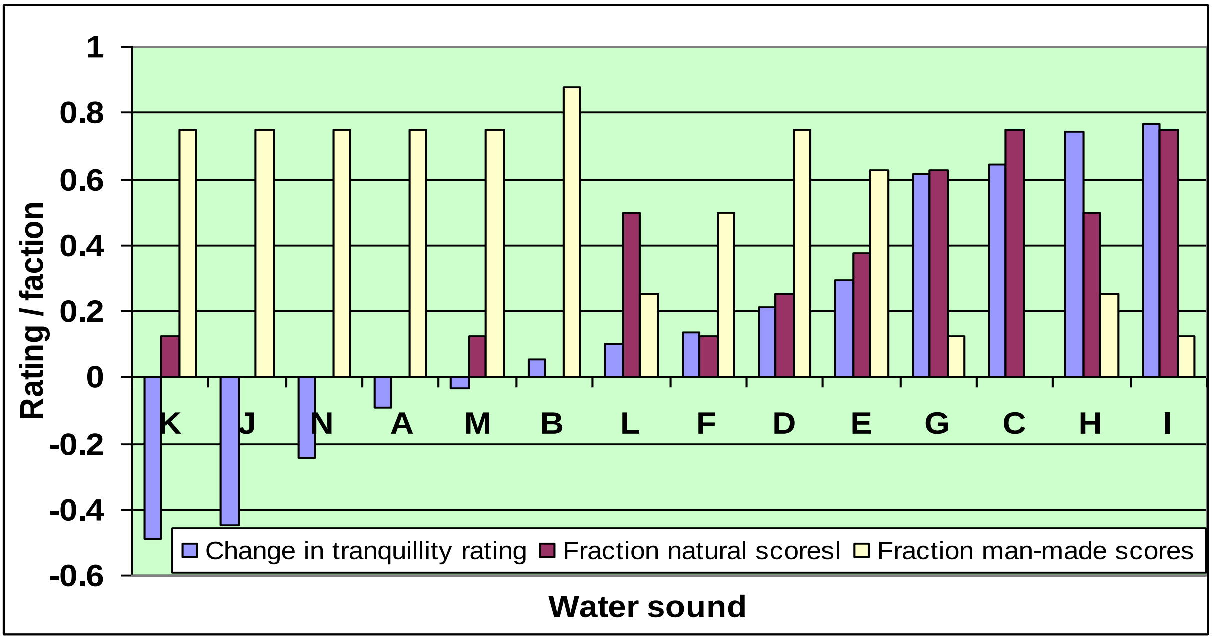


Figure 7: Average ratings based on all 4 experiments together with fraction categorised as natural and man-made



TABLE

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