SUBJECTIVE AUDIO QUALITY TRADE-OFFS IN CONSUMER MULTICHANNEL AUDIO-VISUAL DELIVERY SYSTEMS

PART II: EFFECTS OF LOW FREQUENCY LIMITATION

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The subjective effects of controlled low frequency limitation of the audio bandwidth on assessment of audio quality were studied. The investigation was focused on the standard 5.1 multichannel audio set-up (Rec. ITU-R BS.775-1) and limited to the optimum listening position. The effect of video presence on audio quality assessment was also investigated. The results of the formal subjective test indicate that it is possible to limit the low frequency content of the centre or of the rear channels without significant deterioration of the audio quality for most of the programme material types. Video presence has small effect on audio quality assessment.

INTRODUCTION

There are two trends in development of audio applications. The first one aims at achieving the highest possible audio quality (for example the latest high-resolution audio applications), whereas the objective of the second one is to reduce the cost of equipment manufacturing, cost of audio broadcasting or media storage, resulting in some inevitable degradation of audio quality. In order to achieve the best trade-offs between cost and audio quality it is necessary to optimise systems psycho-acoustically on the basis of formal subjective tests, which in general is a complicated task (the audio quality depends on many factors like: bandwidth, dynamic range, distortions, spatial characteristics, etc.). The objective of the experiment described in this paper was to study only the effects of controlled limitation of low frequencies (LF) on subjectively perceived audio quality in a standard 5.1 multichannel audio set-up [1]. This is a companion paper to the paper describing the effects of high frequency band-limitation submitted for the 112th AES Convention [2]. The results discussed in detail in the companion paper can be summarised in three following points:

- For typical programme material it might be possible to limit the high-frequency content of the centre channel without significant deterioration of basic audio quality. The exception is a group of items having a loud centre channel.
- It might be possible to limit the high-frequency content of rear channels with small deterioration of audio quality for items having F-B spatial characteristic (see Section 2 for description of the F-B spatial characteristic).
- Video presence has a small but statistically significant influence on the audio quality evaluation for some subjects.

The experiment described in this paper was carried out in collaboration between University of Surrey (Dept. of Sound Recording), BBC and Bang & Olufsen within a joint EPSRC-funded project investigating subjective quality trade-offs in consumer multichannel sound and video delivery systems. The main research questions in this experiment were as follows:

1. To what degree does switching off the LFE channel degrade the audio quality?
2. What is the quantitative relationship between the low frequency limitation of main channels and audio quality?
3. Does video presence have any effect on audio quality scores?

The investigation was limited to the optimal listening position. Since optimisation of bass-management for surround systems was not an objective in this experiment, a cinema-like set-up was used (5 main full frequency range loudspeakers and the subwoofer only for the LFE channel).
1 PROCESSING OF AUDIO MATERIAL

The first type of degradation of the audio was just switching off (muting) the LFE channel. Other types of audio degradation were obtained by muting the LFE channel in conjunction with high-pass filtration of the selected channels. For each type of degradation three cut-off frequencies were used:

- **80 Hz** (refers to a roll-off frequency of many cheap loudspeakers for home cinema applications)
- **160 Hz** (one of the standard frequencies recommended for subwoofer cross-overs)
- **500 Hz** (chosen arbitrarily as the highest level of degradation in this experiment)

Each original item had 13 different processed versions to be graded (Tab. 1) (note that LFE channel was switched off in each type of degradation). Since some of the results of the experiment may be relevant for loudspeaker designers it was decided to choose the filter characteristic simulating the analogue characteristic of the typical closed box loudspeaker system. Therefore a second order, IIR, high-pass filter having a Butterworth characteristic was selected. The attenuation cut-off frequencies were used: 80 Hz, 160 Hz, 500 Hz.

The loudness of all stimuli (both original and processed) used in the experiment was equalised in order to minimise the experimental error due to loudness changes. The level of the audio source material was adjusted to achieve the loudness at the listening position equal to 41 sones. This value was assessed by the authors as the most comfortable during informal listening tests. Loudness measurements were accomplished by analysing $L_{eq}$ in 1/3 octave bands over a 32 sec. time window (audio material was looped). Loudness was calculated using Moore’s loudness model [4]. Since that model was originally developed for stationary signals only, it was necessary to check its applicability to the loudness equalisation of the non-stationary, but relatively consistent audio material used in this experiment. Informal listening tests showed that the obtained results were satisfactory.

2 SELECTION OF A-V MATERIAL

The main criterion of selection of programme material was to choose the most generic types of material that are currently used and/or will be used in the future. Therefore it was decided to choose classical music, pop music, movie and TV sport. A special excerpt with surround applause having pronounced LF content was also included to our selection. Since surround audio material may be varied in its spatial content it was important to select a representative selection of the broad range of different characteristics of surround audio recordings. For the purpose of the current experiment two types of spatial characteristics were selected. They were named F-B and F-F respectively. The first characteristic (F-B) describes the case where front channels reproduce foreground audio content (close and clearly perceived audio sources), whereas rear channels contain background audio content (reverberant sounds, not clear, “foggy”). This situation may be compared to the sound impression perceived by the listener sitting in the concert hall (sound stage in the front, reflections from rear and back). The second chosen spatial characteristic (F-F) describes a recording in which the listener is surrounded by clearly identifiable audio sources (foreground audio content both from front and rear directions). This refers to the audio impression when the listener is surrounded by the orchestra. In the authors’ opinion these two spatial characteristics (F-B and F-F) are the most typical ones and therefore they were selected for this experiment.

Another important criterion was to select “critical” material (that is revealing differences of the system under test), which in our case meant material with pronounced low frequency content. To achieve this objective a “short list” of suitable excerpts was created and auditioned by the authors of this paper. Then, after discussion, the final group of excerpts was selected. Finally, the decision was verified objectively by comparing results of spectral analysis of excerpts from the short list. The last criterion of selection of the material was consistency of its characteristics. Long items having variable spectral and spatial characteristics are difficult to assess. Therefore it was decided to use relatively short, looped items with possibly time-invariant characteristic. The exception was the TV Sport material in which case it was impossible to select a static excerpt.

Finally six items were selected for this experiment (Tab. 2). Organ music excerpt was used as an item representing classical music because of its pronounced

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<table>
<thead>
<tr>
<th>Degrad. Type No.</th>
<th>Cut-off frequency</th>
<th>Filtered channels</th>
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<tr>
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<td>C</td>
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</tr>
<tr>
<td>5</td>
<td>80 Hz</td>
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</tr>
<tr>
<td>6</td>
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<td>LS, RS</td>
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</tr>
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<tr>
<td>13</td>
<td>500 Hz</td>
<td>LS, RS</td>
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Table 1: Degradation types used in the experiment
bass content. There was no LFE channel in the original recording. A slide show was used as a video material accompanying audio presentation.

Both pop music items selected for our experiment were live recordings. In the first case most of the instruments were balanced to front channels with reverb in rear channels (F-B spatial characteristic) whereas in the second case the instruments were mixed to all channels including two guitars in the rear channels (F-F characteristic).

The movie item was an excerpt showing an escape of people surrounded by collapsing buildings. There were many dynamically changing video scenes. Front channels contained LF audio effects. Some voices were mixed to the centre channel. There was also loud orchestral music in the front channels. Rear channels contained quite music with reverberations.

The sport item was a BBC recording of tennis from Wimbledon. The chosen excerpt contained crowd effects (applause) in all channels. There was a commentary between front left and centre channels and umpire’s voice between centre and front right channel. Details about this recording are described in [3]. There was no LFE channel in this excerpt.

Table 2: Audio-visual material selected for the experiment.

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Programme type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Classical music (F-B)</td>
</tr>
<tr>
<td>2</td>
<td>Pop music (F-B)</td>
</tr>
<tr>
<td>3</td>
<td>Pop music (F-F)</td>
</tr>
<tr>
<td>4</td>
<td>Movie (F-B)</td>
</tr>
<tr>
<td>5</td>
<td>TV Sport (F-F)</td>
</tr>
<tr>
<td>6</td>
<td>Applause (F-F)</td>
</tr>
</tbody>
</table>

Figure 1: Loudspeaker set-up used in the experiment.

The listening tests were automated using the “Alex” software developed at the Department of Sound Recording. It was run on the SGI computer with a built in digital audio (ADAT) and analogue video extension cards. The audio items were stored using 6 channel uncompressed wav audio files whereas the video material was stored in M-JPEG format using 0.85 spatial compression factor. The audio signal was transmitted digitally from the SGI to the digital mixing desk (Yamaha O2R) and then fed to the active loudspeakers using the analogue connections.

According to current standards the bandwidth of the LFE channel can range up to 120 Hz [7, 8]. The subwoofer used in our experiment had bandwidth limited to 85 Hz which might have caused the loss of the signal within the spectrum range from 85 Hz and
120 Hz. To overcome this problem a simple bass management was applied (Fig. 2). This solution theoretically allowed to preserve the full bandwidth of the LFE channel by redirecting high frequency components (> 85 Hz) to the centre loudspeaker and low frequency components to the subwoofer. The gain of the LFE channel in the console was set up +10 dB higher than the gain of the main channels.

Absolute level alignment was carried out using a band-limited pink noise at reference recording level (200 Hz – 20 kHz). The sound pressure level in the listening position was equal to 78 dBA for each channel separately and 85 dBA for all active channels measured at the reference listening position.

5 EXPERIMENTAL DESIGN
The listening panel consisted of 14 experienced listeners. They were recruited during a special screening procedure during which a questionnaire, audiometric measurements and a special “discrimination” test were carried out to verify listener’s reliability and consistency.

It was decided to use a MUSHRA method [6] as a basis for experimental design because of its suitability for assessment of medium and large impairments. After the training phase each listener took part in 4 sessions each lasting about 30 minutes. During the listening tests subjects were asked to grade the Basic Audio Quality. This term was defined as the global attribute that described any and all detected differences between the reference and the evaluated excerpt. The subjects were assessing the quality of the items according to the five-interval continuous quality scale with intervals defined as follows:
- Excellent (80-100)
- Good (60-80)
- Fair (40-60)
- Poor (20-40)
- Bad (0-20).

Since the interpretation of the terms (labels) from the scale may be context and application dependent, listeners were asked to assume (imagine) that they were assessing the audio quality of an ‘audio-visual home-theatre system’ installed in a living room.

It was emphasised that during the audio-visual presentations they were still expected to grade the quality of audio, not video.

The listeners were asked to have their eyes closed during audio-only presentation and to keep eyes opened and fixed on the screen when the audio-visual material was presented. It was possible to switch between the items “by touch” using the computer keyboard.

6 DATA ANALYSIS
The data from 2 listeners were post-screened due to a high error and inconsistency in grading. It was assumed
that the obtained data was independent because of randomisation of the experimental factors. The distribution of the data was not normal in about 50% of all populations. Moreover, the variance was not homogenous between the populations. However, since the analysis of variance (ANOVA) is robust to non-normal distribution of data provided the number of cases is large enough and the number of cases is the same in all populations (which to some extent was fulfilled in our experiment) it was decided to use this method for our purposes. Multiple comparisons for observed means were carried out using a Dunnett’s C method (this method did not require equal variance between populations).

7 RESULTS

According to ANOVA analyses, the significant factors affecting the basic audio quality were: degradation type, programme material and subjects. Moreover, interaction between the type of degradation and programme material was also statistically significant, indicating that particular degradation types had different effect for different programme items. Therefore it was decided to inspect the obtained scores for each item separately. Results of ANOVA analyses did not show any significant global effect due to video presence, however some interaction between video presence and programme type was detected with significance level equal to 0.096 (this level was equal to 0.05 when the date from post-screened listener were taken into analysis suggesting that post-screened listeners were sensitive to video presence). The issue of video influence on audio quality evaluation will be discussed further at the end of this section.

The effect of degradation of basic audio quality due to switching off the LFE channel is shown in Figure 4 (results are shown only for items having the LFE content in the original recording). As a result of switching off the LFE channel basic audio quality was degraded from “Excellent” (80-100) to “Good” (60-80) for 3 items. For one item (Pop F-B) this effect was perceivable (small shift of scores from 100 to about 95) but the audio quality was not degraded very much. The obtained results show that excluding of the LFE channel from surround audio reproduction systems may have significant effect on degradation of audio quality, however resultant quality is still “Good”. Therefore it may be concluded that LFE channel is not critical (necessary) for good reproduction of typical surround audio material.

Figure 5 shows the effect of switching off the LFE channel in conjunction with high-pass filtration of all channels. Effects of switching off the LFE channel without any filtration of the main channels are also presented in this figure in order to compare the magnitude of the effect for these two types of degradation. Switching off the LFE channel combined with high-pass filtration of the main channels degraded the audio quality considerably. For all items shift of the lower boundary of the bandwidth up to 500 Hz and switching off the LFE channel degraded the audio quality to “Poor” (20-40). Obtained results show that simultaneous reduction of low frequencies in all channels considerably degrades audio quality. A similar result was obtained for the front left and right channels (Fig. 6). High-pass filtration of front left and right channels in conjunction with switching off the LFE channels caused also substantial degradation of audio quality, however a bit smaller than in the previous case. Moreover, for some items (Pop F-F and Applause F-F) band-limitation of left and right channels caused small deterioration of quality in relation to degradation of quality due to switching off the LFE channel. It can be explained by the fact that loss of LF content in left and right channels was not so noticeable because of the pronounced LF components in remaining channels.

![Figure 4: Effect of switching off the LFE channel.](image-url)

In contrast to previous cases, limitation of LF content in the centre channel had an insignificant effect on audio quality for most items. Fig. 7 shows that switching off the LFE channel had a greater effect on quality than switching off the LFE channel in conjunction with band-limitation of the centre channel. For example, for the “Applause F-F” switching off the LFE channel deteriorated the quality from “Excellent” (80-100) to “Good” (60-80). However, switching off the LFE channel and high-pass filtration of the centre channel did not cause any further degradation of quality (insignificant differences between means).
Figure 5: Degradation of the basic audio quality caused by band-limitation of all channels. Dashed line between mean values indicates no significant difference between them.

Figure 6: Degradation of the basic audio quality caused by band-limitation of front left and right channels.
Figure 7: Degradation of the basic audio quality caused by band-limitation of the centre channel.

Figure 8: Degradation of the basic audio quality caused by band-limitation of rear channels.
High-pass filtration of rear channels had only a small effect on degradation of audio quality for most items (except of classical music). The degree of deterioration of quality due to switching off the LFE channel with simultaneous high-pass filtration of rear channels was only slightly greater than the degree of deterioration of quality caused by only switching off the LFE channel (Pop F-B, Pop F-F, Movie F-B, Applause F-F). For organ music (Classical F-B) and sport item (Sport F-F) limitation of LF content of rear channels up to 80 Hz caused negligible degradation of quality. For organ music the loss of LF content was difficult to notice (probably due to masking effect) because of the pronounced bass in remaining channels. The lack of differences in quality for sport item was caused by the spectral characteristic of this item in which there was no perceivable LF content below 80 Hz.

Figure 9: Differences between basic audio quality scores obtained with picture presence and without picture for different programme material. Asterisk denotes that means are significantly different from zero.

There was no global effect of video presence on grading of audio quality, however small but statistically significant interaction between audio and visual modalities was detected for two items. Figure 9 shows differences between scores obtained during audio-visual presentation and audio-only presentation. Positive mean values show improvement of audio quality due to video interaction whereas negative values indicate deterioration of audio quality caused by video presence (zero represents no audio-visual interaction). For organ music (Classical F-B) the scores given during audio-visual presentations were lower than scores given during audio-only presentation (mean value less than zero). It was probably caused by “boring” video content (static pictures). The opposite interaction was observed for Movie F-B. In that case video presence “improved” the grading of the audio quality. It may be explained by interesting and involving content of the video presentation, which “positively” affected grading of the audio quality. In both cases video presence “shifted” the scores up to 3 % only, which shows that mentioned effect is small, however statistically significant. This observation is in line with results obtained Beerends et al. [9]. It was also found that some of the listeners are more susceptible to video influence than others. For example, subjects No. 3, 7 and 13 had tendency to grade audio quality slightly “better” for audio-visual presentation than for audio-only one (Fig. 10). In general, obtained results showed that video presence had a small (but statistically significant) effect on audio scores.

Figure 10: Differences between basic audio quality scores obtained with picture presence and without picture for different subjects.

8 DISCUSSION

One of the most interesting (and perhaps surprising) outcomes of the experiment is that the audio quality does not change a lot when the centre channel or the rear channels are high-pass filtered. It is believed that this effect is caused by masking and/or perceptual streaming.

Two objective analyses were made in order to find out what kind of psycho-acoustical mechanisms were responsible for obtained results and also in order to check whether “truly critical” material (containing LF content in the centre and rear channels) was used. The first analysis was just to compare the RMS level of the audio signal (averaged over the duration of each item) between each channel (see Tab. A1). The second type of analysis was to make inter-item and intra-item (between channels) comparison of LF content. Since it was difficult to compare visually spectrograms and obtain quantitative information about any differences in LF content it was decided to use a special spectral coefficient “k_{LF}” defined as the energy of the signal for
frequencies less than 80 Hz ($E_{f<80\text{Hz}}$) normalised to the total energy of the signal averaged over the total duration of the item ($E_{\text{Tot}}$):

$$k_{LF} = \frac{E_{f<80\text{Hz}}}{E_{\text{Tot}}}$$

The frequency of 80 Hz used in definition of this coefficient is related to the lowest cut-off frequency employed in the experiment. When the coefficient $k_{LF}$ is equal to unity (0 dB) it means that the whole energy of the signal is concentrated at low frequencies. The LF content of each item is presented in Table A2.

The results of objective analyses show that for most of programme material (except of sport item) the centre channel had significant LF content (similar to other channels). The level of the centre channel was higher than the level of other channels only for one item - Pop F-F. It explains the obtained result that for this item the changes in quality due to high-pass filtration are most noticeable. For other items changes in timbre of the centre channel caused by high-pass filtration of the centre channel are masked by (or “perceptually compensated by”) LF content of louder channels.

According to objective analyses there was also a significant LF content in rear channels for 4 items (all items except of Movie F-B and Sport F-F). Nevertheless, the deterioration of quality of these items due to high-pass filtration of rear channels is smaller than the effect of high-pass filtration of all channels. It is probable that masking or perceptual streaming (or both) are responsible for this result. When the audio impression of the audio coming from front and rear channels is perceptually “blended” (the same pitch, similar timbre, good correlation of time cues) the loss of LF content in rear channels is probably compensated by LF content of front channels.

As it was stated before, the high-pass filtration of the centre or of the rear channel does not cause substantial degradation of audio quality. In particular, limitation of the bandwidth of the centre or of the rear channels using the high-pass filter having 80 Hz cut-off frequency caused only negligible degradation of quality. To some extent this result may “justify” using small satellite loudspeakers for the centre or for the rear channels. However, other factors (not investigated in this experiment) related to using small loudspeakers, like poor power handling or limited dynamic range, should also be taken into consideration.

According to the results obtained in the listening test the video presence had a marginal effect on evaluation of audio quality. However, the experimental procedure was limited to a passive way of watching of the video (listeners were not asked to do any particular task related to video while evaluating the audio quality). Therefore, one can not exclude the case, in which video may have greater effect on audio evaluation than the effect observed in this experiment. The audio-visual task dependent effects will be the subject of future experiment.

9 CONCLUSIONS

Effects of low frequency band limitation in standardised (5.1) multichannel audio system on subjectively assessed basic audio quality were investigated. Limitation of bandwidth at low frequencies in all main channels of the system caused significant deterioration of basic audio quality at the optimum listening position. Low frequency band limitation of front left and front right channels also resulted in significant deterioration of audio quality. However, it was found that limitation of bandwidth at low frequencies in the centre channel did not cause significant deterioration of quality, although some changes in quality were noticeable. Also band-limitation of rear channels did not have a great effect on quality for most items. The obtained results indicate that for the typical programme material it might be possible to limit the bandwidth of the centre channel or limit the bandwidth of the rear channels at least up to 80 Hz without significant deterioration of basic audio quality. Therefore in applications where limitation of low frequencies is unavoidable (for example because of the technical and/or economical constraints) it is suggested that one might choose to “sacrifice” the centre channel or rear channels. Band-limitation of front left and right channels or band-limitation of all channels would result in substantial loss of audio quality.

The importance of the LFE channel was also investigated. According to the obtained results switching off the LFE channel caused a drop of basic audio quality from “Excellent” to “Good” for some of the programme material types. Therefore it may be concluded that the LFE channel is important but not essential to achieve a good quality of surround audio presentation.

During the experiment the same material was presented to subjects in both audio-only and audio-visual form. It was identified that video presence may have a small (but statistically significant) influence on the audio quality evaluation for some types of programme material and for some subjects.
ACKNOWLEDGEMENTS

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REFERENCES


APPENDIX

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<tr>
<th>Item</th>
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Table A1: RMS levels (in dB) for each item

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Table A2: LF content coefficient $k_{LF}$ (in dB) for each item