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AS LIGHT AS YOUR FOOTSTEPS: DESIGN AND EVALUATION OF A PORTABLE DEVICE FOR CHANGING BODY PERCEPTION THROUGH A SOUND ILLUSION

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ABSTRACT.

People's body perception is highly malleable. Recent works have demonstrated that the dynamic modification of footstep sounds can lead people to perceive their body as thinner/lighter, walk more dynamically and feel happier, potentially supporting health. Previous studies modified the spectra of footstep sounds through a stereo 9-band analog graphic equalizer. While this system had minimal latency, it was not optimal as a wearable device, considering its weight (near 2 kg) and necessity of an electric outlet, which limited its applicability to real-world scenarios.

Consequently, several substitute solutions were tested to improve portability, lightness and freedom of movement. For some, a non-satisfactory attempt was made to replicate the spectra of the original system. Therefore, it was hypothesized that a standalone digital microcomputer could increase portability and replicate the spectra. A novel device, using Bela.io and SuperCollider programming language, was tested, in which the spectral behavior of the original equalizer was replicated using cascaded biquad IIR filters.

Objective and subjective experimental results suggest that, subject to the original system, we have successfully reduced weight and increased portability while keeping latency and spectral difference negligible. We foresee this novel system as a portable robust solution to induce illusory changes in body perception.

RESUMEN.

La percepción corporal de las personas es altamente maleable. Recientemente, se ha demostrado que la modificación dinámica del sonido de los pasos puede hacer que la gente perciba su cuerpo como más ligero/pesado, camine más dinámicamente y se sienta más feliz, lo que puede tener un potencial efecto sobre la salud. Existen estudios previos donde se modifica el espectro sonoro de los pasos mediante un ecualizador gráfico estéreo analógico de nueve bandas. Aunque este sistema tiene una latencia mínima, no es óptimo como un dispositivo vestible, si se tienen en cuenta su peso (cerca de 2 kg) y la necesidad de corriente eléctrica. Estas características limitaban su aplicación en escenarios reales.

Para solventar estos problemas se han probado diversas alternativas, con el fin de mejorar la portabilidad, ligereza y libertad de movimientos. Sin embargo, el espectro del sistema original no pudo replicarse para algunas de estas alternativas. En consecuencia, se consideró que se podría replicar el espectro en una microcomputadora digital autónoma ligera. Así, se probó un dispositivo novedoso, basado en Bela.io y con lenguaje de programación SuperCollider, en el que se replicó el comportamiento espectral del ecualizador original mediante cascadas de filtros bicuadráticos IIR.

Se realizaron pruebas objetivas y subjetivas que sugieren que, mediante el uso de este dispositivo, hemos conseguido mejorar la portabilidad y reducir el peso, manteniendo una latencia y unas diferencias mínimas con respecto al sistema original. Presentamos, por tanto, este nuevo dispositivo como una alternativa portátil y robusta para inducir cambios ilusorios en la percepción corporal.

1. INTRODUCTION

People's bodies do not often change quickly, but how people perceive them is actually highly malleable [1]. Neuroscientific works have shown that people's body perceptions are constantly updating through the sensory signals received by the brain [2,3]. Through the use of immersive virtual reality applications where people embody an avatar, it is possible to create perceptual illusions of one's body changing, for instance the illusion of having a longer arm [4] or having a smaller or bigger body [5]. Recent works have also shown that such "body transformation" experiences can also be created using sound [6,7]. One of such works showed that the dynamic modification of the frequency spectra of people's walking sounds can lead people to perceive their own body as thinner/lighter, and in turn walk more dynamically and feel happier, opening possibilities to support people's physical and emotional health [7,8]. This is because the spectral properties of the walking sounds that relate to the walker's body weight were manipulated.

Research in [7,8], built on the work by [9] showing that people listening to the walking sounds of an unknown walker are able to make judgments about the body of the walker (e.g., sex of the walker), based on the spectral properties of the walking sounds. Indeed, in [9] it was demonstrated that shifting the spectral mode of pre-recorded walking sounds of unknown walkers to lower frequencies (at least to 125 Hz) could increase the perception of maleness of the heard walker, while shifting the spectral mode to higher frequencies (1000 Hz) could increase the perceived femaleness of the heard walker. In [7], a similar system to that used by [9] was employed, consisting of an analog graphic equalizer with a 24-dB dynamic range and nine frequency bands; this was complemented with a pair of microphones placed on the walker's shoes, a pre-amplifier and a pair of headphones. The equalizer allowed creating a "*High frequency*" and a "*Low Frequency*" version of the walking sounds in real time, which were consistent with sounds produced by a lighter body and a heavier body, respectively. In the "*High frequency*" version, the higher frequency bands (1–4 kHz) of the footsteps' sounds were amplified by 12 dB and the lower frequency bands (83–250 Hz) were attenuated by 12 dB; while in the 'Low Frequency' condition this pattern was inverted. Results showed that in the "*High Frequency*" condition, as compared to the "*Low Frequency*" condition, participants wearing this system perceived their own body as being slimmer and lighter, and changed their walking pattern to show more dynamic swings and shorter heel strikes (i.e., a gait pattern consistent with that observed in people with lighter bodies [10,11]).

This study was the first showing that the perceived own body weight can be altered by this dynamic modification of own walking sounds and opened opportunities for the design of a system that can help people to adopt more active walking styles. A subsequent study showed how such a system allowing the dynamic modification of walking sounds could help people to perform two more physically demanding exercises, using a gym-step and climbing stairs [8]. However, the original system needed to be adapted to make it lighter and to eliminate the power (AC) supply cable of the equalizer, therefore allowing its portability in the climbing stairs scenario.

Although these studies have shown great effects on the perception of one's own body and potential changes in people's health, there is a major drawback for their use in everyday situations: their portability. For instance, the Realistic 31-2020A equalizer used in [9] weights approximately 2.8 kg and has standard pro audio equipment dimensions (i.e., 42 cm wide, 21.5 cm deep and 6.7 cm high). Conversely, the Behringer MiniFBQ FBQ-800 equalizer used in [7], although lighter and more compact than the previous one, is still too bulky, with a weight of 0.6 kg and dimensions of 24.3 cm wide, 12 cm deep and 4.8 cm high. In addition, both equalizers require AC power connection, which hinders their portability due to the power cord.

Therefore, and considering that this equipment is generally used in conjunction with other devices and sensors that also require wiring, it was decided to seek a more compact and portable equalization, without the need for AC power, that, nevertheless, would maintain the same filtering performance as the MiniFBQ FBQ-800 in both its "*High Frequency*" and "*Low Frequency*" configurations. This search and deployment of a portable alternative to the equalizer used in [7] was the purpose of the research presented in this work.

The rest of this communication is organized as follows: Section 2 presents the original system and the two main found alternatives, summarizing their features. Section 3 describes the methodological process followed for the objective assessment and enhancement of the systems. Section 4 shows the main results of this research, comparing the performance of the three systems. Last, Section 5 enumerates the main conclusions of our research.

2. SYSTEM DESCRIPTION

An audio system, in which the MiniFBQ FBQ-800 equalizer was used, was developed and used by some of the coauthors in previous researches [7,8], to generate the sound illusion over the sound of footsteps. This system, as it has already been introduced, was inspired by similar systems employed in previous experiments conducted by other researchers [9].

The actual system, a schematic description of which can be seen in the *Figure 1*: left, takes the sound of the footsteps through two microphones, each of them attached on or near one of the shoes. The signal picked up by each of these two microphones is then sent to a preamplifier, to efficiently adapt the signal from the microphones to the next device in the system, a stereo graphic equalizer. Through this equalizer, and in real time, the sound spectra of the captured footsteps is modified. Finally, the equalized signal is sent to headphones for the listening by the participant.

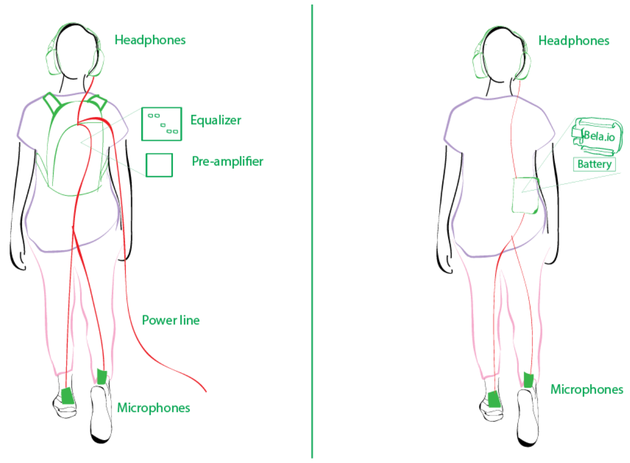

Figure 1 - Schematic description of the system. Left: original system. Right: final proposal.

As it can be seen in the previous description, as well as in Figure *1*: left, the equalizer is the key element of the system, being in charge of modifying the sound spectra of the captured footsteps. It is therefore essential not only that it generates the desired spectral modifications, but also that it is lightweight and portable.

However, as evidenced in the tests performed in [7,8], the employed equalizer did not meet any of the conditions regarding size and portability. To deal with this, the research presented in this communication was carried out, aimed at solving these shortcomings while maintaining the quality of the spectral filtering. Several alternatives were considered that could potentially fulfill all these objectives, with two main alternatives being identified as potentially the most appropriate. The final proposal, as it will be described further in this communication, is shown in Figure *1*: right.

The main characteristics of the equalizer originally used in the research, as well as those of the two most relevant alternatives, are presented below.

2.1 Original equalizer

The original equalizer (*Figure 2*: left), as already employed in previous experiments regarding body illusion, is a Behringer MiniFBQ FBQ-800. This stereo 9-band analog graphic equalizer covers the octave bands with central frequencies between 63 Hz and 16 kHz, allowing a maximal amplification and attenuation of 12 dB in each of these bands. In addition, it allows to globally amplify and attenuate both the input and the output by 12 dB.

This equalizer, as already introduced, weighs 0.6 kg and has dimensions of approximately 24.3 cm wide, 12 cm deep and 4.8 cm high. Although these dimensions and weight may seem small under normal circumstances, it is quite bulky for this kind of experiments, especially considering the need for an additional preamplifier and cables for its connection with the microphones, which makes the whole system to weight almost 2 kg. Furthermore, the fact that it can only be powered by AC power makes its portability challenging.

Figure 2 - Tested analog equalizers: Behringer MiniFBQ FBQ-800 (left, original equalizer); SourceAudio PEQ SA170 (right, tentative analog alternative).

2.2 Alternative analog graphic equalizer

Before considering the digital implementation of an own-designed equalizer, we took into account the possible use of another, lighter and more portable analog graphic equalizer. After assessing various analog equalizers, it was concluded that those generally used in pedalboards for stringed instruments might be the most practical, due to their light weight, small size, and feasibility of use with batteries. A SourceAudio PEQ SA170 was, therefore, considered as a good alternative.

The PEQ SA170 equalizer (*Figure 2*: right) allows the input signal to be filtered in octaves in the range covered by the central frequencies of 63 Hz and 8 kHz, with a maximum amplification or attenuation of 18 dB in each of these bands. This should allow it to perfectly match both the "*High Frequency"* as well as the "*Low Frequency"* configurations commonly used in the Behringer MniFBQ for the previous experiments. Being the PEQ SA170 a mono device, the use of two of these elements was necessary to cover the stereo setup of the experiment.

This equalizer, with a width of 6.4 cm, a depth of 11.4 cm, a height of 5 cm and a weight of 0.28 kg, is approximately three-quarters less bulky than the original. Nonetheless, with the need to use two of these equalizers simultaneously to achieve stereo sound, the complete equalization stage is about half as bulky as the original, while maintaining the same weight. Although the reduction in size was already considerable, the great advantage of this alternative over the original equalizer was the possibility of being powered by batteries, making the system truly portable. In addition, the use of the device with batteries avoids the possible effects of the well-known 50 Hz AC power supply noise.

This equalizer seemed a potentially appropriate alternative to replace the original equalizer, but the subjective comparison of the sound filtered with this equalizer subject to that filtered by the original equalizer did not report perceptually similar results. For this reason, objective measurements were carried out, following the procedures described in Section 3.1, to truly assess the similarity between the frequency response of both equalizers under the "*Low Frequency*" and "*High Frequency*" configurations.

These tests allowed observing that the spectral behavior of both equalizers was, indeed, very different. In Section 4, comparative graphs of the spectral behavior will be presented, as well as some hypotheses about the reasoning for the observable differences.

In any case, the large differences between both equalizers led to the development of a digital alternative, with filters specifically designed and tuned by us, to replicate the behavior of the original equalizer.

2.2 The Bela.io digital implementation

Considering the lack of similarity of the analog alternative assessed, it was decided that the most reasonable option was to realize a digital implementation, in which the frequency response of the original equalizer could be tightly replicated, by means of digital filters, for both "*Low Frequency*" and "*High frequency*" configurations. It was decided to use, for this implementation, a Bela.io device (i.e., the circuitry in *Figure 3*), due to its theoretical appropriateness and efficiency in digital audio processing.

Figure 3 - Complete test system with the Bela.io implementation.

The Bela.io is a hybrid system which combines a single board computer (the Beagle Bone Black) with 1 GHz ARM Cortex A-8 processor with 512 RAM memory, 4 GB on board memory and a SD slot, and an audio cape designed by Augmented Instruments Laboratory. The Bela.io system is implemented using a Linux Xenomai with the real time extension for the kernel and a custom driver that takes advantage of the Programmable Real Time Unit (PRU's) available in the same chip with the CPU. This implementation makes it possible to detach the audio processing from the operating system and give it the main priority, allowing hard real time or firm real time, achieving latencies of 1 ms or less [12].

For the implementation of the filters that had to replicate the frequency response of the original equalizer we used SuperCollider (i.e., version 3.12.3), which is a computer language devoted to music and audio processing but is very powerful like a general-purpose language [13].

The whole system in *Figure 3* only includes, in addition to the Bela.io device itself, an acquisition of the signal stage comprising a Core Sound Binaural Microphone Set which has a range from 20 Hz to 20 kHz, and a playback stage comprising a pair of Sennheiser HDA 300 headphones. This system no longer requires the use of a preamplifier between the microphones and the equalization stage.

The Bela.io system we implemented has a width of 9.5 cm, a depth of 6.5 cm, a height of 3.5 cm and a weight around 0.1 kg. All the system which substitutes the preamplifier and equalizer from the previous version has a weight around 0.6 kg (as opposed to the near 2 kg of the original system) and the final case with all included has an approximate dimension in width of 10.0 cm, a depth of 11.0 cm and a height of 6.0 cm. This size and weight bring a large improvement with regards to the previous proposal, in terms of weight and portability, making it easier to use in experiments. In addition, the possibility of using this device with a compact battery eliminates the need for power supply wiring as well as the possibility of getting 50 Hz AC noise into the audio signal.

2.2.1 Digital filter implementation

The use of the Bela.io, for the above-mentioned reasons, allows great versatility when designing and implementing the filters used to replicate the behavior of the original equalizer.

There are different ways to implement digital filters. Among them are the FIR implementations, very controlled, with an available linear phase, and the IIR, more unstable and with larger phase variations [14]. The decision of using one type of filter or the other is usually subject to a trade-off between performance and efficiency. While FIR filters demand high orders of magnitude, involving many coefficients, IIR filters require fewer coefficients, with a significantly lower hardware consumption [14]. This computational advantage of IIR filters over FIR filters has resulted in IIR filters being used for applications that require fast and efficient signal filtering for many applications where phase response is not critical. Considering that our system requires from this efficient and fast filtering to deliver the processed sound to the participant's headphones with negligible latency, IIR filters were those of choice.

Parametric IIR filters can be implemented using very simple structures of few delay blocks, known as Second-Order Sections (SOS). SOS are defined, in their simplest topology (i.e., Direct Form I), by Equation (1) and are a ratio between delayed samples of the input signal and the output signal, each weighed with one coefficient (i.e., a_0-a_2 and b_0-b_2). The calculation of these coefficients is straightforward and depends on certain gain parameters (i.e., gain at $\omega = 0$ and at $\omega = 2 * \pi * fs/2$ (i.e., Nyquist frequency), and gain at the tuning frequency), the tuning frequency and the bandwidth, defined by the Q factor[15–17].

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{a_0 + a_1 z^{-1} + a_2 z^{-2}} \tag{1}$$

The design of these SOS, and the obtaining of their coefficients, can follow two main approaches: (1) the design of an analog prototype, which is then mapped to a digital one by means of a bilinear transformation with frequency warping correction [16,18,19]; and (2) the implementation of the filters purely in the digital domain [15,17]. The obtention of the coefficients also depends on the topologies followed to implement these SOS. While Direct Form I, described in Equation (1) is the most straightforward, additional topologies such as Direct Form II and all-pass have been proposed, which can sometimes be more efficient or less prone to the coefficients’ truncation errors [19], which can perturbate the frequency response of the filter from its original shape and value[14]. However, as stated in [16], with convenient transformations, all of them are equivalent and can be expressed following Equation (1). Our implementation follows, for its simplicity and ease of application, the mathematical approach based on an analogical model described in [20], considering a Direct Form I topology.

While filters with many coefficients, such as FIR filters, can cover the entire spectrum at once, a single SOS can only modify the spectrum of a signal around a specific central frequency. It is therefore necessary to use several SOSs at the same time to cover the entire spectrum. Although there are different ways to make several SOSs operate simultaneously, cascaded SOS implementations are the most common to implement audio equalizers [14,17,18]. These cascades, besides using very efficient SOS to cover the whole spectrum, reduce the relevance of the truncation errors of the coefficients, considering that each SOS is independent [14] and that, therefore, the truncation errors of a section do not affect the others, something that happens if, instead of using SOS, filters of higher orders are used.

Our implementation uses a total of 11 SOS in cascade, each SOS being centered on the middle frequency of the octaves covered by the original equalizer. Although the truncation errors were small, due to the use of cascaded SOSs, an iterative tuning process, described in Section 3.4, was carried out to correct small perturbations in the frequency response due to such truncation.

3. TEST METHODOLOGY

To achieve the planned objective, a series of actions were carried out, the details of which are presented below.

3.1 Frequency response characterization

The ultimate goal of our research was to obtain a device that could replicate the frequential behavior of the original equalizer, while reducing its size and weight. Therefore, one of the fundamental actions was the objective characterization of the frequency response of both the original equalizer and the various tentative alternatives.

For this purpose, an experimental setup was designed to provide the equalizers with a sinusoidal tonal sweep at their input and to measure the frequency response at their output. Brüel and Kjaer's Pulse acquisition system was used to perform this task.

As such, through one of the outputs of Pulse, a sinusoidal tonal sweep between 20 Hz and 20 kHz was fed to the input of each of the equalizers. The excitation signal was configured to provide a significantly higher level than that of the noise floor of the equalizers, yet low enough to avoid overloading the instrumentation. In particular, a 50 mV rms signal was supplied to the equalizers.

Simultaneously, the output of the equalizers was connected to one of the Pulse's inputs. The acquisition system software was configured to use a 3200-line FFT analysis on the configured input to obtain the modulus of the frequency response, with high spectral resolution (i.e., 8 Hz). Although the spectral resolution of the analog equalizers was in octaves, the decision was to use a FFT type analysis with high spectral resolution, instead of a CPB analysis in octaves, with the purpose of adjusting the real frequency response of the equalizers as much as possible, allowing a detailed analysis of the frequential overlap between filters.

3.3 Latency measurement

Although the main objective of the research was to obtain a portable and lightweight version of the equalizer that would be able to replicate its frequency response accurately, it was also imperative that the latency of the digital implementation was kept to a minimum. If the latency was too large, participants would perceive a delay between their footsteps and the listening of the processed audio. If this were to happen, participants might hear two types of footsteps sequentially: their original footstep sounds propagated through the air; and the same footstep sound processed by the equalizer. This would ruin the whole experiment, as it would result in a loss of agency over the produced sounds [21] and break the illusion of changes in a perceived body weight.

For this reason, digital implementation latency measurements were carried out.

These measurements were also carried out using the Pulse measuring device. The setup on this occasion was different. A time signal with several Dirac delta approximations was fed to the Bela.io device, through one of the outputs of Pulse. This output was, at the same time, directly fed to one of the inputs of Pulse (i.e., an output-input direct loop). Furthermore, the output of Bela.io was fed to one of Pulse's input channels. This setup allows to address the difference in time of arrival of the deltas at both inputs, when the signal is coming from the loop and when it is coming from the output of Bela.io, hence allowing to assess the latency of the Bela.io device.

3.4 Adjustment of the digital filters

In the first instance, the digital filters were designed to exactly replicate the settings selected in the frontend of the original equalizer. In this way, the central frequencies of each of the digital parametric filters were tuned to the central frequencies of each of the analog graphic equalizer bands. Conversely, the gains of the digital filters were also set to the same value as the one selected, by means of the sliders, in the frontend of the analog equalizer. Finally, considering that the analog graphic equalizer had octave bandwidth resolution, the quality factor of the cascaded digital parametric filters was set at $Q = 1.41$, to replicate the aforementioned bandwidth.

Once the design, tuning and programming of each of the cascaded parametric filters in the Bela.io device was completed, an iterative tuning process, consisting of three steps, was started:

(1) frequency response measurements of the digital implementation were carried out, for the three usual configurations,
(2) these measurements were compared with those of the original analog equalizer to assess spectral differences,
(3) the parameters of the parametric filters necessary to minimize the observable spectral differences were readjusted.

This process was repeated, iteratively, until the observed differences between the original equalizer and the digital implementation were considered negligible.

4. MAIN RESULTS

The following comparative graphs show the difference between the frequency response of the original equalizer, its compact analog alternative and the digital implementation based on Bela.io, for the three usual configurations of use. In particular, *Figure 4* shows the frequency response of the equalizers for the "*Low Frequency*", with *Figure 5* representing the frequency responses of the equalizers for the "*High Frequency*" configuration.

As it can be seen in *Figure 4*, the frequency response of the original equalizer (i.e., MiniFBQ in the legend of *Figure 4*) presents a ripple due to the overlapping between the adjacent octave filters. Since in the "*Low Frequency*" configuration three consecutive filters (i.e., those of the 63 Hz, 125 Hz and 250 Hz) are configured with the same gain, the ripple effect is even more noticeable. The same thing happens in the higher frequencies, in which the configuration is equivalent but with negative gain.

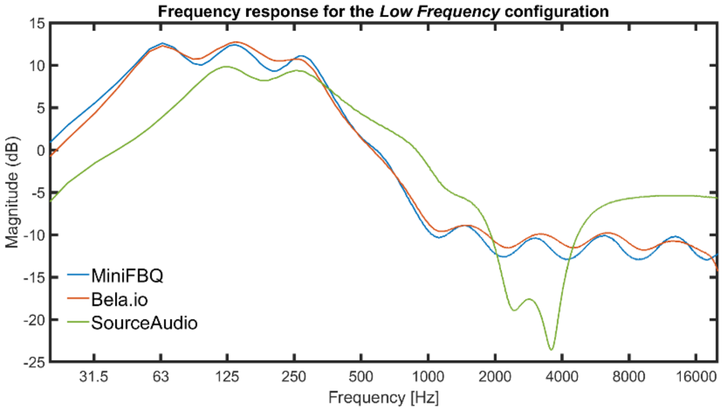

Figure 4 - Comparison of the frequency responses of the original system and the two alternatives. Low Frequency configuration.

This ripple is a well-known behavior of graphical equalizers. However, the particular shape and behavior of the ripple normally defines the quality of the equalizer. In the case of the MiniFBQ FBQ-800 the ripple is relatively small and proportional. If we now focus on the SourceAudio response in *Figure 4*, we can see that its spectral behavior, for the same configuration, deviates considerably from that of the MiniFBQ, even after a fine-tuning trial. In this second case, while the ripple itself looks smaller with positive gains, it appears to be totally unbalanced with negative gains, with deep valleys in the frequency response, more similar to the behavior of notch-type filters, and very uneven than expected. Lastly, as it can be seen in the curve for the Bela.io device, the frequency response of the original equalizer has been successfully replicated with the Bela.io device, with negligible differences around all central frequencies and just slight differences in the range 0.5 to 1 dB in some transition frequencies. While these differences are really small, a fine-tuning of the quality factor of some filters might easily overcome them.

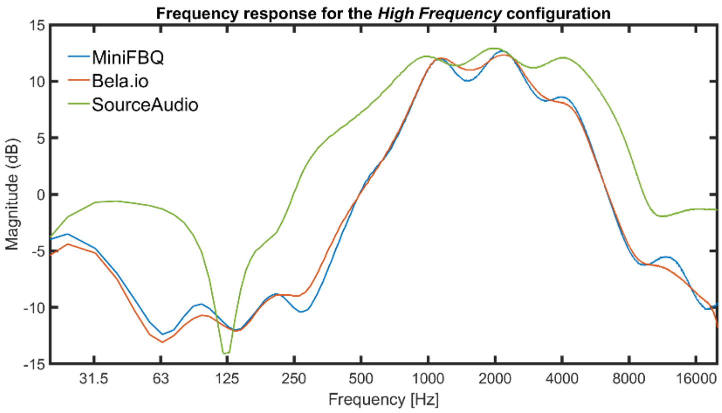

Figure 5 - Comparison of the frequency responses of the original system and the two alternatives. High Frequency configuration.

The same behavior can be observed in *Figure 5*, for the "*High frequency*" configuration, being our Bela.io digital implementation the best option to replicate the original response of the MiniFBQ FBQ-800 analog equalizer.

Finally, concerning latency, it can be noted that the analysis of the latency tests performed has resulted in an average latency of 1.6 ms from the input of the analog signal from the microphones in Bela.io, to the analog output of the filtered signal in the digital domain to the headphones. This low latency, which is negligible from a perceptual point of view, paves the way for the use of more complex systems based on Bela.io for real-time applications.

3. CONCLUSIONS

A novel, portable and light digital device, using SOS IIR filters in cascade, has been successfully programmed to replicate the spectra of the original analog equalizer.

No significant differences were found between the spectral behavior of the original and the novel systems, for any of the configurations, when objectively compared through the measurement of the transfer function of both systems. Additionally, no perceptual differences arose when conducting informal subjective comparisons.

One of the most challenging factors, the latency, was kept under recommended values to avoid perceptual issues. This was solved by using a novel audio-focused microcomputer and software language, Bela.io and SuperCollider respectively, as well as through the implementation of filters on the basis of highly efficient IIR biquadratic SOS filters in cascade.

Formal subjective tests will be conducted, to precisely assess the perceptual differences between the Bela.io digital implementation and the MiniFBQ equalizer.

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