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Internship Report

Tinnitus characterization methods for virtual reality therapy

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Abstract

Tinnitus refers to a perceptive trouble that causes phantom auditory sensations in the absence of any external acoustic stimulus. At the moment, there are no curative treatments for this common and disabling pathology, which has severe emotional consequences. Londero et al in 2011 proposed a therapy involving virtual reality that consisted on promoting the dissociation between the tinnitus perception and its emotional consequences. This master's thesis aims at presenting and evaluating new tinnitus characterization methods, i.e. the synthesis of a sound reproducing the auditory characteristics of the perceived tinnitus in order to build a reliable avatar that would be further exploited in this therapeutic protocol. Under the hypothesis that the tinnitus spectrum is related to the hearing loss, these methods will exploit the individual auditory thresholds. The adjustment quality of the synthetic tinnitus and its reproducibility will be determined by objective and perceptive evaluations.

Keywords: tinnitus, virtual reality, characterization methods, audiometry, auditory threshold

Résumé

Les acouphènes sont un trouble perceptif désignant un ensemble de sensations auditives fantômes en l'absence de stimulation acoustique extérieure. Aucun traitement curatif n'est pour l'instant connu pour cette pathologie fréquente et invalidante, ayant de lourdes conséquences émotionnelles. Londero et al proposaient en 2011 une thérapie en réalité virtuelle consistant à favoriser la dissociation entre la perception de l'acouphène et ses conséquences émotionnelles. Ce rapport de fin de stage vise à présenter et évaluer de nouvelles méthodes de caractérisation des acouphènes, c.-à-d. la synthèse d'un son reproduisant les caractéristiques auditives de l'acouphène perçu afin de créer un avatar qui pourra être exploité après dans ce protocole thérapeutique. En partant de l'hypothèse que le contenu spectrale des acouphènes est lié à la perte auditive, ces méthodes exploiteront les données individuelles des seuils d'audition préalablement établies. La qualité d'ajustement de l'acouphène synthétique et sa reproductibilité feront l'objet d'évaluations objectives et perceptives.

Mots-clés : acouphènes, realité virtuelle, méthodes de caractérisation, audiométrie, seuil d'audition

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Terminology

– AT: Auditory threshold
– CBT: Cognitive Behavioural Therapy
– Contralateral ear: ear opposite to tinnitus
– GUI: Graphical User Interface
– HRTF: Head-Related Transfer Function
– Ipsilateral ear: tinnitus ear
– P&B: Pitch and bandwidth
– RI: Residual Inhibition
– TMNMT: Tailor-Made Notched Music Treatment
– TRT: Tinnitus Retraining Therapy
– VAS: Visual Analogue Scale

Chapter 1

State of the art

1.1 Introduction

Tinnitus is defined as the perception of sound in absence of any external acoustic stimulus [1]. The English term has a latin origin, which means "to ring, tinkle" and its first known use dates from 1843 [2]. In other languages (e.g., *acouphène* in French) the term has an ancient greek origin: *akoúô* (listen) and *phaínô* (appear).

In the general population, it is estimated that around 10–15% suffers from tinnitus and in 20% of these cases the tinnitus sensation is sufficiently loud to affect their quality of life, involving sleep disturbance [3], dificulties on speech perception [4], auditory hypersensibility [5], work impairment and psychiatric distress [6][7] among other comorbidities. Tinnitus is specially commun among aged people, smokers, hypertensive sufferers and people who are regularly exposed to high pressure level sounds (e.g. musicians) that present hearing impairment [8]. Specifically, in patients attending otology clinics it is estimated that 70–90% experience tinnitus either as the main or associated symptom. Furthermore, due to the fact that in most of the cases it is associated with some kind of auditory impairment induced by noise exposure or the ageing process, the prevalence of tinnitus could be increasing as the senior population grows and as young people are increasingly exposed to industrial and recreational noise [9].

Multiple types of tinnitus have been reported: most tinnitus can be categorized as subjective, refering to an internal sound that is perceived only by the patient. On the other hand, objective tinnitus is considered a real noise that can be heard by the patient and the examiner, and is much less common than subjective tinnitus [10]. Tinnitus may affect one ear (unilateral) or both ears (bilateral), remain stable or fluctuating and it can be transient or chronic[11]. Regarding its general sound sensation they are commonly described by the patients as ringing, buzzing, cricket-like, hissing, whistling or humming [12].

At the moment, there are no curative treatments for tinnitus. The failure of many types of them, drugs in particular, has led several authors to propose treatments based on different concepts. In our work we focus on the therapy proposed in [13], which is based on the auditory-motor loop training in virtual reality and rests on the characterisation of the subjective tinnitus allowing the synthesis of an artificial tinnitus, called tinnitus avatar. The purpose of the presented study is to study the different characterization methods existing in the literature in order to build a reliable tinnitus avatar that would be further exploited in this therapeutic protocol.

1.2 Neurophysiological models underlying tinnitus

Current consensus is that damage to the afferent input to the auditory pathway initiates events that result in plastic changes at the central level giving rise to the percept of tinnitus [14]. Models of these plastic changes describe changes in specificity or functional organization of the auditory nerve fibers and central auditory neurons, or hyperactivity with increases in cortical neural synchrony, or increases in central gain. These models account for the percept of tinnitus (hearing the tinnitus sound) but do not account for the reactions to tinnitus, which can include psychological effects including anxiety, depression, and insomnia, which affects quality of life [6].

1.2.1 Tonotopic and cortical reorganization model

The reorganization model of tinnitus generation proposes that as peripheral hearing loss deprives central auditory neurons of their normal input, the deprived neurons begin to show responsiveness to the characteristic frequency of neighboring neurons that have retained their original place in the tonotopic map[9]. This process may involve either neuronal rewiring or be the result of unmasking or disinhibition of latent cochlear inputs to those regions newly deprived of direct inputs. The resulting overrepresentation of certain characteristic frequencies, all of which will show spontaneous activity, is proposed as a mechanism of tinnitus generation. Inducing reorganization is therefore a potential mechanism for reducing overrepresentation and interrupting tinnitus. Long-term exposure to a spectrally enhanced acoustic environment was observed to induce tonotopic map reorganization in juvenile cat auditory cortex, without inducing hearing loss [15] and compensatory sound enrichment can interrupt the tonotopic cortical changes normally associated with noise-induced hearing loss [16].

1.2.2 Homeostatic plasticity model

This model suggests that tinnitus is caused by homeostatic mechanisms, which aim to compensate reduced sensory input by reduction of inhibitory and/or increase of facilitatory mechanisms. It predicts that changes in the processing of neuronal activity occur predominantly in the frequency range of reduced sensory input, which finally results in ongoing increased neuronal activity and/or synchrony in the respective central auditory pathways [14][17]. According to this theory the frequency of tinnitus perception should correspond to the frequency of hearing loss.

1.2.3 Studies exploring the relationship between dominant tinnitus pitch and audiometric profile

The different neural mechanisms of tinnitus generation postulate somewhat different relationships between dominant tinnitus pitch and audiometric profile. A number of studies to date have explored this relationship in human participants, but with mixed results.

Most report a specific relationship between tinnitus pitch and the region of hearing loss. However, it has been a matter of debate whether the tinnitus' internal spectrum extends over the region of the auditory loss or it shows preponderance at or near its edges. Pan et al in [18] reported an association between tinnitus pitch and degree of hearing loss and [19] suggested the frequency at the worst hearing level as most relevant for tinnitus generation. In contrast, some authors found an association between tinnitus pitch and edge frequency in a soubgroup of patients which reported tonal tinnitus [20][21]. On the other hand, [22] postulated that the frequency of the audiometric profile equating to a threshold of 50 dB HL was more relevant to tinnitus than the edge or maximum hearing loss frequencies, as it represents the approximate degree of hearing loss required from transition from outer (OHC) to inner (IHC) hair cell loss [23].

Furthermore, methodological differences between studies can make the comparison difficult. Noteworthy differences are the degree of hearing loss of the participant sample, the frequency range of the audiometric and tinnitus spectrum measurements, the method for determining audiometric edge and the method for determining dominant tinnitus pitch:

- *Degree of hearing loss of the participant sample*: while some of the studies included participants with a wide range of audiometric profiles from normal to severe hearing loss [18][24], others limited their sample to participants with mild to moderate hearing loss [25][19] or moderate to severe hearing loss [20].
- *Frequency range of the audiometric and tinnitus spectrum measurements*: since the majority of studies reported tinnitus pitch within the area of hearing loss, it is likely that the dominant tinnitus pitch may exceed the 8 kHz standard clinical range for audiometric assessment for those people with a mild hearing loss or a sloping hearing loss affecting high frequencies. In the case of studies in which the tinnitus spectrum has been measured only up to 8 kHz [26][25][19], it would not be possible to distinguish those patients with an increasing spectrum [26] from those with a tinnitus spectrum peak at 8 or 10 kHz [22]. This can

limit the accuracy of patient subgrouping, as well as the interpretation of the results.

- *Method for determining audiometric edge*: when it comes to determining the edge frequency, methods vary from visual inspection of the audiogram to fully automated computer algorithms [24].
- *Method for determining dominant tinnitus pitch*: there are also marked differences in methods of calculating tinnitus pitch between studies. Some of them rely only on patients self-report and others try to objectivize this measure. We will see them in detail in the following sections.

1.3 Tinnitus treatments

At the moment, there is no curative for tinnitus totally effective. In this work we study tinnitus characterization as part of the rehabilitation therapy using virtual reality introduced in the previous section. However, other treatments based on different concepts have proved high effectiveness. Some of them make use of tinnitus characterization as well. Here, we summarize the one that concerns us involving virtual reality and the mainly used in the last years.

1.3.1 Virtual reality treatment

Techniques of immersion in virtual reality environments have demonstrated their usefulness in different domaines of health research. They have been applied to several anxious disorders [27] and used to reduce phantom limb pain when an amputee patient sees a virtual limb placed at the position of its phantom limb and manages to transfer his sensations to this virtual limb [28].

The tinnitus therapy involves a setup with dedicated auditory and visual 3D virtual reality environments in which unilateral subjective tinnitus sufferers are given the possibility to voluntarily manipulate an auditory and visual image of their tinnitus (tinnitus avatar). By doing so, the patients are able to transfer their subjective auditory perception to the tinnitus avatar and to gain agency on this multimodal virtual percept they hear, see and spatially control.

The overall procedure comprises two phases:

1. The creation of an auditory avatar following the frequency patterns of the patient's tinnitus by means of a tinnitus characterization method.
2. Its inclusion in an interactive auditory-visual virtual environment where the different audio components are spatialized according to the navigation and manipulation of the patient. The spatialization process is based on binaural technology using a database of either generic or individual HTRFs and the

task of the subject is to navigate in the virtual environments and to steer the visual and auditory avatar to place it in different positions.

Repeated sessions of such virtual reality immersions contribute to tinnitus treatment by promoting cerebral plasticity and helping to dissociate the tinnitus perception and its emotional consequences. A comparison study between this therapy and the Cognitive Behavioural Therapy (CBT) was performed in [29] and virtual reality therapy resulted to be at least as effective as CBT in unilateral subjective tinnitus patients.

1.3.2 Cognitive Behavioural Therapy (CBT)

Cognitive Behavioural Therapy has been widely and successfully included in the multidisciplinary therapeutic management of tinnitus patients. It is a form of psychological treatment addressing the affected individual's reaction to tinnitus. It aims not to eliminate auditory perception as sound but to reduce or correct one's negative response to tinnitus. CBT identifies negative automatic thoughts and then evaluates their validity with the patient. It also aims to change negative the automatic thoughts to a more positive and realistic thoughts [30].

Many studies have supported the efficacy of CBT for treating tinnitus, [31] reported that 75% of 96 patients improved significantly after one year of therapy. In spite of that it has little effect on tinnitus loudness, it has been proven to be effective for alleviating the annoyance caused by tinnitus and has some positive effects on other emotional symptoms. In this way, tinnitus sufferers can function well despite the presence of tinnitus [30].

1.3.3 Auditory stimulation treatments

Sound-based therapies imply the use of external noise or music in order to alter a patient's perception of, or reaction to, tinnitus. They function on four general mechanisms of action (putative processes or reasons why a given intervention is effective). Different products may emphasize a specific aspect or include a combination of approaches:

- Distraction: using external sound to divert a patient's attention from the sound of tinnitus
- Habituation: helping the patient's brain classify tinnitus as an meaningless sound that should can be consciously ignored, producing a decline in the reactions to and the perception of tinnitus over time.
- Masking: exposing the patient to an external noise at a loud enough volume that it partially or completely covers the sound of their tinnitus
- Neuromodulation: the use of specialized sound to minimize the neural hyperactivity thought to be the underlying cause of tinnitus

In this subsection we present some of the main auditory stimulation treatments used in the last years:

Tinnitus Retraining Therapy (TRT)

TRT is the most established and protocol-driven tinnitus management strategy to promote habituation. It aims to facilitate habituation of reaction to tinnitus through counseling to make the problem more manageable and habituation of perception through use of sound. Patients are advised to continuously enrich their sound environment with low-level, relatively pleasant sounds or white noise, thus creating a constant "passive listening" environment that promotes habituation by neural plasticity. This external sound is presented at a low level to avoid altering the tinnitus percept so that habituation can take place [32].

Tailor-Made Notched Music Treatment (TMNMT)

This recent traitement consists on listening to music with a notch filter centered at the tinnitus frequency. This results on a reduction on the neural activity evoked by the tinnitus frequency and in a reduction of the tinnitus loudness [33][34]. The neural mechanism underlying this reduction in auditory processing is lateral inhibition within the neural networks, which is a type of connectivity that serves as a basic mechanism in several sensory systems and is important for local processing of sensory information. Furthermore, the effect of lateral inhibition in this treatment is intensified by the fact that listening to pleasant music chosen by the patient can initiate the release of dopamine, which promotes cortical plasticity [35].

Recent studies investigated which additional filter parameters could alter the music spectrum such that the reduction in the auditory processing was maximized. Stein et al in [36] found that strongest reduction was achieved with the amplification of the signal components of the filter's border frequencies and Okamoto et al in [37] determined that a notch bandwidth of 1/4 octave leads to the greatest lateral inhibitory effect.

TMNMT has been proven to be an affective treatment. In [33] patients showed significantly reduced subjective tinnitus loudness and at the same time reduced evoked activity in auditory cortex areas corresponding to the tinnitus frequency after 12 months. However, Lugli in [38] found out that it had no measurable effect on patients with high frequency tinnitus (above 8 kHz), which presents a limitation to the therapy. This fact could be due to the lower spectral energy presented at high frequencies in most of the music recordings, which might be not enough for the lateral inhibition to take effect.

Hearing aids

They are small electronic devices worn in or behind the ear. Using a microphone, an amplifier and speaker hearing aids supplement the volume of outside noise and increase the amount of sound stimuli received and processed by the body's auditory system.

Hearing aids can be classified as a type of sound therapy for patient's with hearing loss and tinnitus because they can be effective due to the reduction of the contrast between tinnitus perception and the external sounds, thereby reducing the relative salience of tinnitus [39]. Alternatively, the amplification of external sounds help to focus attention on sounds that are different from the tinnitus sound, diverting patient's attention from the sound of tinnitus. By other hand, it is known that loud tinnitus can make it difficult for patients to participate in regular communicative and social activities. Hearing aids improve this communication, so the patients may feel less personal frustration and social isolation, indirectly leading to improved tinnitus self-report. Lastly, acting as a form of sound enrichment they may be decreasing the possibility of sensory deprivation and thus decreasing neuroplastic changes within the central auditory system that contribute to tinnitus generation [40].

Sound maskers

These are devices or applications that expose the patient to an external sound at a loud enough volume that they partially or completely cover the sound of their tinnitus. The sounds used vary from white or pink noise to nature or other ambient sounds. This masking is sometimes thought of as a relief therapy [41], providing a sense of relief from stress or anxiety caused by tinnitus. Hazel et al. found in [42] that a reduction in the effects of tinnitus on sleep and overall quality of life was greater for those who used sound masking devices. It was concluded that masking therapy was a useful approach, but it was acknowledged that counseling was important to overall therapy success.

One potential outcome of high-intensity masking is residual inhibition (RI), a partial or total suppression of tinnitus typically lasting seconds to minutes following the presentation of relatively intense sound [43]. RI has been used clinically as an aid for counseling and to demonstrate that broadband noise can impart a beneficial effect. Although sound masking devices are typically only effective during or immediately after active use due to the RI, at least one company (*Tipa Tinnitus Corporation*) is marketing a device that is claimed to produce prolonged RI.

Furthermore, some sound maskers like certain hearing aids, are able to create more complex stimuli like wide band sounds that can be adjusted by the audiologist to meet the final user's needs by means of high-pass or low-pass filters.

1.4 Tinnitus characterization

Tinnitus is characterized by means of questionnaires [44] and psychoacoustic measures. Questionnaires provide useful information about tinnitus' effect on quality of life and improvements with treatment, whereas psychoacoustic evaluations attempt to replicate what the individual experiences by matching to sound. These evaluations are essential because they can assist in diagnosis (including differentiation of real versus malingering tinnitus), contribute to development and evaluation of treatments, and assist in determining its mechanisms [45]. Moreover, psychoacoustic characterizations of tinnitus can also be part of the treatment: in the virtual reality therapy it is necessary for the creation of an avatar representing the individual subjective tinnitus.

It is a fundamental issue that this avatar preserves the psychoacoustic properties of the individual real tinnitus in an accurate way. However, at this moment it does not exist any purely objective method able to obtain totally reliable measures and recordings of the tinnitus presence and characteristics due to the subjective nature of the tinnitus sensation. Important efforts have been made in the latest years trying to find alternative methods in order to objectify the presence and characterization measures of tinnitus.

1.4.1 Classic characterization methods

Dominant tinnitus pitch and its relationship to the shape of the audiogram are the most relevant psychoacoustic measures of tinnitus. Here we present the main characterization methods in the literature aiming to measure the tinnitus spectrum:

Forced choice method

This is one of the first methods aiming to estimate the tinnitus frequency, where two sounds of different frequency are presented to the patient, who has to chose the one that is more similar to the main pitch of its tinnitus. The chosen sound is presented then with another sound with different frequency and the procedure is repeated until a stop criterion is reached [46][47].

Method of adjustment

This is the simplest method. Its procedure only consists on varying the frequency of a continuous pure tone to match it with the dominant tinnitus pitch [48]. Variants of this method can be found in the literature. Basile et al in [49] divided the pitch matching procedure into three rounds, reducing the frequency range where the patient could match its tinnitus after each round. This aimed to improve the matching precision and reduce octave errors.

Contribution rating method

After, Norena et al proposed in [50] a new method aiming to better portray the complex tinnitus sensation. It estimated the different frequency components contributing to the global tinnitus sensation: first, hearing thresholds were measured at all 500-Hz steps between 500 and 8000 Hz and up to 14 kHz in 1000-Hz steps. Then, a pure tone with a frequency pseudo-randomly selected from the same test frequencies used in the previous step was presented. The subject had to match the intensity of the tone to the loudness of its tinnitus and then indicate whether the pitch evoked by the tone corresponded to one of the components of its tinnitus spectrum. If this was the case, the subject had to rate from 0 to 10 its contribution to the overall tinnitus spectrum. This process was repeated until all test frequencies were tested. The comparison tone was always presented in the tinnitus ear (ipsilateral) in unilateral tinnitus cases and in the ear in which the tinnitus sensation was reported to be louder in the bilateral cases. A combination of these tones weighted by their respective ratings formed the internal spectrum of the perceived tinnitus.

Likeness rating method

Roberts et al presented in [43] a computerized procedure called Tinnitus Tester similar to the one presented by Norena et al. It assessed the quality of the tinnitus sensation (tinnitus ear, loudness, bandwidth, temporal properties and its frequency spectrum). It characterized the tinnitus spectrum using eleven sound clips with a central frequency ranging from 0.5 kHz to 12 kHz. For each subject, the bandwidth of these eleven sound clips was chosen according to a self-described tinnitus timbre as being “tonal”, “ringing” or “hissing” (pure tone, 5% of the centre frequency (CF) at -10 dB and 15% of the CF at -10 dB, respectively). Then, subjects adjusted the loudness of each sound to match the loudness of their tinnitus. Finally, subjects rated the pitch of each of the sounds presented in the previous step for likeness to the pitch of their tinnitus using a Borg CR100 scale [51](0 = not similar, 100 = identical). A profile of the tinnitus spectrum was thus generated.

This method and the previous one were compared in [52] and this one resulted preferred by the participants because it did not challenge them with uncomfortable sound choices. Its software was later used by other authors like Sereda et al in [24].

Regarding the *forced choice method* and the *method of adjustment*, some authors have studied their test-retest fidelity and it has been concluded to be low, presenting high variability over time [53]. Likeness rating technique has obtained better results in that point. However, it remains unclear whether this technique, which involves a discrete mode of frequencies presentation, can provide an accurate estimate of the predominant pitch compared to when only one pitch is matched, such as in the continuous-pitch matching in the *method of adjustment*.

1.4.2 Characterization methods proposed for the virtual reality therapy

This section comprises the three different procedures presented by Bertet et al in [54] to create the individuals' tinnitus avatars of the patients in order to use them in the virtual reality therapy (cf.1.3.1)[13][29]. They were derived from the classic tinnitus characterization methods presented above and they were based on the following concepts:

Auditory threshold

This was a semi-automatic tinnitus synthesis method derived from the measurement of the subject's auditory threshold curve based on Norena's conclusion that the tinnitus' internal spectrum mirrors the frequency profile of the auditory loss of the ipsilateral ear. Therefore, audiograms were measured first for both ears using an ascendant method measuring frequencies from 125 Hz to 8 kHz separated in 1/3 octave bands and from 8 kHz to 16 kHz in 1/6 octave bands. These audiograms were stored in order to use them for the different synthesis methods in the study. Then, the frequency content of the tinnitus was automatically built using sinusoids and noise filter envelopes following the auditory threshold curve of the ipsilateral ear (the ear where the tinnitus was located). The sinusoids were centred at frequencies used previously in the audiometries and at new frequencies between 125 Hz and 8 kHz interpolated from the audiogram in order to synthesize the whole frequency range in 1/6 octave bands. The only task of the patient was to determine the relative gain of the sinusoid aggregate stimulus and of the noise stimulus. A global gain slider allowed the matching of the overall signal level to the tinnitus loudness.

Auditory threshold interaural difference

This method was also derived from the measurement of the subject's auditory threshold. However, here it was hypothesized that the analysis of the auditory threshold asymmetry between the two ears may be used as an indicator of the tinnitus' internal spectrum. Therefore, the avatar spectrum was built accordingly: the relative weight of the sinusoids and the noise filter envelope were built upon the auditory thresholds difference between the ipsilateral and the contralateral ears.

Pitch and bandwidth tuning

This was a manual method where the patients were asked to span the frequency range to find the matching frequency. The synthetic tinnitus was composed of two stimuli: a pure tone and a 1/6 octave band noise centred on a single and adjustable frequency. Patients had to adjust the central frequency common to both components, their relative gains and a global level. A comparative made in the same study between this and the two methods previously introduced revealed that most patients chose the tinnitus replica built with this method as their preferred one.

In an attempt to objectivize the previous subjective characterization methods and evaluate their reliability and stability over time, a lateralisation test was performed for the avatars created with this method and it was based on the source lateralisation phenomenon: in normal headphone listening conditions, diotic signals give rise to a unique auditory event located in the centre of the head, so increasing the avatar gain "pushes" the sound image towards the corresponding ear, indicating highly similar spectrum between the real subjective tinnitus and the avatar. If dichotic signals, differing in pitch, are presented, then the fusion does not occur any more and two separate auditory events are heard respectively in the right and left ear.

Chapter 2

Experimental procedure

This chapter presents the new characterization methods implemented on Max/MSP for the test sessions and the experimental procedure aiming to evaluate these methods.

2.1 New characterization methods implemented

These methods are based on the methods from [54] and they pretend to improve the adjustment quality of the the synthesized tinnitus avatar and its similarity to the patient's tinnitus by different means presented below.

2.1.1 Auditory threshold gradient

This is a semi-automatic method similar to the *auditory threshold* or *auditory threshold interaural difference* methods devised on [54]. However, in this case the method is based on the hypothesis that tinnitus spectrum is highly predominant close to the edge of the auditory impairment curve, which was reported by Moore at al in [25] for a small cohort of participants selected with high-frequency sloping audiogram and tonal tinnitus, by Sereda et al in [24] for a subset with narrow tinnitus bandwidth or by König et al in [20] for a small cohort with bilateral tonal tinnitus and moderate to severe noise-induced hearing loss. Heijneman et al in [26] also identified a subgroup of tinnitus participants with tinnitus spectra with a peak on frequencies close to the edge of the hearing loss (5 kHz group median). However, the rest of subgroups of tinnitus patients in that study were not consistent with the edge theory. Therefore, even though in the literature this correlation between dominant tinnitus pitch and edge of the audiogram has only been found on certain subgroups of tinnitus patients, we wanted to study if there would be a predilection for this method specially on patients whose profile was similar to the subgroups in the literature.

In this method, frequency content of the tinnitus is automatically built from the gradient of the auditory threshold curve of the ipsilateral ear (tinnitus ear). Two versions were implemented, one taking into account both positive and negative gradient and other based only on the negative gradient, which was used in the test sessions because it suited better to the hypothesis of the literature supporting that tinnitus spectrum expands at the edge of the audiometric curve for the most common audiometric profile. Small variations of the audiometric curve (less than 5 dB difference between contiguous audiogram frequencies) were discarded for the sound synthesis in an attempt to clean the sound from frequencies not corresponding to the audiometric edge. Like in [54], the method used a combination of two complex stimuli respectively composed of a sinusoidal component and a filtered noise component. This combination was meant to allow the patient to tune between different tinnitus sensations, often reported in the literature as sounding tonal, ringing, hissing, etc [12]. The patient only had to adjust the relative gain of the sinusoids and noise stimulus and the global gain of the overall signal level.

2.1.2 Harmonic auditory threshold

This method is based on the *auditory threshold* method from [54]. Its spectral profile follows the auditory threshold curve of the ipsilateral ear as well, but it differs on the synthesis frequencies. The one in the literature has fixed synthesis frequencies from 125 Hz to 16 kHz in 1/6 octaves summing a total of 43 frequencies. However, in this harmonic method, even though the synthesis frequencies expand from 125 Hz to 16 kHz, the number of them and the distribution across the frequency range is determined by the fundamental frequency of the sound, which is computed according to the patient's audiogram, and the inharmonicity coefficient of the sound, a parameter that can be modified in real time by the patient:

- Fundamental frequency f_0:
  It is derived from an auditory loss threshold parameter as follows: once chosen the auditory loss threshold (5 dB HL fot the test sessions), the fundamental frequency is computed as the lowest frequency from the audiogram in which the patient has an auditory loss above that threshold. This procedure consisting on determining the fundamental frequency of the sound from an auditory threshold was inspired by the fact that Shekhawat et al in [22] suggested the frequency where 50 dB HL of hearing loss was reached (called T50) as the strongest predictor for the dominant tinnitus pitch in the majority of patients. Therefore, setting the threshold parameter to 50 dB HL would allow us to create an harmonic sound whose fundamental frequency f_0 and dominant pitch perception matched at T50. Nevertheless, we finally decided to chose a value of 5 dB HL for the tests sessions. We will discuss the reasons in the next sections.

  In case that the patient's audiogram does not reach the sufficient auditory loss set for the threshold parameter at any frequency, the frequency of maximum hearing loss of the audiogram is considered as the fundamental frequency for the synthesized sound. Therefore, setting a very high value for the threshold parameter assuring that it is above the patient's maximum hearing loss in practice it automatically considers the frequency of maximum hearing loss as the fundamental frequency f_0 for the synthesized sound. Schecklmann et al in [19] suggested this frequency as the most relevant for tinnitus dominant pitch.

- Inharmonicity coefficient β:
  It has been limited from 0 to 0,5. Once f_0 is computed, β determines the frequency of the harmonics according to the equation:

$$f_h = hf_0\sqrt{1 + (h^2 - 1)\beta} \tag{2.1}$$

  Where f_h is the frequency of the harmonic $h - 1$, $h \in \{2,3...\mathbb{N}\}$ and $\mathbb{N}$ is the total number of sinusoids synthesized, which varies for each combination of f_0 and β. Therefore, $\beta = 0$ produces perfectly harmonic sounds whose dominant pitch perception corresponds to the fundamental frequency. As long as the inharmonic coefficient β is increased, the fundamental frequency perception vanishes and the dominant pitch of the sound corresponds to the loudest harmonic (the individual gain of each harmonic is interpolated from the patient's auditory curve). The number of harmonics varies depending on f_0 and the harmonics above 16 kHz are not synthesised.

Figure 2.1 shows the GUI of this method, where the experimenter configures the initial parameters presented above.

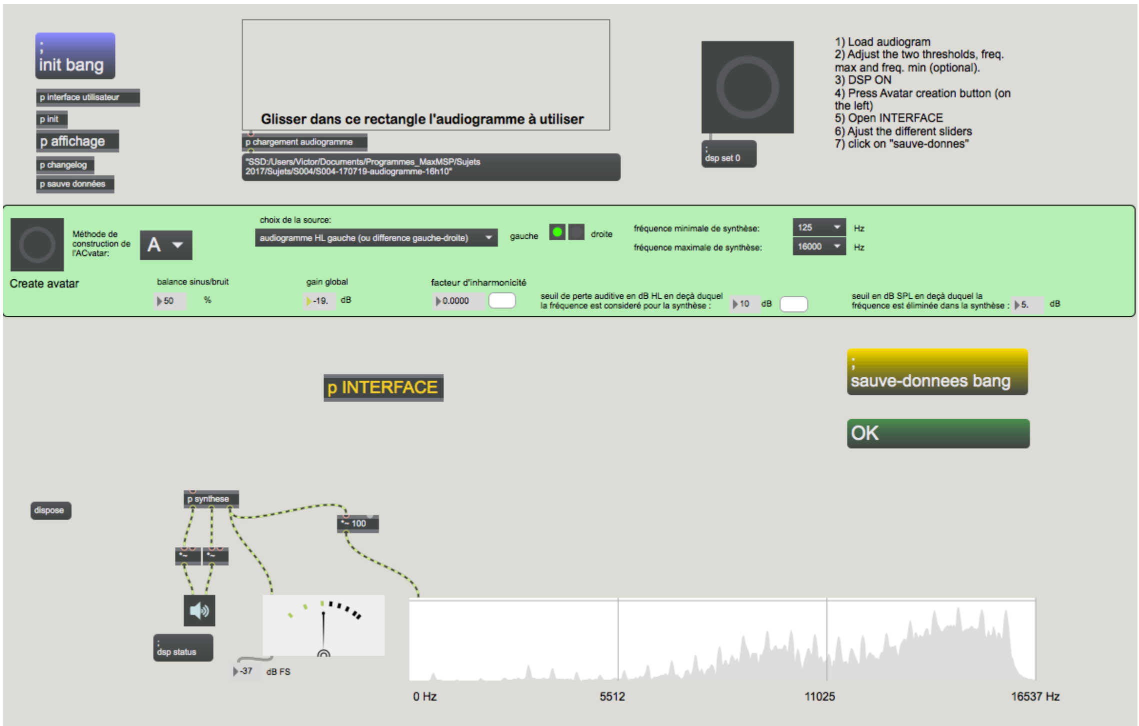


Figure 2.1: GUI of the harmonic auditory threshold method controlled by the experimenter.

2.1.3 Harmonic auditory threshold interaural difference

This method preserves the characteristics of the *auditory threshold interaural difference* method (1.4.2) except for the synthesis frequencies, which are based on the harmonic criteria used in the *harmonic auditory threshold* method (see 2.1.2). Therefore, a new inharmonicity control parameter has been added among the real-time control parameters.

2.1.4 Harmonic auditory threshold gradient

This method is a variant of the *auditory threshold gradient* method (2.1.1). Here, the synthesis frequencies are controlled in real-time by an inharmonicity control parameter as in the two previous methods.

2.2 Detailed experimental procedure

This section details the whole procedure followed in the test sessions that were performed in July of 2017 at IRCAM's installations. Each one lasted between 45 and 90 minutes depending on the patient.

2.2.1 Participants

Eight individuals attended the test sessions. Two participants were not taken into consideration for the results analysis because they could not complete the whole procedure due to lack of time. The six participants that completed the session were two females and four males between 34 and 51 years old. Among them, two suffered unilateral tinnitus, three had several tinnituses that differed in pitch (only the loudest one was tested) and one participant had a bilateral tinnitus.

2.2.2 Apparatus

The whole experimental sessions were performed on a Mac Book Pro equipped with an external RME Fireface 400 sound card set at 44.1 kHz sampling rate and with Beyerdynamic DT 770 Pro closed headphones (figure 2.2). All the characterization methods devising to create an acoustic replica of the patient's tinnitus were implemented using Max/MSP software. The total electro-acoustic chain comprising the computer, the sound card and the headphones model was compensated in order to derive the dB FS to dB SPL conversion curve.

For each synthesis method, a simple graphical user interface (GUI) was implemented to help the patient to tune the different method parameters. The GUI consisted of different virtual sliders represented on the screen, which the patient controlled with the mouse.

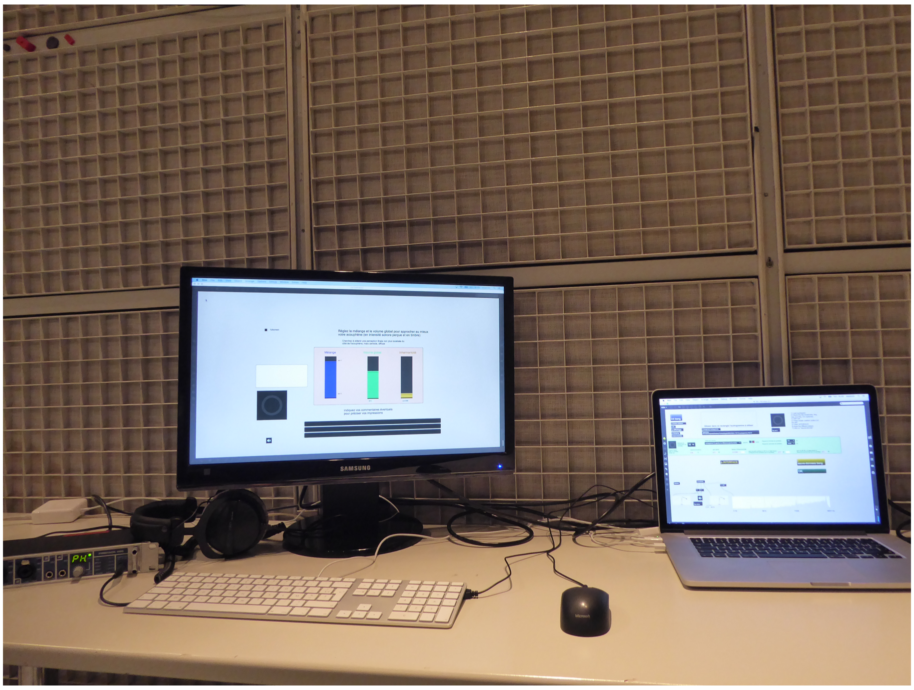


Figure 2.2: Test session instrumentation.

2.2.3 Procedure

Due to the time constraints of the sessions, only four methods among the total set of new methods and the methods from [54] were selected for the test session. The selection was made with the intention of, in one hand, proving if the new characterisation methods and modifications implemented would be satisfying for the patients and if they could improve the similarity of the replica to the patient's tinnitus in relation to the methods used in [54]. On the other hand, we expected to confirm the prevalence of one of the methods as the preferred one for the patients.

In order to avoid sound distortion and hearing injury, the sound level was constrained to stay below an upper limit of 0 dB FS (107 dB SPL at 1 kHz) during the whole test session. Otherwise, the sound was simply muted until the gain parameter was restored to a normal level. The total procedure comprised the following steps:

1. **Test introduction**

   The sessions started with an introductory talk given by the experimenter about the goal and the global context of the test session.

2. **Test information and patient consent**

   After that, an information form explaining the test procedure was read by the patient. Then, a consent form was signed by the patient. For the French speakers all the documents were given in French.

3. **Audiogram measurement**

   Then, the participant was invited to measure his or her auditory threshold with a program implemented on Max/MSP that estimated the hearing curve of the patient from 125 Hz to 16 kHz using an ascendant method. Sequences of one-second fixed-frequency pure tone separated by one second of silence were presented to the patient with a step increase of 3 dB until he or she indicated hearing the sound by pressing the space bar of the keyboard. The stimulated ear and the frequency were randomly chosen. Once the sound was detected, another tone was presented to the patient until all the measurements were done. From 125 Hz to 8 kHz, frequencies were roughly distributed in 1/3 octave band and from 8 kHz to 16 kHz, frequencies were distributed in 1/6 octave band.

4. **Frequency matching task**

   In this phase patients had to match two sinusoidal tones in pitch and loudness. A reference tone of fixed frequency was played in the ipsilateral ear and a variable frequency tone was played in the contralateral ear. The task of the patients was to match the pitch and loudness of the variable tone to that of the reference tone by moving sliders integrated in a graphical user interface situated in front of them. The training was repeated for five tones with increasing frequency from 500Hz to 8000 Hz. The goal of this phase was to train the patient in the frequency matching task needed after for the *pitch and bandwidth tuning* and *harmonic auditory threshold* methods and to familiarize him or her with the octave error concept in order to reduce it then as much as possible.

5. **Avatar synthesis**

   Immediately after, the patient proceeded with the creation of his/her tinnitus avatars using the following selected tinnitus synthesis methods:

   (a) *auditory threshold* method [section 1.4.2].

   (b) *auditory threshold gradient* method [2.1.1].

   (c) *harmonic auditory threshold* method [2.1.2].

   (d) *pitch and bandwidth tuning* method [section 1.4.2].

   This selection combined two methods from [54] and two of the new implemented methods. This aimed to prove if the new characterisation methods and modifications implemented would be satisfying for the patients and if they could improve the similarity of the replica to the patient's tinnitus in relation to the methods used in [54]. All of them used the contralateral ear to drive the tinnitus matching in the case of unilateral tinnitus or the ear where tinnitus loudness was lower in the case of bilateral tinnitus. For all patients, the order of the methods was kept the same.

Before starting a given method, the patient received explanations about the GUI (figure 2.3) and the significance of each tuning parameter (virtual sliders controlled with the mouse). Then, they were asked to adjust them in order to obtain a sound as similar as possible to their tinnitus perception in loudness and timbre. In order to achieve it, they tried to obtain a central and diffused global tinnitus perception.

Default initial parameters were used for the test sessions. In the case of the *harmonic auditory threshold* method, the threshold parameter that computes the fundamental frequency f_0 of the sound was set to 5 dB HL for the test sessions. The initial idea was to set this value to 50 dB HL according to Shekhawat et al in [22], who considered the frequency where 50 dB HL of hearing loss was reached as the strongest predictor for the dominant tinnitus pitch in the majority of patients. Therefore, setting this value for the threshold parameter would allow us to create an harmonic sound whose fundamental frequency f_0 would usually correspond to the patient's dominant tinnitus pitch. In case it would not corresponded, patient should be able to modify the dominant pitch of the sound by increasing the inharmonicity coefficient: in practice, this would lead to start perceiving the loudest harmonic frequency as the dominant pitch of the sound instead of the fundamental frequency f_0.

However, this ideal case was not very likely to occur in practice. Previously to the test sessions we found out after several observations that for most of the patients this threshold value would result in a fundamental frequency above 8 kHz due to they usually present high hearing loss such as 50 dB HL only in the high frequencies range. Therefore, according to the equation 2.1, no harmonic would be synthesized as they would be above 16 kHz (the maximum synthesis frequency). Moreover, in patients with mild hearing loss lower than 50 dB HL it would not even be possible to compute a fundamental frequency f_0 with this threshold value. Due to those facts would be incoherent with the definition and purpose of the *harmonic auditory threshold* method itself, we finally decided to set a value to the threshold parameter which assured that at least one harmonic would be synthesized (i.e. 5 dB HL), implying a lower fundamental frequency f_0 of the sound.

Once the tinnitus matching was accomplished and the patient was satisfied with it, an excerpt of 10 seconds was saved in an audio sound file in order to allow for its subjective evaluation after the avatars creation phase. Sound files were encoded with 24 bits dynamic range and 44.1 kHz sampling rate. In order to better exploit the dynamic of the sound files, signals were amplified before being recorded so as to approach an RMS level of -10 dB FS. The corresponding gain was saved and compensated for when playing back the sound file, in order to restore the tinnitus avatar to its original level.

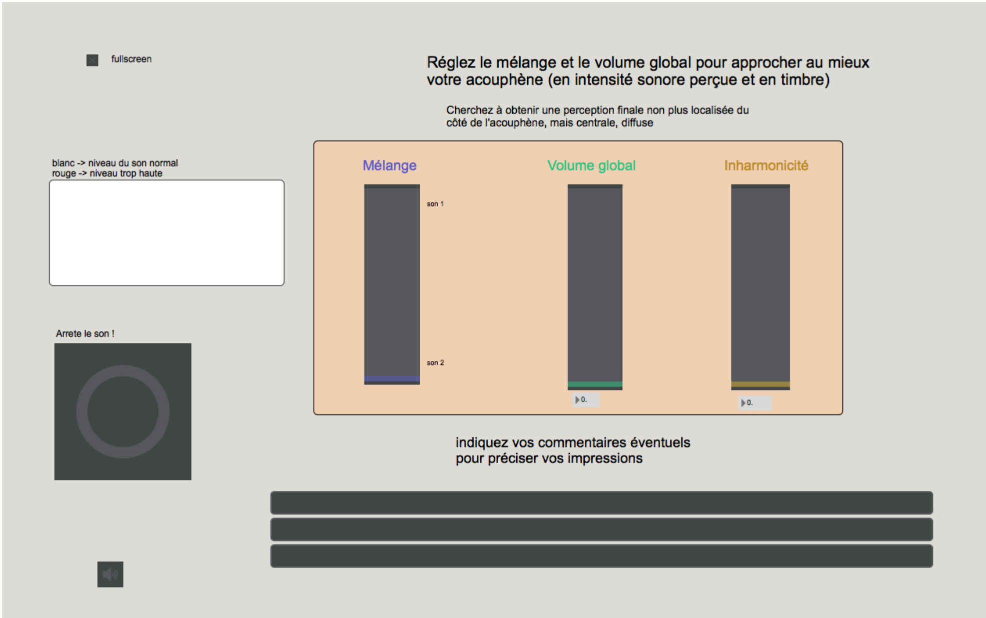


Figure 2.3: GUI of the harmonic auditory threshold method controlled by the patient.

After each avatar creation, the patient was invited to have a short debriefing with the experimenter, to give oral feedback or any free comments about the task itself or about the global or detailed resemblance between his/her tinnitus and the recently created avatar.

6. **Avatar evaluation and comparison questionnaire**

Once the four avatars were created, patients were asked to toggle between the sound files generated. Each avatar was played at the volume level saved at the previous phase. Participants had to rate on a visual analogue scale (VAS) three characteristics (loudness, spectral and global similarity to their tinnitus) of the avatars synthesized with each of the four methods. A total of twelve VAS (three characteristics for each of the four avatars) were assessed by each patient. One end of the scales meant no similarity of that avatar's characteristic to the patient's tinnitus and the other end meant that the tinnitus and the avatar were identical in that aspect (B.1). For the French speakers the questionnaire was given in French.

Finally, the patients were asked to classify the four avatars as a function of the global similarity to their tinnitus. For this, they were allowed to listen to their avatars again.

7. **Lateralisation test**

   This test was based on the source lateralisation concept introduced in 1.4.2. Only the avatar classified as the most similar to his or her tinnitus in the questionnaire was used. It consisted on increasing and decreasing the gain of the tinnitus avatar presented in the contralateral ear in order to localize the global tinnitus perception at five different lateral directions: totally at the left, at a middle between the left and the center, at the center, at a middle point between the center and the right and totally at the right.

   The purpose of this test was:

   (a) To verify if the fusion process between the avatar and the patient's tinnitus occurs in order to measure in an objective manner their similarity based on the fact that in normal headphone listening conditions only diotic signals make possible this process.

   (b) If the fusion is achieved, measure the loudness of the tinnitus perception in an objective manner by checking the avatar gain needed to place the sound image towards the centre and compare the results with the patient's self-report.

8. **Spatialisation test**

   This test was inspired by the method used by Searchfield et al in [55] for matching perceived location of tinnitus in three-dimensional auditory space. However, we decided to simplify the Searchfield's method to two dimensions and fix the head-avatar distance in order to facilitate the task to the patient and simplify the comparison of the results with the ones from the lateralisation test and the patient's self report. The same avatar from the lateralization test was used and the spatialisation of the avatar was made with the help of Ircam Spat software. The GUI controlled by the participant represented a plane with the participant's head and his or her tinnitus avatar, which the patient was able to move around the represented head for a fixed distance. Participants were asked to overlay the avatar onto their predominant tinnitus position. In order to avoid the fusion process experienced in the lateralisation test, the patient was encouraged to regularly switch off and on the avatar and check that its perceived tinnitus location had not changed.

   The goal of the test was:

   (a) To obtain a precise location of the patient's tinnitus perception.

   (b) Verify that the participant's psychoacoustic location agreed with the patient's self report and study the relationship between them.

(c) Check if the patient was able to match the location of the tinnitus and obtain a feedback of the task difficulty.

(d) Verify that the result was coherent with the lateralisation test.

Chapter 3

Results

Results from the test sessions are shown in the following sections. Individual audiometries and avatars spectra are displayed. Secondly, lateralisation and spatialisation tests results are displayed together in order to better analyse its relationship. Finally, the scores of the different avatar ratings are presented individually for each participant and in box plots for the whole cohort.

3.1 Audiometries and avatars creation

The six patients measured its auditory threshold for both ears before the tinnitus characterization phase. Then, four tinnitus avatars were created by each participant with the four characterization methods.

This section comprises the spectral profiles of the avatars synthesized by two patients together with the respective auditory threshold frequency curves of both ears and the normal hearing threshold (figures 3.1 and 3.2). The spectral content of the two avatars in the upper side of the figures was created with *auditory threshold* and *auditory threshold gradient* methods and was automatically derived from the auditory threshold curve of the patient's ipsilateral ear. The other two avatars were built with manual methods where the patient could adjust directly (*pitch and bandwidth tuning* method) or indirectly (*harmonic auditory threshold* method) the frequency of the avatar dominant pitch, which for some patients reached very high frequency values.

3.2 Lateralisation and spatialisation tests

Figure 3.3 displays the results of the lateralisation test in which the six patients were invited to tune the gain of the tinnitus avatar to control the apparent spatial location of their tinnitus. They were asked to place the global tinnitus perception at five different lateral directions (-90º, -45º, 0º, 45º and 90º). The gain was expressed relative to the level tuned to match the perceived loudness of their tinnitus.

The slope of the lateralisation displacement as a function of the tinnitus avatar

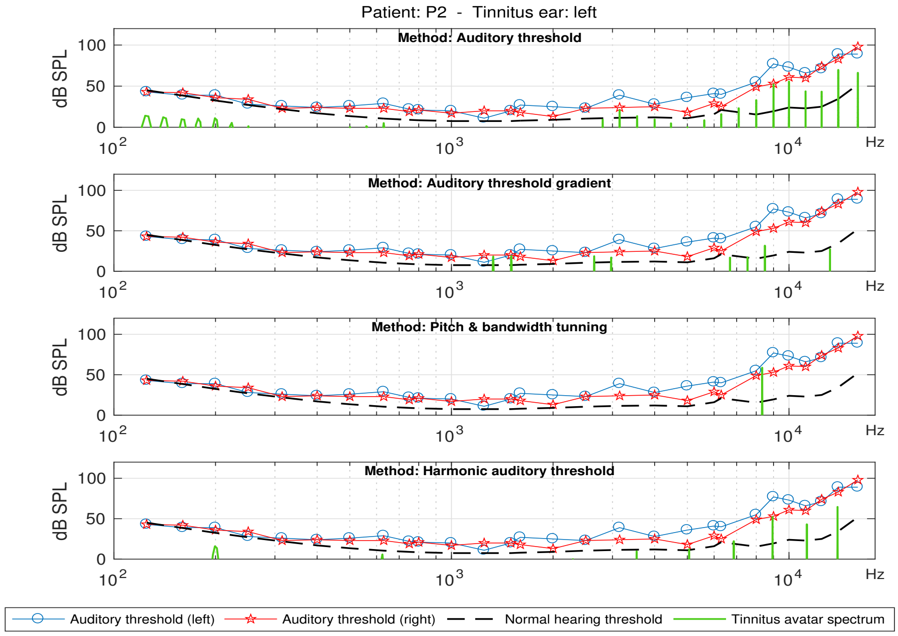


Figure 3.1: Participant 2: avatars spectra.

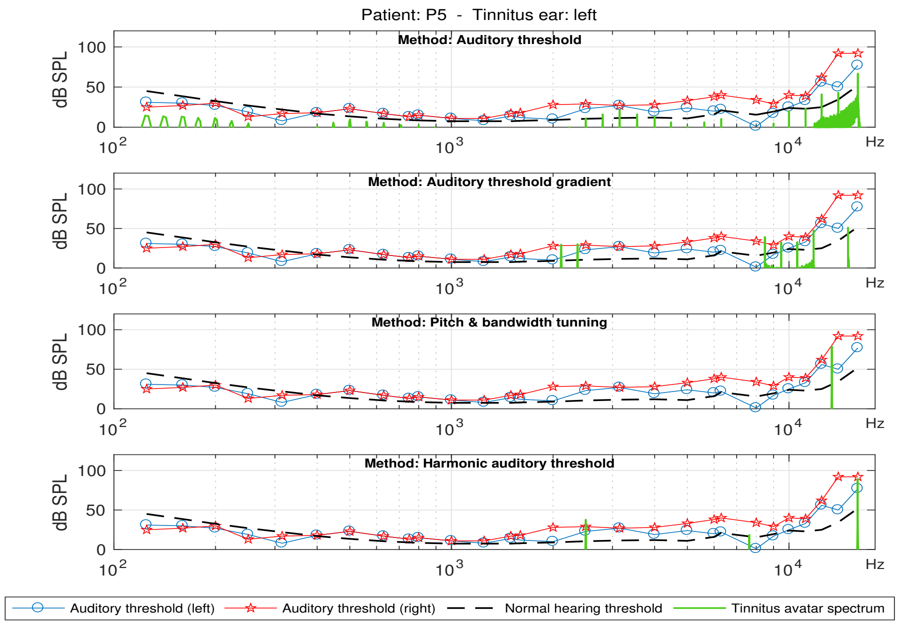


Figure 3.2: Participant 5: avatars spectra.

level was shown to be close to linear for all the patients except one. A mean range of 36 dB was required to obtain a full lateral shift from the ipsilateral to the contralateral side. However, this varied significantly among patients. This would probably be due to the high variability of the tinnitus position among participants measured in the spatialisation test (tinnitus azimut in figure 3.4).

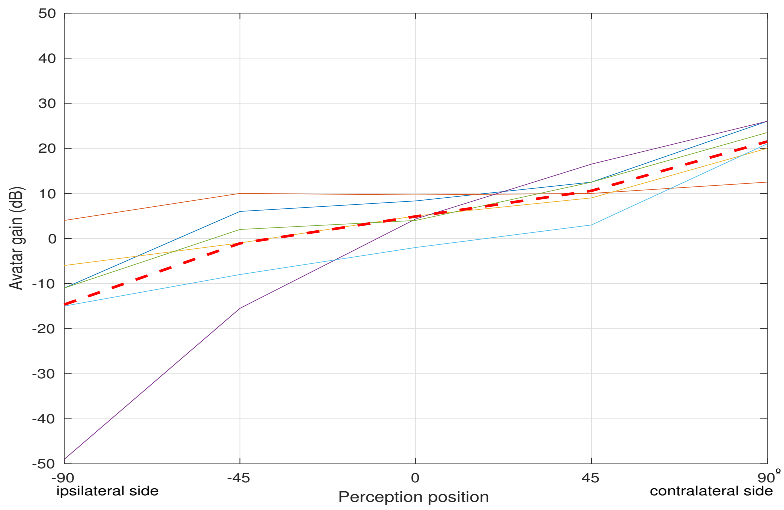


Figure 3.3: Lateralisation test results. Participant's avatar gain needed to place the global tinnitus perception from the ipsilateral to the contralateral side. The dashed line corresponds to the mean among participants.

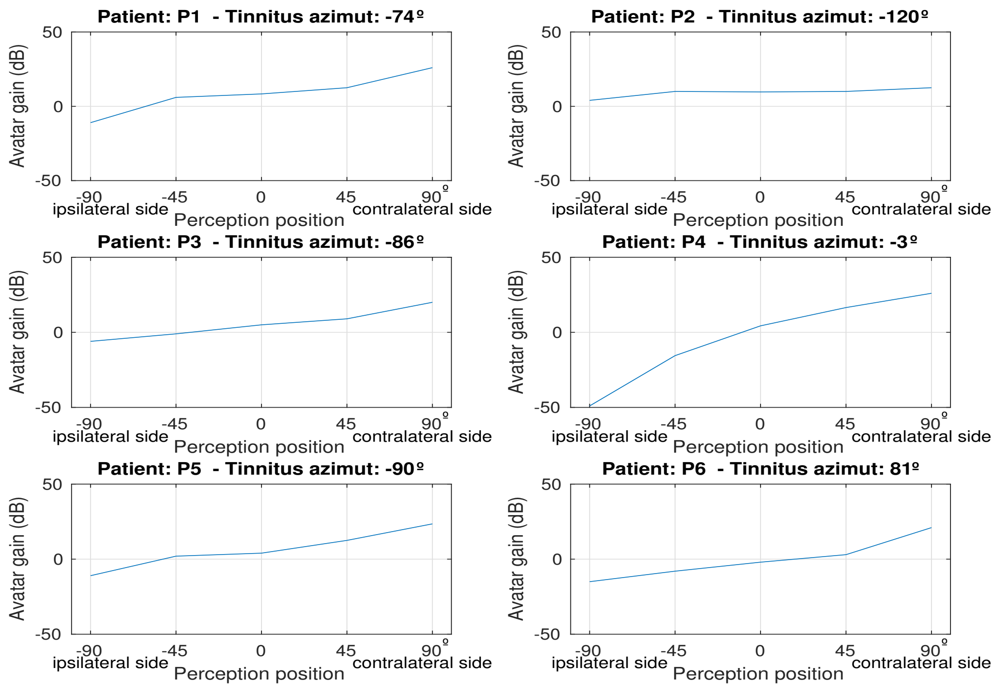


Figure 3.4: Individual lateralisation results along with spatialisation test results. Spatialisation test results are displayed as the tinnitus azimut coordinates and the graphs below corresponds to the individuals' lateralisation test results.

3.3 Avatar VAS questionnaire

After the avatar creation phase, participants were invited to assess the similarity of their avatars to their tinnitus on a VAS from 0 (no similarity) to 100 (identical) in terms of frequency, loudness and globally. Figure 3.5 shows the individual scores obtained in the avatar VAS questionnaire (B.1).

The method *pitch and bandwidth tuning* (method 4) clearly received the best scores in the three avatars' qualities assessed. The two patients with the highest hearing loss at high frequencies were not able to perceive the avatar created with the method *auditory threshold* (method 1) sufficiently loud to be able to assess it even though they increased the avatar gain until the maximum level permitted by the program (0 dB FS). These patients would have needed an avatar gain above 0 dB FS in order to perceive the avatar, which was mainly built with high frequency content.

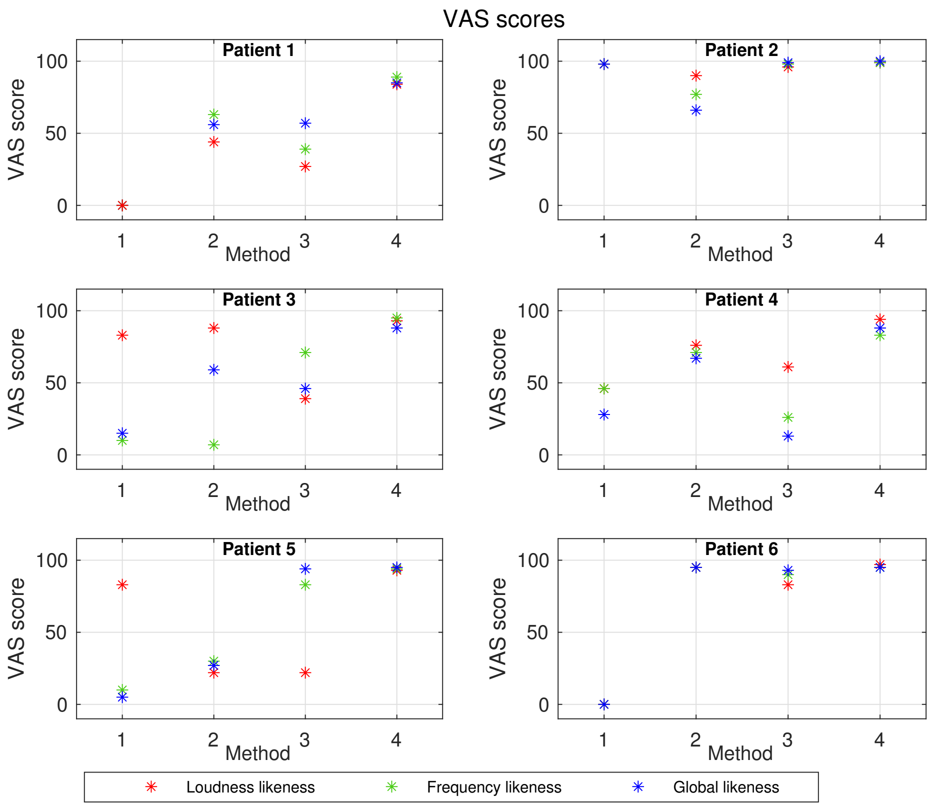
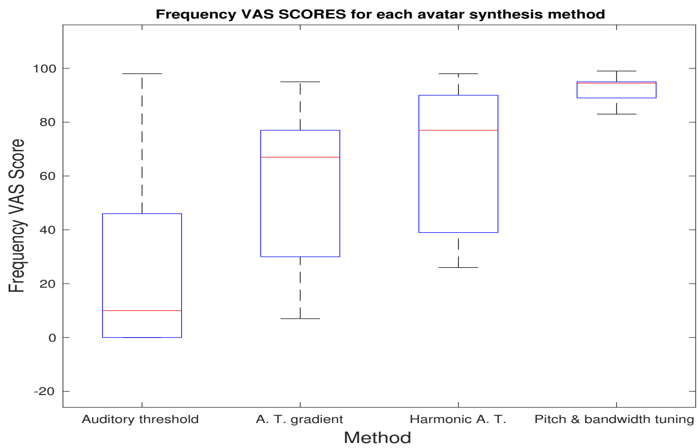


Figure 3.5: Individual scores of the VAS questionnaire. Method 1 corresponds to the *auditory threshold* method, method 2 to *auditory gradient* method, method 3 is the *harmonic auditory threshold* and method 4 is the *pitch and bandwidth tuning* method.

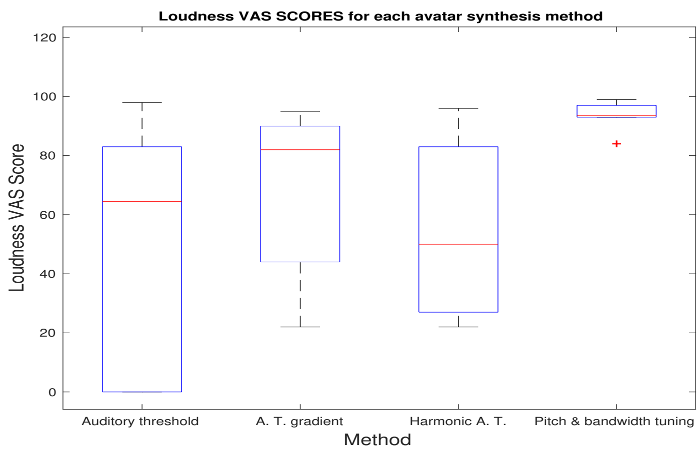
Figure 3.6 comprises three box plots that show the whole cohort scores of the VAS questionnaire for the three avatar characteristics scored by the participants:

likeness similarity (a), loudness similarity (b) and global similarity (c) of the four avatars to their tinnitus. The line in the middle of each box is the sample median. The tops and bottoms of each box are the 25th and 75th percentiles of the samples, respectively. The whiskers are lines extending above and below each box and outliers (values 1.5 times the interquartile range away from the top or bottom of the box) are displayed with a red + sign.

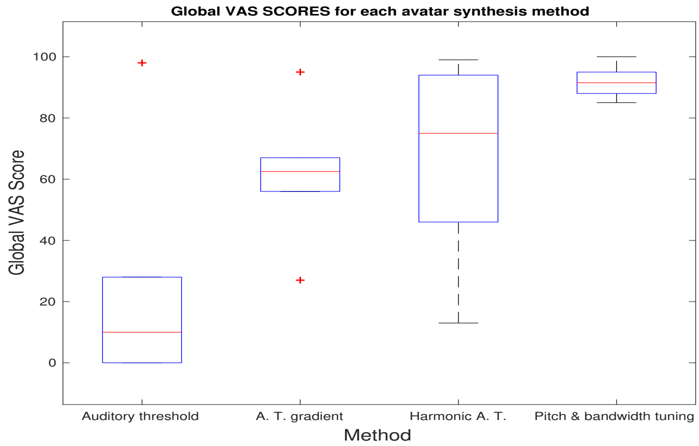
All the participants agreed that the avatar created with the *pitch and bandwidth tuning* method best suited their tinnitus, showing a very high score in terms of frequency, loudness and global similarity to their tinnitus. The second preferred method in terms of global similarity was the *harmonic auditory threshold* method. However it showed an excessive score variability among patients. This could indicate that an individual adjustment of its initial parameters should have been carried out instead of using the same parameters for the whole ensemble. On the other hand, avatar created with the *auditory threshold* method was usually assessed as the less representative of their global tinnitus sensation.



(a) Avatars' frequency similarity VAS scores



(b) Avatars' loudness similarity VAS scores



(c) Avatars' global similarity VAS scores

Figure 3.6: Box plots of the avatar creation methods' VAS scores

The last part of the questionnaire asked the participants to rank their avatars in descending order of preference. As we can see, the *pitch & bandwidth tuning* method was always chosen as the preferred one (table 3.1):

Participant	1st	2nd	3rd	4th
P1	P&b tuning	AT gradient	Harmonic AT	AT
P2	P&b tuning	AT	Harmonic AT	AT gradient
P3	P&b tuning	Harmonic AT	AT gradient	AT
P4	P&b tuning	AT gradient	AT	Harmonic AT
P5	P&b tuning	Harmonic AT	AT gradient	AT
P6	P&b tuning	AT gradient	Harmonic AT	AT

Table 3.1: Avatars ranking

Chapter 4

Discussion

In this study we intended to explore new characterization methods and determine if the avatars created with those methods would be more satisfying for the patients than the methods from [54] in terms of similarity to their tinnitus.

On one hand, we tested two semi-automatic methods, *auditory threshold* from [54] and *auditory threshold gradient* method. They were directly derived from the patient's auditory profile and they were based on the two neurophysiological models presented in the literature (section 1.2), the reorganization and the homeostatic plasticity model, respectively. From the scores in the VAS questionnaire, it can be concluded that the first method did not succeed in convincingly portraying the tinnitus' internal spectrum except for one person. However, the second one, even though it was never chosen as the preferred one, it obtained good scores from at least half of the patients.

On the other hand, we tested two manual methods in which the patient was able to modify the avatar spectrum to some extent, the *pitch and bandwidth tuning* from [54] and the *harmonic auditory threshold* method. The motivation of creating the harmonic-based method was that we wanted to extend the adjustment possibilities of the *auditory threshold* method from [54] while preserving the characteristic in which the avatar spectrum was shaped by the auditory threshold curve, suggested by the reorganization model in [50], among other studies. One of the limitations of the ancient method was that it used the defined frequency tones chosen for the audiogram to build the avatar. These predominant frequencies might not match the tinnitus frequency. In our new method, we included the inharmonicity control parameter β, which indirectly allowed the patient to modify the avatar synthesis frequencies on small steps according to the equation 2.1 at the same time the gain of the harmonics was shaped by the auditory threshold curve. Another limitation of the ancient method was that, for the two patients with the highest hearing loss, the avatar created contained excessively high frequency content for the patient to be perceived at the maximum level permitted by the program (0 dB FS), which could be solved adjusting the parameters included in the new method aiming to modify the frequency content.

Scores from the VAS questionnaire showed that the harmonic-based method obtained in general slightly higher scores in terms of global similarity to the patient's tinnitus than the *auditory threshold gradient* method. Although it was never chosen as the preferred one, it obtained very good scores from half of the patients. However, it was intriguing the high score variability among the total ensemble of participants. This may be due to the threshold parameter that computes the fundamental frequency f_0 of the the sound: we fixed a very low value (5 dB HL) for all the sessions in order to get a low fundamental frequency f_0 and assure that at least one harmonic would be synthesised for all patients. We decided to use the same value for all the participants in order to simplify the avatar creation task and avoid stretching on the test sessions. However, it would have probably been more satisfactory to adjust this parameter depending on the auditory threshold curve for each patient, or even including this parameter among the real-time control parameters controlled by the patient. Several patients judged the avatars created with this method as containing too much low frequencies. Adjusting individually this parameter would have solved the issue. In any case, even without this adjustment, the *harmonic auditory threshold* method obtained generally much better scores in the VAS questionnaire than its predecessor *auditory threshold* method.

The last method, *pitch and bandwidth tuning*, which proposed a simpler stimulus profile centred on a single frequency, performed comparatively better. Although the stimulus proposed by this method was often judged to lack of complexity and to match only the dominant pitch of the tinnitus, it obtained the highest scores on the three characteristics assessed in the VAS questionnaire. Furthermore, it was always chosen as the preferred method by the patients.

On the other hand, we expected to find out that the similarity score of the avatars in the VAS questionnaire and the preference of one or another type of avatar would be related in some way to the relationship between the patient's dominant tinnitus pitch matched and its auditory curve. Among the six participants, two matched their tinnitus pitch in their hearing loss region (around 40 dB HL), two near the steepest slope of their auditory curve and the other two far from the hearing loss region. Unfortunately, due to the reduced cohort of patients we could not come to a clear conclusion on this point.

Lateralisation test can be used as an alternative approach to characterize the subjective intensity of the tinnitus, where its value is obtained indirectly from a localisation task rather than a direct loudness evaluation. Figure 3.3 shows a positive mean offset of 5 dB on the lateralisation curves at 0º. This means that, on average, the central position was obtained with a tinnitus avatar level higher than the level tuned to match the perceived loudness of their tinnitus. This contrasts with the results obtained in [54], which resulted on a negative offset of 6 dB. One hypothesis is that this could be due to the fact that, as opposed to that study, we included in our test sessions patients with bilateral or several tinnituses and the presence of these additional tinnituses and the risk of confusion between two sounds overlapping on the same ear could be biasing the results.

Comparing both lateralisation and spatialisation tests, it was observed that the four participants who located its tinnitus near the lateral extremes (-90º and 90º) obtained a similar lateralisation slope (figure 3.4). On the other hand, the only patient that located its tinnitus at the back of his head (-120º) obtained the most horizontal slope. Interestingly, the participant who reported its tinnitus near to the central point (-3º) was coherent with its lateralisation result, obtaining an extremely low gain value in the ipsilateral position (-90º) in an attempt to "push" the global tinnitus perception to that side with no satisfactory result.

Overall, even though the scores obtained in the VAS questionnaire for the new methods implemented were generally good, they varied significantly from one patient to another. This indicates the necessity of adjustment of the control parameters of the methods. In the case of the harmonic-based method, it seems obvious that the threshold parameter should be adjusted independently for each patient. For the gradient-based method, it could be interesting to automatically constraint the synthesis frequencies to the region of steeper slope of the audiogram and test if these isolated frequencies correspond better to the patient's tinnitus spectrum. On the other hand, although the *pitch and bandwidth tuning* method is often judged to lack of complexity and relies on the subjective patient adjustment, its prevalence on the VAS questionnaires makes it the best candidate at the moment for the virtual reality therapy. However, octave errors seen frequently in the frequency matching task carried out in our test sessions suggest that a mechanism trying to avoid them like the one used by [49] presented in the section 1.4.1 could improve the accuracy of this method.

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Appendix A

Individual avatars spectra and audiometries

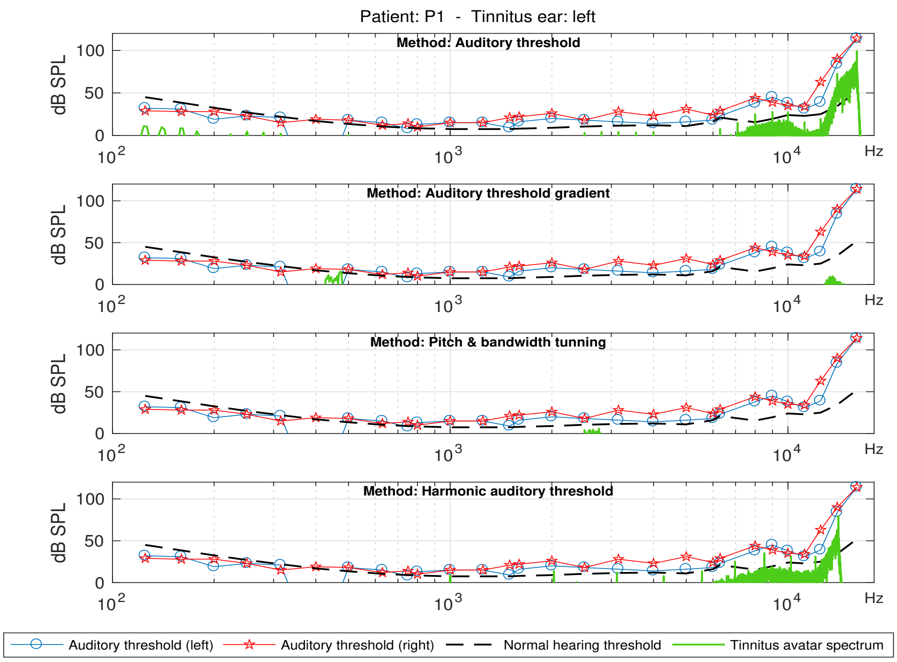

Figure A.1: Participant 1: avatars spectra.

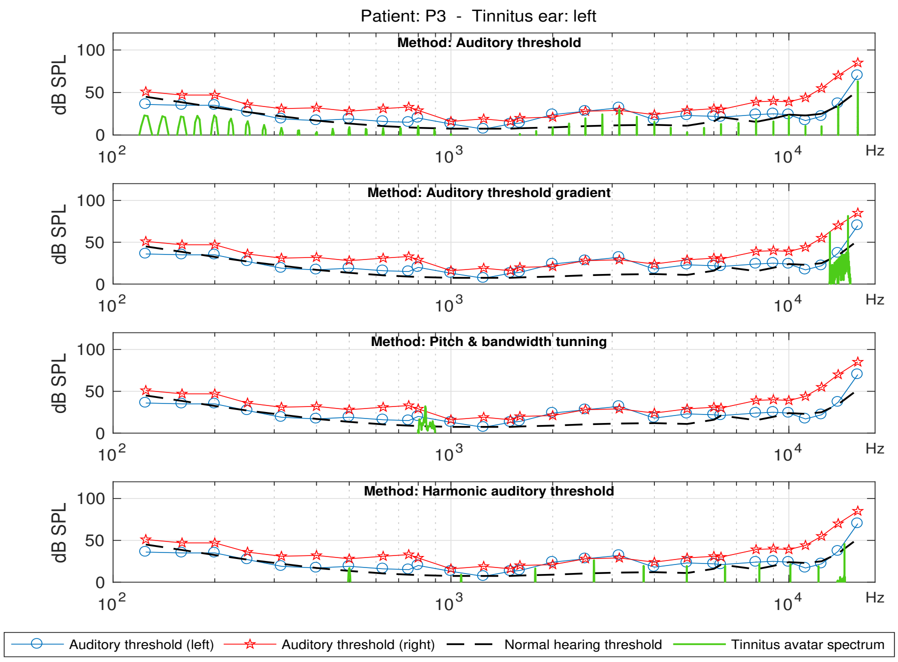

Figure A.2: Participant 3: avatars spectra.

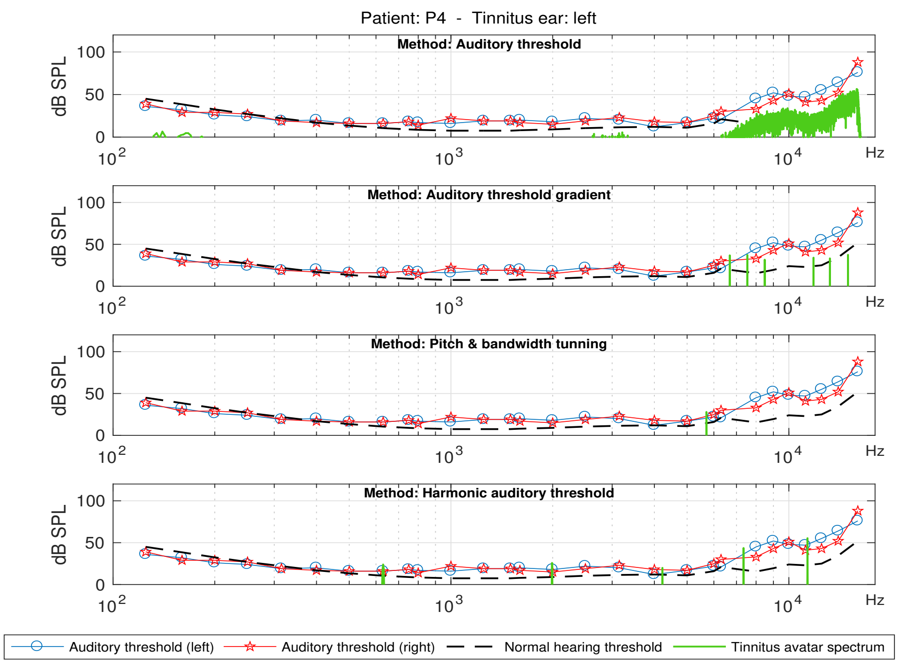

Figure A.3: Participant 4: avatars spectra.

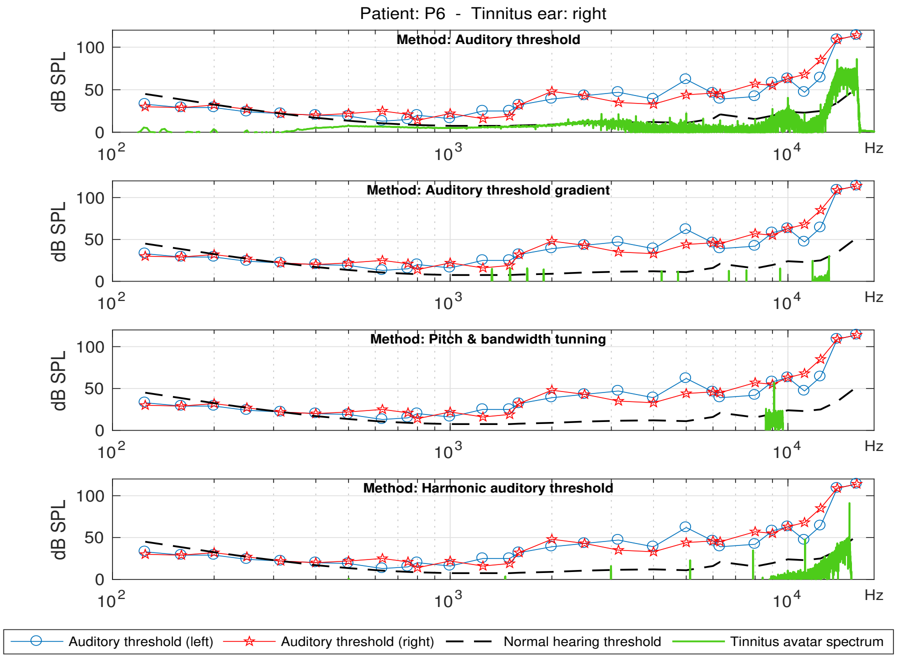

Figure A.4: Participant 6: avatars spectra.

Appendix B

Avatar VAS questionnaire

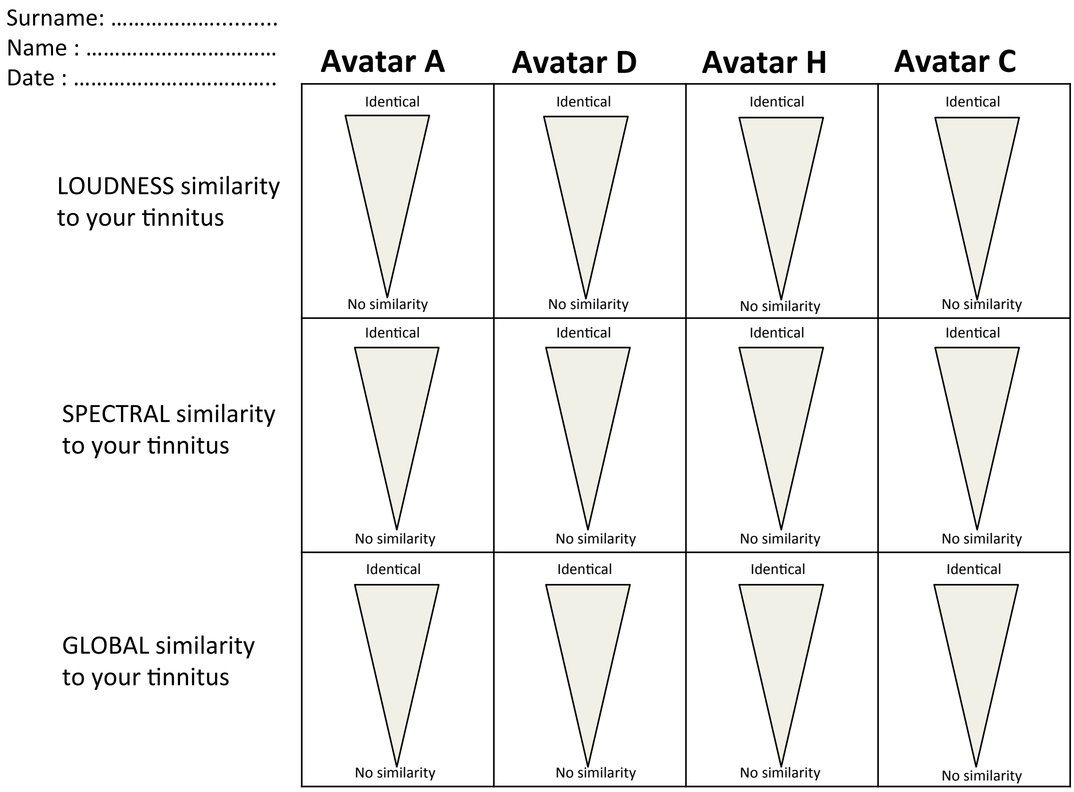

Figure B.1: Avatar VAS questionnaire. Avatar A corresponded to the one created with the *auditory threshold* method, avatar D with the *gradient auditory threshold* method, avatar H with the *harmonic auditory threshold* method and the avatar C with with the *pitch & bandwidth tuning* method.