Towards Defining the Potential of Electroacoustic Infrasonic Music

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ABSTRACT

Infrasounds, frequencies ≤ 20 Hz, occupying the sonic landscape beyond pitch, offer a wide terrain of musical potential to the contemporary electroacoustic composer, a potential that has so far been poorly defined or exploited. This paper is a brief tutorial on employing infrasounds in electroacoustic composition. Infrasounds possess musical potential within the auditory and tactile modalites as either airborne and solidean vibrations, either containing or psychoacoustically suggesting a fundamental wave ≤ 20 Hz. The infrasonic composer must consider a range of issues with respect to 1) equal-loudness contours (the detection threshold being > 70 dB below 20 Hz), 2) intersubject variability within these contours, 3) obstacles in finding hardware to diffuse these oscillations at the SPL needed for their detection, 4) their safe usage (anticipating harmonic distortion in hardware when working at high SPLs), as well as engineering an aesthetic context through interactivity and sensory conditioning to optimize a positive-valence response. There is great potential for sonic, vibrotactile, and intersensorial composition with respect to space and the body, e.g., interacting with or conveying large architectural spaces, evoking psychosomatic interactions through biorhythmic suggestion, and exploring the musicality of the body through its peak resonances.

1. INTRODUCTION

This paper evokes and addresses some practical issues concerning infrasonic composition, touching a range of subjects including hardware, perception (auditory and tactile), and music cognition (specifically factors contributing to emotional response). I equally outline infrasounds' aesthetic potential to resonate with architectural space, the human body, and more metaphorically with the (embodied) mind, evoking the state of the art as well as several of my own projects. As such, I hope to better inform and inspire the curious composer.

Infrasonic oscillations have previously made appearances in electroacoustic music through use of low frequency oscillators (LFOs), "sub-audio" FM, and monaural and binaural beating. Most notably, in Kontakte (1959-1960), Stockhausen famously investigated the continuity of pitch to rhythm. Outside composition, infrasounds have notoriously been used in acoustic weaponry (at extremely high SPLs) but also on the other extreme, as a means of relaxation in music therapy. Our typical encounters with infrasounds include situations where we come into contact with vehicles of transportation, machinery, wind turbines, large architectural structures as well as with more natural occurrences like earthquakes and waterfalls. Lastly, the biorhythms of the body are certainly the infrasonic oscillations most familiar to us as living creatures.

2. DEFINING INFRASOUND

For the purposes of this paper, infrasound is defined here as any frequency at or below 20 Hz, 16-20 Hz being the approximate threshold of pitch to rhythm [1, 2]. Infrasounds may be thought of in numerous ways. They exist as mechanical waves: vibrations effectuating a rarefaction and compression of molecules, propagating in air or any other medium, either as part of a sound source consisting of a sinusoidal wave at an infrasonic frequency or as an acoustic by-product, such as (monaural) beating. Yet, to speak of infrasonic oscillations is to also speak of rhythm; as such, a regularly occurring pulse under 20 Hz consisting of any variety of other frequencies may also be considered as an infrasound or perhaps, more precisely, as simply being infrasonic. Infrasounds may also, of course, be evoked psychoacoustically, such as through binaural beating [3] or through the missing fundamental phenomenon [4].

Acoustically propagated infrasounds are perceived multimodally, through both audition and tactility at high sound pressure levels (SPLs); under 10 Hz, one can distinguish individual oscillations and such frequencies are characterized by a sensation of pressure at the ears [2].

3. CONSTRAINTS TO CONSIDER

In composing with infrasounds, there are several key perceptual and material considerations to take note of. In addition to highlighting what these parameters are, I will address how other composers and myself have confronted these or similar issues artistically, within our own works.

3.1 Perceptual Constraints

3.1.1 Hearing threshold

Though 20 Hz is the value oft cited in literature as the lower frequency threshold of human hearing, it is a rather arbitrary number in terms of perception: human hearing does not cease below this point [2]. This value simply accounts for a point after which the threshold for detection continues to climb above 70 dB or so, as illustrated in Figure 1.

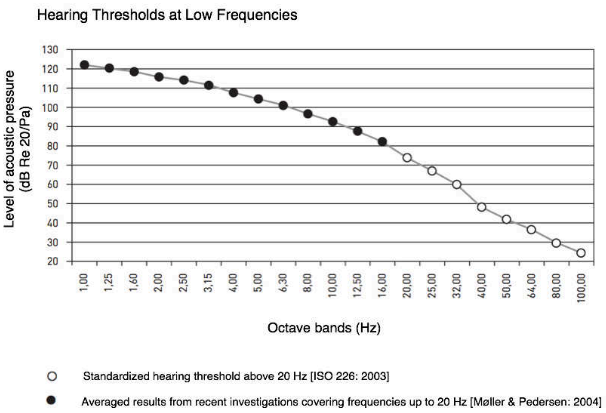

Figure 1. Threshold of hearing below 100 Hz, after Chatillon [5].

In addition to these values, one must consider the rather large inter-subject variability in the perception threshold occurring in this low frequency range. Certain authors claim discrepancies between subjects by as much as 29 dB more sensitive [6]. Given the plasticity of the brain in other frequency discrimination tasks, Leventhall (2009) [7] posits the possibility for infrasonic sensitization to occur after long-term exposure; this doubtlessly necessitates targeted empirical research.

The prospect of better sensitizing individuals to infrasounds through artistic conditioning has been a research inquiry of my own. I am currently developing a sound and art installation with sculpture and visual artist Robert H. Lamp called *La Galerie d'Ondes* which explores using various visual objects, including cymatic art, as a means of infrasonic visualization and intersensorial reinforcement [8]. We plan on organizing formal empirical studies around the exhibition to determine if subjects might improve performance on infrasonic detection tasks after exposure to the exhibit. A preview show was realized as part of the Journées d'Informatique Musicale in 2013 and the full show is set to open at the Maison des Sciences de L'Homme in early 2015 in Paris. Already, with the use of some mylar-based membrane sculptures and a cymatic object using oobleck (a non-Newtonian fluid made from cornstarch and water), verbalized comments from spectators express promise of the installation's ability to encourage and enhance listening in this low-frequency range.

3.1.2 Equal-loudness contours

Shown in Figure 2 are Møller and Pedersen's proposed infrasonic continuation of the ISO 226:2003 curves.

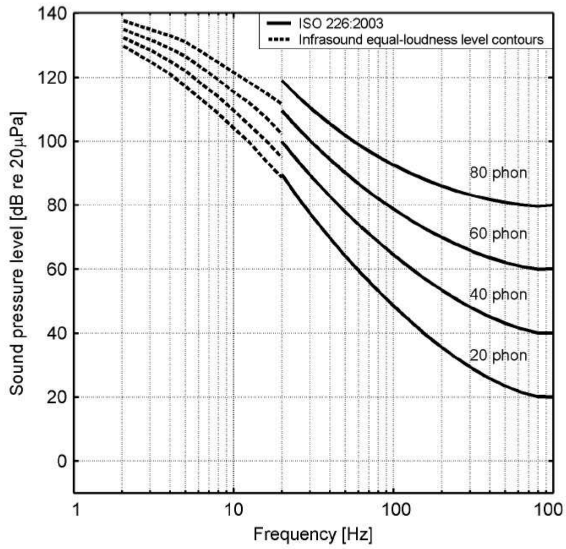

Figure 2. Dashed lines indicate the proposed equal loudness contours below 20 Hz [2].

However, inter-subject discrepancies are also manifest when measuring levels of perceived intensity, evident even in an artistic context. Gupfinger et al. (2009) [9] in their sound installation *Interactive Infrasonic Environment* noted inter-subject variability with respect to reported perceived intensity/discomfort of 10 subjects to three diffused levels of intensity, which the authors characterize as *low*, *middle*, and *high* —regrettably, the dB levels are not specified. Using a custom-made organ pipe device, they diffused a continuous frequency at 15 Hz and employed a tracking system in Max to allow participants to vary the amplitude by one's position in the venue space. Although the tone was perceptible by all participants, the threshold of discomfort varied: for two, it occurred at the middle level, five subjects reported discomfort only at the high level, and the other three experienced no discomfort at all. Interestingly, despite having been exposed to feelings of discomfort, all reported that their experience with the device and installation had been pleasant. One could perhaps attribute this fact to the sense of voluntary participation in this study, all within the context of an artistic installation, and/or to the sense of perceived control that the subjects could exercise in this interactive environment.

As such, to address this non-linearity across individuals and to optimize the potential for a positive-valenced experience, the composer, particularly in respect to sound installations, might consider creating an aspect of audience interactivity, thus providing a context where an audience member can calibrate his or her own exposure.

3.1.3 Vibrotactile threshold

While Dodge & Jerse (1997)[10] specify 120 dB as the *threshold of feeling* at which the whole body feels sound vibrations from acoustic waves, Møller and Pedersen (2004) [2] pinpoint the threshold of vibrotactile perception at low frequencies to be at around 20-25 dB above their hearing threshold for certain points on the body such as at the lumbar region, buttock, thigh, and calf. Additionally, a sensation of pressure may be felt at the upper chest and throat. A comparison between hearing and vibrotactile thresholds can be found in Figure 3.

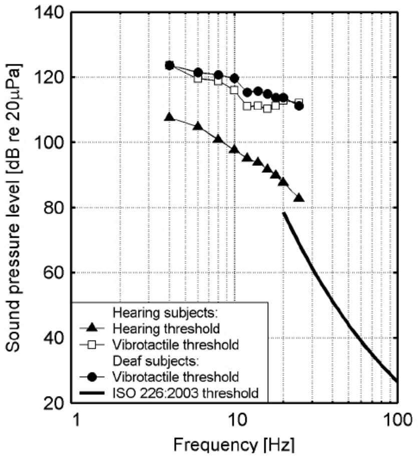

Figure 3. Vibrotactile detection thresholds to air-propagated infrasounds for hearing and deaf individuals, after Landström et al. (1983) [2].

When diffusing low frequencies from a speaker, one should also consider the conduction of such low frequencies through solid objects, such as the floor or seats. This may occur as a result of transduction of airborne waves or may simply be a direct result of the vibrations from the speaker passing through to the surface onto which it is coupled.[1] As such, the perception of these infrasounds is dependent on the threshold of touch.

3.2 Consequences for Diffusion

The constraints of our perceptual mechanisms do not account for the popularity of the figure 20 Hz as some sort of cutoff point for auditory perception. In fact, the reason for this value has been perhaps due in part to lack of access to hardware capable of replicating these frequencies at the high dB levels needed to detect them. Most professional subwoofers do not perform at these infrasonic frequencies. To produce the greatest range of frequencies under 20 Hz at a significant SPL and using a standard subwoofer design, such a speaker must employ a more massive coil than most current widespread models, which would greatly compromise its ability to produce bass frequencies in the pitched audio domain. To cover an infrasonic range from 5 to 20 Hz, such a coil would already have to be able to produce a two-octave frequency range — a range between 1 and 20 Hz would instead be about 4.3 octaves. It's a compromise that has been deemed, for the most part, to be commercially uninteresting to most manufacturers.

The diameter and mass of the speaker cone are other highly pertinent factors. Increasingly larger diameter membranes are recommended to allow for sufficient impedance with the air at lower frequencies; the sound pressure level that one can produce is directly proportional to the cubic volume of air that one can displace per second.[2] To illustrate the magnitude of the cone's task, consider the wavelengths of infrasounds. A wavelength in meters of a given frequency (in Hz) may be calculated according to the celerity (speed) of sound in m/s by the following equation:

$$\frac{c}{f} = \lambda \qquad (1)$$

Given a celerity of 337.16 m/s (with room temperature at 20°C), 20 Hz has a 16.86 m wave, 10 Hz a 33.72 m one, and so on. To illustrate the problem of impedance and proper coupling to the air, consider that one can open and shut a door at a rate of 1 cycle per second and create a 1 Hz wave; of course, due to insufficient coupling, this approximately 337.16 m wave will be imperceptible.[3]

One should equally be mindful of highpass filters (including DC blockers). Even if certain high-end subwoofers have the potential to produce infrasonic waves, many of these subwoofers possess active crossover filters to optimize power towards producing pitched bass frequencies. In addition to one's speakers, the composer must do a bit of detective work to verify that one's sound card, amplifier, software, etc. don't already filter out these frequencies.

Given all the above listed limitations, there are a number of options to circumvent certain of these issues. Concerning more commercially available products, if one internally modifies the active crossover filters in certain subwoofers, such as the 600-HP and 700-HP of the Meyer Sound High Power series, one may obtain infrasonic frequencies.[4] One of their latest models, a "low frequency control element," the LFC-1100, is distinctly not marketed as a subwoofer, conceived for producing lower frequencies. It is also capable producing infrasonic frequencies.[5] Other products such as the Bag-End PD-18E-AD possess an "External Infra Integrator," with a frequency

[1] From personal correspondence with Roger Schwenke, PhD, Chief Scientist at Meyer Sound Laboratories: August 29, 2012.

[2] From personal correspondence with Roger Schwenke, PhD, Chief Scientist at Meyer Sound Laboratories: August 9, 2012.

[3] Idem.

[4] From personal correspondence with Roger Schwenke, PhD, Chief Scientist at Meyer Sound Laboratories: November, 2011.

[5] From personal correspondence with Roger Schwenke, PhD, Chief Scientist at Meyer Sound Laboratories: August 29, 2012.

response going down to 8 Hz and a maximal output of 97 dB at 10 Hz.[6]

There are also solutions in rare and prototype devices. Rotary subwoofers such as the TRW-17 by Eminent Technology seem promising; they can be installed with an infinite baffle and use pitched blades to produce frequency. The company claims a flat frequency response down to 5 Hz.[7] However, their high cost is certainly a deterrent at around 22,000-26,000 USD. Certain artists have constructed custom devices such as organ pipes [9] or "bass cannons" (using a speaker cone bolted to a 22-foot galvanized-steel pipe) like composer Marina Rosenfeld for her piece *Cannons*, 2010.[8]

Locating the proper diffusional hardware has also proven a creative constraint. I've also looked into producing vibrotactile infrasounds via tactile transducers and actuators. In general, I've found linear actuators (such as those manufactured by Crowson Technologies) to have a wider and more refined frequency response in the infrasonic range than transducers (such as the Aura Bass Shaker Pro, which is greatly constricted by a resonant frequency at around 40 Hz). Vibrotactile infrasounds offer their own set of musical potential, which I will briefly outline later on.

High-quality headphones may provide the simplest solution for listening and infrasonic studio composition. They are not subject to the same problems of propagation as speakers, being more or less directly coupled to the ear. One model I've successfully used is Beyerdynamic's DT770 Pro (250 ohm), with a frequency response purportedly down to 5 Hz, although through my own personal use and trials, I've only been able to work down to 9 Hz with a pure sine wave in a quiet studio, which is still impressive of the model, nevertheless [10].

Hopefully, with increasing interest in developing content for these low range frequencies, the technology to support their composition will continue to develop and become more commercially available and affordable.

3.3 Issues of Safety and Comfort Pertaining to Amplitude

When working with frequencies that necessitate a high SPL for their detection, a composer must consider the listener's comfort and safety. Chatillon in his review of infrasonic literature [5], proposes a series of limit values regarding exposure to infrasounds, outlined in Table 1:

<u>**Continuous Infrasounds**</u>

Expositional Calculation	**- Using G-Weighting** **- Summation of energies received between the octave bands comprised between 1 Hz and 20 Hz**
Expositional limit value in dB[G] for a duration of 8 hours	102 dB[G]
If the expositional duration is reduced by a factor of 2	Increase the limit value by +3 dB

<u>**Impulsive Infrasound**</u>

Expositional Calculation	**Without Weighting**
Expositional limit value	145 dB[Lin]

Table 1. Proposed expositional limits to infrasounds [5].

Altmann (1999) outlines isosonic curves in respect to thresholds for pain and eardrum rupture, found in Figure 4:

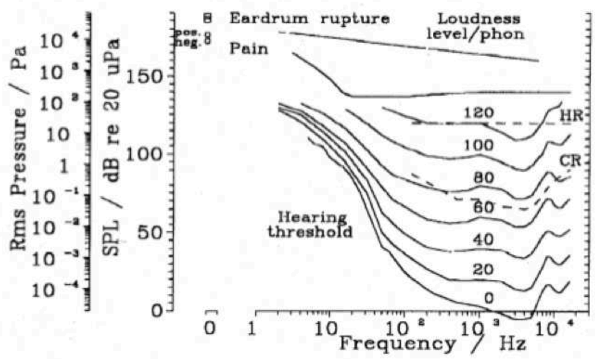

Figure 4. Aural pain curve in context to equal loudness contours [12].

While the thresholds for auditory pain and damage in the infrasonic range are higher than those for pitched frequencies, the utmost precaution should nevertheless be exercised at high amplitudes, particularly in anticipating any harmonic coloration or artifacts above 20 Hz that one's sound system may produce. Again, to reiterate, one should avoid using frequencies above 120 dB, the general threshold of pain for pitched frequencies, as most widespread sound systems cannot produce unadulterated infrasonic waves.

On the subject of comfort, one approach to addressing this matter may be through cultivating a sense of perceived trust within the artistic environment. Many of the negative connotations around infrasound, given the use of

[6] Full Compass. Bag End specifications: PD-18E-AD. Source: http://www.fullcompass.com/common/files/3173-PD18E-AD%20Bag%20End%20specs.pdf
[7] Eminent Technology. (2005-2011). Woofer Comparison. Eminent Technology, Inc. Planar Magnetic Loudspeakers and Audio Technology. Extracted September 5, 2012 from http://www.eminent-tech.com/woofercomparison.html
[8] From personal correspondence with Marina Rosenfeld: February 26, 2014.

low frequency in sonic weapons, are not valid in an artistic context. The use of sonic weaponry is too vast a subject to thoroughly treat in the scope of the paper, but one should bear in mind that their potential for harm is equally a factor of certain psychosomatic responses given an involuntary infliction by a high intensity stimulus. Not only are excessive SPLs employed in these circumstances, but these levels are coupled with the emotional and situational context in which they are used: the listener perceives malicious intent on the part of their author. Music in the pitched domain has also been used as an instrument of torture; context is key.

When using a high intensity stimulus, the composer can follow or investigate certain measures to cultivate a sense of trust between artist and audience. In a concert or installation, the audience member should feel like they have the freedom to leave at will. As mentioned earlier with the Infrasonic Interactive Environment [9], providing for interactive parameters, particularly in modulating the amplitude, might be ideal for accounting for more sensitive individuals. In *La Galerie d'Ondes*, the musical component shifts between alternating movements of sound sculpture (with stationary waves) and composition. The non-linearity in the distribution of such waves in the space (see Figure 5) creates an experience dependent on one's participation and interaction in the space over time.

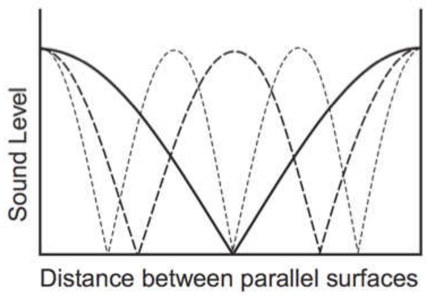

Figure 5. Standing waves in a given space: fundamental frequency (—), second harmonic (---) and third harmonic (- - -). [13].

We further encourage movement around the space by placing objects at different points of the wave maxima and minima. The object *Mirror, Mirror*, shown in Figure 6, acts as a node finder, with wheels and a handle to allow the spectator to displace it.

Figure 6. Visual object *Mirror, Mirror* as part of the preview show for *La Galerie d'Ondes* as it was presented at Les Journées d'Informatique Musicale (2013).

The reflective mylar creates a funhouse effect in reaction to low frequency oscillations. As such one's experience of amplitude is dependent on voluntary and investigative movement around the space, allowing for a more favorable context in which to explore infrasonic perception and music.

Sensory conditioning of one's venue can also be a powerful tool given a high-intensity sensory stimulus. Take for instance La Monte Young's Dream House installation (1969-). Before entering the New York apartment that contains it, a dense grid of high-amplitude superimposed sinusoidal waves, one must take off their shoes. Upon entering the space, one is conditioned through tactility with plush carpeting underfoot and through visual cues: warm immersive colors in pinks and purples. The pillows strewn on the floor act as an invitation to pass time in the venue and further couple one's body to the soft floor. The space also has an interactive element as well, as the slightest movement of the head emphasizes different frequencies. There were even individuals napping on the floor during my visit. As such, due greatly to a carefully curated sensory immersion, these waves, although intense, are perceived as comforting, like a bath. Thus, such considerations in installations, or in cultivating installation-like conditions in concert halls, may optimize the audience's potential to positively receive high-intensity infrasonic waves.

4. THE INTEREST IN COMPOSING WITH INFRASOUNDS

Why infrasounds? Apart from their frequency, there is no significant physical distinction between infrasonic waves and pitched ones [14]. And yet, their unique relationship to space and to the human body distinguish them from higher frequency waves. As rhythms and being at the lower end of our frequency range perception, they have interesting effects on pitched frequency. Given their vibrotactility, they are equally a vehicle with which to explore intersensorial music creation.

4.1 Illustrating magnitude and force

Infrasounds can convey large spaces and powerful forces. Our physical world conditions us to recognize a causal relationship between a sound's frequency and the size of its given source: the lower a sound's pitch, the larger the source from which it was likely generated. We also tend to associate higher amplitudes with higher energy sources, as to achieve higher SPL levels, there needs to be a significant vibration of molecules.

As discussed in Section 3.1.1, high amplitudes are typically required to perceive an infrasound. Thus, we have an internal schema in place to inform us that any perceptible airborne (mechanical wave) infrasound we experience has likely been emanated from a sizable and powerful source.

The use of low frequencies to illustrate such “greater than life” magnitude has already been culturally exploited, particularly in provoking emotional responses in fear and awe. Many modern horror film composers lace their soundtracks with low frequencies and such frequencies also appear in large cathedrals, emanating from 32’ organ pipes producing 16 Hz tones. At the same time, infrasounds are also used in contexts of healing and relaxation as part of music therapy.

4.1.1 Their capacity to delineate large architectural spaces

Infrasounds can be diffused to directly interact with significantly large venue spaces or be composed to illustrate them perceptually.

The room modes of large architectural spaces with dimensions exceeding 8.43 m fall within the infrasonic range, given a celerity of sound at 337.16 m/s and a rectangular space. One may easily determine the frequency of the first harmonic of a standing wave to activate such a room mode. It may be calculated with the following equation [15] given the length L, and where c is the celerity of sound in m/s:

$$f = \frac{c}{2L} \tag{2}$$

The activation of these standing waves may be harnessed artistically in a musical composition or in a sound installation. Concerning the former, one can use them to punctuate key moments as I did in my composition *Larry* (2012): this piece was composed for and calibrated to the dimensions of the architectural space, *La Chapelle des Carmelites*, in Saint-Denis, France. Other projects such as the series of installations *Infrasound* (2001-) by artists RHY Yau and Scott Arford, play with architecture, provoking resonant frequencies and other acoustic reflections across various spaces around San Francisco, highlighting the architectural acoustical properties unique to each space. The reported effects according to the given space have ranged in description from a “lulling salve” to jackhammer-like. [9]

There is also further potential for exploitation through physical modeling synthesis. As such, one may evoke sonic, virtual architectures of immense size.

4.2 Rapport with the human body

Infrasonic oscillations have a profound relationship with the human body. They not only evoke our familiar cardiac and respiratory biorhythms, but, as solidean vibrations, transmitted through the seat, they can provoke certain peak resonances.

4.2.1 Biorhythms

As our cardiac and respiratory rates are themselves infrasonic oscillations, infrasounds have the potential to evoke an association with such rhythms. Furthermore, it is even possible for such rhythmic to provoke biorhythmic entrainment, where the internal rhythm synchronizes with an external sonic source [16].

Respiratory rhythm for an adult at rest is approximately between 0.2 and 0.33 Hz [17] (usually higher for children or during physical activity). The typical resting heart rate falls between 1-1.33 Hz. This figure tends to rise with age and is generally lower for physically fit individuals. One’s heart rate during physical activity should ideally be at 50-85 % of their maximal heart rate. This maximum rate in Hz can estimated as a function of age using the following equation: [10]

$$f = \frac{(220 - age)}{60} \tag{3}$$

As such, for adults between the ages of 18-90 years, this maximal rate slows from 3.37 Hz to 2.17 Hz, with a target active heart rate being 1.685-2.8645 Hz for an 18 year-old and 1.085-1.8445 Hz at age 90.

Provided these ranges, one can evoke the excitative and sedative physiological states associated with such rhythms. Furthermore, in a well-crafted composition, one can potentially convey and even elicit certain emotions with such states.

This evocation of biorhythms is particularly powerful when coupled with a peak resonance at the rib cage that occurs as a result of air-propagated low frequency at around 30-80 Hz and is evident at 107 dB [18]. Monaural beating over such frequencies may produce a pulsing sensation at the chest. Such an effect was present in composer Kasper T. Toeplitz’s musical contributions to the 2012 music-dance performance *Bestiole* at the Centre Pompidou, whether intended or not on his part [11]. These beatings at excited-state respiratory and cardiac oscillations gave the sensation of shortness of breath, an effect better appreciated by some concert-goers than others (I personally enjoyed the experience). When using such techniques, particularly at excited-state rates or with arrhythmic pulsation, it is recommended to take actions to cultivate artist-audience trust within the venue, perhaps through interactivity or sensory conditioning, as mentioned earlier, or by informing/cautioning them beforehand. (This latter approach, however, might have the opposite effect, creating negative preconceived notions).

4.2.2 Biodynamic responses to vibrotactile infrasound

As M.J. Griffin outlines in his text *The Handbook of Human Vibration* (1990) [19], there are three frequency ranges possessing distinct corporal responses. 1) Below

[9] J. Haynes, “The brown note,” in Low Bass Theories, *The Wire*, vol. 341, pp. 34, July 2012.

[10] American Heart Association. Target Heart Rates. Source: http://www.heart.org/HEARTORG/GettingHealthy/PhysicalActivity/Target-Heart-Rates_UCM_434341_Article.jsp

1-2 Hz, waves act more or less uniformly on the body (below 0.5 Hz is the range often associated with motion sickness). 2) Above 1-2 Hz, vibrations may be amplified in certain parts of the body. Concerning vibrations to a seated individual, Kitazaki and Griffin (1998) [20] confirmed that a converged principal peak resonance may occur at around 4.9 Hz, with combined resonances of the head, spinal column, and viscera. These values, obtained with healthy male subjects of similar height and weight, were modulated between 4-5.2 Hz according to erect or slouched body posture. Various second mode resonances were identified between 8.1-9.3 Hz, although these were less pronounced than the combined first resonance. Resonances in this second spectral range are subject to variability across individuals according to such additional factors as height, weight, sex, and muscle to fat ratio. 3) The third range is above such resonances, characterized by vibrotactile sensation localized at its point of entry to the body (attenuated elsewhere).

Given such factors, and taking into account inter-subject variability, one could envisage harnessing such resonances musically, creating vibrotactile infrasonic works tailored to certain individuals or for larger groups of similar body type. Equally, with a more mixed group, one could advise the audience to alter their posture to calibrate their body towards their peak resonance.

Visual acuity is also impacted by certain vibrotactile infrasounds. In several studies cited by Ohlbaum (1976), visual acuity was impacted at frequencies between 14-27 Hz without a helmet and between 3-10 Hz with a helmet [21]. I have noted changes to my visual acuity in using an Aura Pro Bass Shaker when seated on the object between the frequency range of 15-35 Hz [11]. Such effects offer a wealth of potential for use with visual art and might inspire vibro-audiovisual pieces that contrapuntally play between all three modalities.

Wanting to test these various corporal resonances, I made a rudimentary instrument using a phasor in Max 6 hooked up to a Crowson Technologies tactile actuator (attached to a plank for sitting). Thus, I created a *body piano* (2013) for myself containing 5 notes, one pertaining to the under 1-2 Hz frequency range, two calibrated to my first and second peak resonance, a localized frequency at the seat, and a frequency impacting my visual acuity, respectively. I eventually hope to do more sophisticated exploratory work with my simple “instrument” and integrate it into future projects.

4.3 Other musical parameters in the sonic and virotactile modalities

Among the salient features of air-propagated infrasounds is an ability to affect frequencies within the pitched frequency domain, evidenced through amplitude modulation [2]. In addition, with a fundamental frequency in the infrasonic range, and the entire expanse of the pitched frequency range at one’s disposition, one can create dense and intricate polyrhythms with inharmonic partials using such basic synthesis techniques as additive and FM. Using two channels, one can further enhance such effects, creating rich polyrhythms with complex phase relations and monaural beating, particularly with FM [11].

In respect to vibrotactile infrasounds, frequency (i.e. rhythm and polyrhythms- when creating infrasonic “harmony”), timbre (with a sense of smoothness to loudness depending on the complexity of the waveform) and spatialization (with multiple tactile devices across the body) are among the most salient exploitable musical parameters. Phase and beating might also contribute some unique effects in the tactile domain. In some recent preliminary qualitative tests I performed on myself and a few other individuals, diffusing a stereo signal to a tactile inertial shaker on either side of the forearm, anterior and posterior, demonstrated that subtle phase variations of around $\pi/5$ between two sinusoidal waves of the same frequency were cutaneously detectable, also producing a tugging sensation along the length of the arm. Frequency beating between the two shakers, within a range of around 1-10 Hz of difference, can produce the illusion of rotational movement around the axis of the arm. Further studies are currently being conducted to investigate the scope and nature of these effects and pinpoint the spatial conditions under which these effects occur, with respect to the anatomy of the human body. Additionally, one can create the illusion of cutaneous phantom sources when activating multiple tactile sources on the skin (of a certain proximity) at rates of approximately 6.65-13.33 Hz [22].

With respect to spatialization in the sonic domain, it is worth pointing out that one can create infrasonic effects through circular panning as composer Anne Sedes did using phasors in her octophonic composition *Electrified out of the Coma* (2011).

Sonic and vibrotactile infrasounds can equally be combined to create intersensorial contrapuntal relations. For example, in my piece *Larry* (2012), using cardial rhythms and machine-like sounds (two familiar sources of both sonic and tactile infrasounds) I played between moments of synchrony and counterpoint to play with intersensorial expectations.

5. CONCLUSION

This paper marks perhaps the first interdisciplinary description of information pertinent to infrasonic music creation. Infrasounds can be exploited in the audio or tactile domain (and sometime the vestibular and visual ones too) in various ways: to describe real architectural features or acoustically suggest immense spaces, to interact with the human body through biorhythmic associations or activated resonances, to modulate pitched frequencies, or to play with intersensorial expectations.

As they require a high SPL to be perceived, one must take the necessary precautions to ensure that one’s hardware is capable of producing such frequencies at the prerequisite amplitude, and that one does not put their listeners at risk of aural pain or discomfort. As infrasounds are typically perceived as an intense stimulus affecting multiple sensory modalities, their highly immersive potential may amplify one's emotional state, given the context. As such, using elements of interactivity or sensory conditioning to cultivate either a sense of control over one's exposure to these frequencies or a sense of ease, is recommended.

My own research, realized through my various musical projects to date, only serves as a stepping stone towards more profound explorations. Luckily, emerging and novel technologies are increasingly enabling infrasonic music creation and diffusion. I hope to have provoked some interest among fellow composers and researchers into further investigation of this growing field of creative potential.

Acknowledgments

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