Electro-Somaesthetic Music: Spatial Approaches

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ABSTRACT

This paper introduces the concept of electro-somaesthetic music (ESM) and a set of spatial approaches unique to its realization. We describe ESM as computer-generated music intended to engage the human somatosensory system as an essential artistic aim. Specifically, ESM arises from mechanical waves engaging vibration-sensitive corporeal senses by non-cochlear means. Somatic spatial perception affords vibration-based content high spatial acuity within our most proximal, intimate space: at and within the threshold of our perceived self/body from our perceived external environment. We propose that these spatial properties set ESM expressively apart from hearing-based spatial music and present a novel, nuanced territory for compositional exploration. To facilitate in spatial ESM composition and to promote compelling results therein, we advance a theoretical system of technical and aesthetic concerns, accompanied by illustrative proofs-of-concept. This paper examines three paradigms for yielding spatial content within ESM: the manipulation of physical, acoustical parameters; of virtual, computational parameters; and of non-intuitive perceptual armatures. Additionally, we examine each of these paradigms through two lenses: egocentric reference (where spatial content is limited to the body) and allocentric reference (where content is distributed within an external environment).

1. INTRODUCTION

This paper presents a theoretical map and practical landmarks for navigating the creative spatial parameters of a new compositional area—electro-somaesthetic music (ESM), introduced here. We define this area of practice as a sub-category of electro-acoustic music where the engagement of the somatosensory system (via mechanical waves) is artistically fundamental to the work. The somatosensory system encompasses various corporeal senses including tactility (cutaneous touch), proprioception (the positional sense of the body), kinaesthesis (the sensation of corporeal movement), haptics (the kinaesthetic engagement of tactility [1]), and interoception (the internal sensing of body states). The most relevant components of the somatosensory system in ESM include those connected to mechanoreception, particularly vibrotactility (vibratory touch), haptics (particularly in conjunction with vibrotactility, but also concerning other aspects like shape detection), the vestibular senses (the semi-circular canals and otoliths at low bass frequencies [2]), and certain aspects of interoception (e.g. mechanical sensations in the viscera, muscles, and joints).

In terms of delineating the bounds of ESM, some categorical framing and orienting is needed, particularly with respect to contemporary terminology. ESM is an example of non-cochlear sonic music (although it may have additional auditory components) that concerns somatosensation. It encompasses music conveyed via mechanical waves propagated through any medium, though the examples here will focus on airborne and solid-based propagation. It also entails both passive and active touch. As such, vibrotactile music—as introduced by Eric Gunther [3, 4], which focuses on solid-based propagation, cutaneous stimulation, and (mostly) passive touch—falls under the umbrella of ESM but is not synonymous.

When we speak about spatial expression in ESM, we refer to somatically perceptible spatial differences in the position or movement of a (somatic) sound-object or in the position or movement of the perceiving subject proper (as a consequence of mechanical wave stimuli).

Why focus on space? Spatial expression in somatosensation is particularly intriguing as it is qualitatively distinct from audition. It is arguably its most defining creative parameter. The difference is a perceptual proxemics [5] one. In somatosensation, and particularly tactility, the locus of a stimulus is typically perceived as occurring at the threshold of the *phenomenal body*—the perceived body schema—and the *phenomenal external*—the projected perceptual construction of the world (to borrow two terms from Jack Loomis [6]). It is also possible for the stimulus to be interoceptive: perceived as occurring within the phenomenal body. This can occur from either cutaneous stimulation [3] (with an apparent motion illusion) or from biomechanical stimulation (specifically, the resonance of internal structures). As such, the body can be treated as a permeable volume as opposed to an impermeable surface. In audition alone, most sonic events are perceived as occurring outside the phenomenal body, out in the phenomenal external, although exceptions (e.g. from binaural beating) are possible. However, such aural exceptions do not enjoy the same potential degree of spatial precision over the same potential spatial scope (of the entire body) at or within this critical threshold. As such, in spatial musical expression, the phenomenal body is the available canvas in somatosensation, whereas the phenomenal external is the operable canvas in audition.

Another reason to focus on space comes from the growing attention on spatialization in digital audio and particularly in spatial computing (e.g. virtual and augmented reality). Addressing the aesthetic and technical concerns from the angle of ESM could have overarching applications to these areas.

The state of art for ESM has roots in several intersecting practices. These areas include electroacoustic music (especially its explorations of spatial sound [7, 8, 9], gestural control [10], infrasonic music [11, 12, 13], and vibrotactile music [3, 4, 14, 15, 16]), sound art (particularly sound sculpture [17, 18, 19, 20] and soundwalking [21, 22]), somaesthetic [23]/somatic art (including dance [24] and HCI design [25]), the field of haptics (particularly haptic rendering [26, 27], and haptic illusions [28, 29, 30, 31]), aspects of archimusic [32] (as advanced by architect Marcos Novak, including navigable music [32], invisible architectures [33], and liquid architectures [34]), and spatial computing (including in virtual [35] and augmented reality). In particular, this work builds off our previous work in infrasonic music [11], and the aspects therein that pertain to the somatosensory and spatial.

The core of this paper presents several spatialization paradigms (*physical*, *virtual*, and *perceptual*) through two spatial referential lenses each (*egocentric* and *allocentric*). Egocentric refers to spatially relative approaches, where the perceiver's body is the frame of reference and field. Allocentric denotes more spatially absolute approaches, where the external environment serves as the frame of reference and field.[1] The definitions of these terms are informed by Roberta Klatsky's general distinctions of them [36]. In a *physical space paradigm*, one spatializes content by exploiting the principles of acoustics. Here, we look at resonance-based approaches with frequency as a digital-signal spatial-control parameter. A *virtual space paradigm* uses physical computing to computationally construct spatial relationships, which can be used in conjunction with multichannel *tactor*[2] displays and/or with spatial trackers. A *perceptual space paradigm* takes advantage of the spatial idiosyncrasies or non-obvious illusions of somatosensory perception. Such effects could be triggered through certain signaling patterns using a multichannel display, with a resulting spatial percept distinct from what might be anticipated computationally. The above listed paradigms can be integrated together (especially those for virtual and perceptual spaces), and all three paradigms will necessarily be collectively in play in the execution and experience of ESM. What matters in terms of this classification is the primary mechanism or knowledge system at work in the designing of particular spatial gestures or trajectories.

The following sections provide a detailed discussion of physical, virtual, and perceptual spatial approaches through egocentric and allocentric lenses, including illustrative artworks for five of these six permutations.

[1] Regarding the categories of egocentric and allocentric, it is necessary to make one important qualification. While egocentric approaches may be largely passive (without kinesthesis) and allocentric may be largely active (with kinesthesis), these terms are not synonymous. An egocentric experience may entail kinaesthetic movement to modulate egocentric percepts, as will be discussed in the project *Asclepias* in Section 2.1.

[2] Tactor refers to a tactile actuator. In this paper, we use voice-coil vibrotactile actuators exclusively unless otherwise specified.

2. PHYSICAL SPACE: ACOUSTICS

The *physical space paradigm* exploits acoustic properties of the physical environment where signals are diffused to achieve spatialized effects. Approaches such as acoustical focusing (e.g. [37]) or resonance can create such heterogeneous energy across a shared sound field.

Focusing on resonances, one way we can leverage their spatial properties at the digital signal level is through frequency. Frequency is yoked to space through wavelength. Different wavelengths can produce different spatial acoustic responses in a given physical structure.

To engage somatosensation, this approach typically entails the activation of biomechanical resonances in the body to create interoceptive sensations. Certain cutaneous implementations are also possible, as we will discuss.

For egocentric implementations, one can either target the biomechanical resonances of spatially distinct structures within the body (e.g. the skeletal system, viscera) or the mechanical resonant properties of objects in contact with different parts of the body.

In an allocentric implementation, spatialization occurs through engaging the acoustical properties of spaces or other objects in the phenomenal external. This includes the use of room acoustics or the acoustic properties of other objects distributed in the environment.

In this physical spatialization paradigm particularly, one can harness air-propagated waves to create spatial variations. For air-propagated waves to qualify as electrosomaesthetic, there are a few applicable approaches, both biomechanical and simply mechanical.

Among the biomechanical approaches, air-propagated waves can correspond in frequency to the acoustic-activated chest resonance, which is most pronounced around 30–80 Hz [38]. More generally, at low frequencies, they can also surpass the *threshold of feeling*, which is about 20–25 dB greater than the threshold of hearing and concerns certain areas of the body (e.g. lumbar region, buttocks, thigh, calf, upper chest, throat) [39]. (Otherwise, this threshold of feeling is around 120 dB [40].)

Another approach altogether entails the creation of analog, resonance-activated actuators. One can engage the resonance properties of objects (e.g. bladders of some kind) placed across some physical environment (allocentric) (inspired by [20, 14]) or put into direct contact with different points of the body (egocentric). These resonating objects then invite interactive cutaneous touch in an allocentric setting, or transfer vibrations cutaneously in an egocentric one. In such a wearable egocentric implementation, it is advisable to employ differing objects, with varying resonant responses, so that they can be activated separately, thus allowing for spatial nuance.

In our physical spatialization research, we have focused on implementations with biomechanical resonances, using solid-propagated waves to illustrate an egocentric approach, and air-propagated waves to illustrate an allocentric approach.

2.1 Egocentric Practice: Biomechanical Resonances

To model an egocentric approach, we focused on biomechanical resonances during seated whole-body vibration with solid-propagated waves. These resonances typically occur within a constrained frequency range starting above 1–2 Hz and below frequencies where vibrations become more localized to the stimulation site [2]. These resonances are both inter- and intra-subjectively variable. Inter-subjectively, anatomical differences including biological sex, height, muscle-to-fat ratio, etc. impact biomechanical resonant frequencies [2, 41]. Intra-subjectively, such resonances can be further modulated (in real time) by changes in posture [41]. Given inter-subject discrepancies, the idea of composing a universal biomechanical work that could spatialize across human bodies uniformly is unrealistic. While some general trends may be possible, it is recommended to allow subjects to self-calibrate using intra-subjective factors within their immediate control (e.g. postural changes). This is in accordance with suggestions from previous work [11].

We explored that idea in a hybrid performance-installation (2018) and simple installation (2019) of *Asclepias*, a collaboration with the somatic dance artist brooke smiley. The first version of *Asclepias* was presented at the 2018 Alliance of Women in Media Art and Technology (AWMAT) Conference and the second was hosted as part of the evening event for the 2019 Body Mind Centering Association (BCMA) Conference. The first had a cross-modal gustatory component in collaboration with the Santa Barbara restaurant Barbareño. Across both versions, the work focused on the modulation of skeletal and visceral resonances through postural changes. Participants were encouraged to focus on the shifting internal spatial sensations as they altered their posture. Both works featured a combined auditory and vibratory musical composition. We conveyed the vibratory portion to vibrotactile benches upon which subjects were seated. Regarding hardware, we equipped the benches with Crowson Technology Shadow-8 tactors, which actuate vertically, along the same axis as the seated spine.

To develop this work, we conducted a considerably informal qualitative study (using ourselves as subjects) informed by a study on posture and resonant modes by Kitazaki and Griffin [41]. Our aim was to identify a selection of frequencies between 1.00–10.00 Hz with spatially distinct biomechanical responses. When seated in erect, normal, and slouched postures upon a vertically actuating seat, we noted a range between 4–6 Hz where spinal activation was more perceptually prominent, with sensations around the cheekbones and face at the upper end of this range. Visceral responses in the heart, lungs, and kidneys were perceptible in a slouched posture around 5.70–6.28 Hz but were more masked by skeletal resonances in other postures. Some pelvic and visceral responses were more isolated to us around 1–2 Hz, with a distinct steady bouncing sensation of the spine around 1.59 Hz. These ranges differed somewhat from the results of Kitazaki and Griffin [41], although their study was concerned with quantitative resonance measurements with accelerometers as opposed to the qualitative reporting of sensations. In consistency with our observations, they had observed a principal resonance between 4–6 Hz where there are overlapping structural resonant modes for the spinal column and viscera at 4.9 Hz. We also found that modulating our posture impacted the responses. In their report, however, vertical visceral resonance modes were at the higher frequencies of 4.9 Hz and 9.3 Hz. Pelvic responses did occur lower at 2.2 Hz and 3.4 Hz. We suspect that structural differences relating to height and sex might be contributing factors here: all the subjects in the other study were taller and male and we were shorter and female. In a second informal study with five additional subjects, we tested the cross-modal impacts of these resonances on taste, and found certain biomechanical ranges amplified certain tastes over others. Given our results, we created a vibrotactile score using eight frequencies (1, 1.59, 2, 3, 3.64, 4, 5, 6 Hz).

In the earlier performance version of *Asclepias*, the vibrotactile part consisted of sustained, pure sinusoids at the selected frequencies. smiley guided participants verbally through changes in postures to bring out different spatial nuances in the resonances. In contrast, the second installation comprised of four short movements with more timbrally rich content, over corresponding fundamentals. These fundamental-unified phrases were also sustained, though more rhythmically varied and lively. In this version, participants were only given a written instruction to explore through varying their posture.

2.2 Allocentric Practice: Architectural Acoustics

In our allocentric acoustic research we have explored the spatial use of room modes in enclosed rectangular spaces where the first three harmonics for both length and width fall within or close to the air-propagationally activated chest frequency range (30–80 Hz [38]).

Room modes are frequencies at which standing waves involving two or more room boundaries occur [42]. For example, in a rectangular space, between two parallel, flat surfaces, the first harmonic has the relationship

$$f = c/2L \qquad (1)$$

where f is the frequency in Hz, c is the celerity of sound in *m/s*, and L is the length between the surfaces in *m* [42]. Given the phasal folding inherent in this phenomenon, different harmonics produce different spatial profiles of amplitude maxima and minima—more noticeably under a certain frequency threshold (~150 Hz for rooms) [42, 43].

In our experimentation and creative practice, we have observed that the frequency tolerance for this effect seems to be generous. In studies conducted with the assistance of Nicole Boutte, (single axis) modal spatial profiles persist for frequency harmonics calculated for around ±2% (and sometimes up to ±5%) the length of a given dimension. For frequencies beyond these limits, non-linearities of maxima and minima still manifest but undergo spatial drift (with likely contribution from multiple axis modes [42]), creating new spatial profiles. When we superimpose these close frequencies with offset spatial profiles, frequency beating emerges in the overlapping maxima pockets. A larger variety of close frequencies introduced into the space (each with their own spatial profile) can create a rich topography of varying polyrhythms. Critically, for our somatosensational aims, when these frequencies correspond with the resonant range of the rib cage, this effect becomes a drumming sensation on the chest, modulating according to one's position in the space. We have found that humming in the low range of one's voice accentuates this sensation. We have encouraged humming in the public exhibitions of this work.

In total, this approach combines three acoustic phenomena: 1) composite and drifting room modes, 2) frequency beating, and 3) the resonance of the rib cage. We name this particular approach a *kroumatograph*, from the ancient Greek words κρούμα meaning beat or stroke and γραφή meaning drawing or delineation.

We have explored and publicly presented this polyrhythmic spatial topography approach in the pieces *Kroumatograph* (No. 1) (Santa Barbara Center for Art, Science, and Technology (SBCAST), 2016 inaugural event), *Kroumatograph* (No. 2) (2016 UCSB Media Arts and Technology (MAT) End of Year Show *White Noise*), *Kroumatograph No. 3* (SBCAST, May 2017 First Thursday and 2017 UCSB MAT End of Year Show *Re-Habituation*), and *Kroumatograph No. 4* (Fridman Gallery, 2019 ICMC). In the latter two iterations, we created a spatial path score on the ground to guide the temporal experience of the work.

3. VIRTUAL SPACE: COMPUTATION

Virtual space paradigms construct spatial relationships jointly through computation and tactor displays. Egocentric examples entail multichannel tactor displays to convey vibrotactile stimuli to different locations across a designated area of the body. These displays can be wearable [3, 4, 44] or be embedded in a surface in contact with the body such as a chair or bed [14, 16]. Allocentric examples employ spatial tracking in conjunction with a tactor display (of ≥1 tactors), and they provide haptic feedback within a navigable virtual environment.

In this section, we will outline several main considerations for thinking about virtual environments before detailing specific egocentric or allocentric implementations. We start with three core concepts: *field*, *self*, and *phenomena*. The *field* is a spatial coordinate system with bounds and refers here to the mapping relationship between the physical environment and the virtual environment. The *self* concerns the relationship between the physical body and a virtual representation of the self: the avatar. *Phenomena* here pertains to the virtual events and objects that populate the virtual environment, specifically how they are rendered.

With the notion of *field*, given aspects of the physical environment (0D, 1D, 2D, 3D…ND) can be mapped onto spatial dimensions of a virtual environment (0D, 1D, 2D, 3D…ND) by means of tracking or other sensing technologies [34].

For establishing a notion of *self* through body-avatar representation and mapping, one must consider up to five aspects herein: *physical motor body sensing*, *body-to-avatar motor mapping*, *virtual avatar properties*, *avatar-to-body sensory mapping*, and *physical sensory body display*. An egocentric implementation only needs to attend to the last three categories, while an allocentric one will entail all five. Many of these ideas are inspired and informed by Marcos Novak's essay addressing *avatarchitectures*, which discusses opportunities for virtual avatars to occupy ND environments [45]. 1) In the first matter of *physical motor body sensing*, one must determine the placement of a tracker or tracker array onto the physical body. One can allocate these sensors over a selected, constrained area of the body and according to various distribution schemes: equal distances, points of interest (e.g. major articulations, muscle groups),[3] or homunculus (i.e. weighted concentration according to local motor precision or sensory accuracy). 2) *Body-to-avatar motor mapping* describes how tracker read-in positions from a physical coordinate system are mapped into a virtual coordinate system. One tracker (or a collection of trackers) can be assigned to a given virtual motor position, area, or scope in any number of dimensions (0D–ND). We will use the term *region* to henceforth refer to this versatile possibility of position, area, or scope. 3) *Virtual avatar properties* concern *a.* how virtual motor region data collectively affects the movement of a virtual body, b. where sensory regions are located on this body and how these positions interrelate or not to motor regions or to each other (e.g. where is the surface, where is the body permeable or impermeable), and *c.* how sensory regions are triggered by information in the virtual environment corresponding to these locations (i.e. rendering approaches). We will address this last issue further later in the discussion of *phenomena*. 4) *Avatar-to-body sensory mapping* involves how triggered avatar sensory regions are mapped to signal read-out channels. An avatar sensory region of any number of dimensions (0D–ND) can be mapped to any number of available signal output channels (≥1) in any proportion. 5) Finally, *physical sensory body display* addresses channel-to-tactor mapping and tactor placement on the body. Channel outputs can be assigned to any number of tactors. Like tracking sensors, these tactors can occupy any selected or constrained area of the body and follow the same kinds of distribution schemes: equal distances, points of interest, homunculus. To be clear, in a physical computing implementation using both tracking sensors and a tactor display, these distribution and mapping schemes do not have to match and can be creatively combined to explore new approaches to embodiment. Still, the simplest approach may be to follow a direct tracker-to-tactor mapping model, where tracker and tactor positions on the physical body are (nearly) overlapping and their respective virtual positions overlap as well.

With the last major notion of *phenomena*, we treat questions of rendering objects and events in the virtual environment, looking at two key issues: how these phenomena map to sensory regions on the avatar (and thus output channels), and how phenomena (as comprised of signals) are represented in a virtual environment.

The first matter—object/event-to-region/channel mapping—is in essence the somatic equivalent of many spatial audio approaches. As with spatial audio, one can take a Vector Base Amplitude Panning (VBAP) [46] (in a multichannel array) or Distance-Based Amplitude Panning (DBAP) [47] approach, where the object/event has a given width for distal detection. Another possibility is to

[3] Points of interest can also be derived from a highly thresholded homunculus approach.

operate by *taxel*[4] read-out. This approach can apply to a single defined taxel or a cluster (0D–ND), activated only upon direct intersection. Other approaches may be possible.

The second question of how to computationally represent virtual, signal-based objects and events invites six key considerations: *state*, *addressed space*, *signal time scale*, *signal generation*, *spatial behavior*, and *movement*. 1) *State* concerns whether the virtual phenomena are spatially static or dynamic. 2) *Addressed space* concerns the spatial region (0D–ND) that a given signal unit occupies. It is essentially used as a spatialized bin or buffer, depending on the scale of the signal content it contains. The addressed space can be at any spatial scale (micro–macro) with respect to the participant, provided that in all spatial dimensions it remains within the constraints of the tracking system accuracy when mapping the addressed space to physical space. The addressed spaces can form composite objects, groups of objects, or fill an entire room, among other possibilities. 3) Regarding *signal time scale*, there are two kinds of signals to consider: waveform signals and control signals. Waveform signals refer to any signals that can be diffused to create sound (here somaesthetic, of course, as opposed to auditory), whether or not they are periodic or not. Their time scales range from the microsonic to the suprasonic (e.g. sample, period, grain, phrase, piece, œuvre)—scales outlined in Curtis Roads's *Microsound* [48]. Control signals refer to control parameters for waveform signals (e.g. amplitude envelopes, filters). 4) *Signal generation* can consist of either playback or direct calculation. Playback (reading from a buffer) can occur once or loop. This looping can be for a specified and finite number of times or it can be non-specified and "infinite." Direct calculation entails generating a given waveform in real time (e.g. a sine wave). Signal generation can also be subject to either a constant or varying sampling rate as a function of position, as inspired by certain theories of spacetime [49] 5) *Spatial behavior* pertains to how the read-outs of signal information in different addressed spaces interrelate. One the one hand, one can have isolated triggering, where the resulting signal output is monophonic (with new information cutting off previous information) or polyphonic (with information overlapping, which can be purely additive, or employ other operators). On the other hand, one can interpolate. 6) The last major consideration is *movement*. In certain implementations, the notion of frequency is contingent upon space and upon the speed of the user.

Such approaches may encompass somaesthetic and navigable implementations of such recent spatial audio endeavors and concepts as spatiotemporal granulation [50], 3D wave voxel synthesis [51], and spatial chords [7], among others.

3.1 Egocentric Practice: Multichannel Wearables

A computational egocentric approach entails the use of a display of multiple independent channels to exploit a vibrotactile apparent motion illusion. Apparent motion is comparable to the phantom source illusion in audio, where amplitude adjustments across multiple sources can induce an illusion of continuous movement [28, 29, 30]. Eric Gunther's work [3, 4] explores several wearable approaches in this vein, and Bernhard Leitner's *Sound Suit* (1975) is the first artistic implementation of this idea.

Our installation *Vibrotactile Sleeves* (2014 UCSB MAT End of Year Show) featured a compositional study for six vibrotactile channels and two audio channels. We placed six tactors across both arms of a participant: on each wrist, elbow, and shoulder. Computationally, the work used a polar, DBAP approach, treating the six tactile outputs as being at equidistant azimuths along a ring. We specified the two audio channels as being at a higher elevation in this polar coordinate system, allowing for panning within and between aural and tactile domains. Symmetric and asymmetric panning trajectories were explored along both arms, and the rate of panning was paced so as to allow for clear tactile perceptibility.

3.2 Allocentric Practice: Virtual Environments

The addition of spatial tracking to a wearable display allows for vibrotactile musical sculptures, among other possibilities. Of the approaches we have implemented, for brevity, we will describe two simple approaches that have been presented publically.

We presented several versions of a static, spherical musical sculpture (with a 1 *m* radius), computationally implemented in two distinct ways. One implementation took a 3D scrubbing approach, using playback with a tracked, single-tactor glove. In this implementation, we created a radial buffer for a pre-composed music file of bins 0-N. The radius was divided into N bins with the Nth bin in the center, the preceding bins radiating outward like the layers of an onion, and the 0th bin as the outermost layer. The frequencies in the composition were calibrated to be low (<250 Hz) within the receptive frequency range of certain glabrous skin mechanoreceptors in the hand. This implementation was presented as part of a performance and installation *To Eleusis, To Tanayan* (2018 UCSB MAT End of Year Show *Re-Habituation*). A second separate implementation entailed changing control signals across several boundary conditions divided across the radius. These radial markers determined the envelope of these control signal changes. The apparatus for this presentation was a tracked, two-tactor armband placed on the dominant forearm of participants. The sculpture had two modes: one where we offset the frequency in one of the two channels (introducing frequency beating) and one where we introduced phase changes in one of the two channels. In previous informal studies, we had found these changes to provoke two unique spatial illusions, which we will cover in greater detail in the next section. In this way, this project was a marriage of allocentric virtual and egocentric perceptual approaches. We presented this study entitled "A Vibrotactile 'Musical Sculpture' in VR Exploring Apparent Motion Illusions of Frequency Beating and Changing Phase" as a demonstration at the 2018 IEEE Haptics Symposium and as part of the exhibit *Transpiration(s)* (SBCAST, April 2018 First Thursday).

4 A taxel is a portmanteau of a tactile pixel, and here refers to a cell unit in the virtual environment matrix.

4. PERCEPTUAL SPACE: (NON-INTUITIVE) ILLUSIONS

The *perceptual space paradigm* emerges from somatosensory illusions with non-obvious spatial characteristics. Although apparent motion illusions are already implicit in the virtual space paradigm, the difference between the virtual and perceptual approaches is in where the spatial trajectories are compositionally determined and how they need to be planned for. In a perceptual approach, the resulting spatial trajectory is not inherent in or obvious from the computational design: rather, the spatial trajectories emerge from the particular perceptual architecture of the human body. Due to the non-intuitive nature of these perceptual idiosyncrasies, they may require empirical investigative probing with unusual triggering patterns or with unusual display hardware to uncover.

Egocentric illusions of this kind may be more tactile in nature with an apparent motion, phantom source-type effect, or they may be more kinaesthetic, incentivizing certain kinds of movement. An example of the latter is a pulling sensation illusion from asymmetric vibrations [31]. Additionally, we believe we have identified two original egocentric illusions in the course of this research, both with an ambiguous apparent motion and kinaesthetic effect. It is worth mentioning that the parameters that trigger all such illusions can be integrated into an allocentric virtual space, where they can be activated allocentrically, at given locales in a virtual environment (as we did in the project described in Section 3.2). However, such an implementation will not be an example of an allocentric perceptual implementation proper.

In terms of potential allocentric perceptual approaches, the phenomenon of *vection* is promising but quite qualitatively distinct from the other approaches we have examined thus far. Vection describes the illusion of self-motion, and it can arise from sound alone [52], albeit auditory. It is not clear if vection through wholly somatic mechanoreceptive cues is possible, but its cross-modal influence in inducing vection is well demonstrated in the literature. Research has been conducted into the compelling cross-modal influence of vibrotactile cues with both optical flow (e.g. [53, 54]) and audition (e.g. [52, 55]). Insofar as potential ESM implementations, the content itself would not be perceptually in motion but would be contributing to perceived displacement of the subject as a spatial musical parameter. We have not yet explored vection in our work, but in future work, we hope to experiment with vection cues in the somaesthetic domain.

4.1 Egocentric Practice: Amplitude Patterns

The two egocentric illusions we believe to have discovered [11] both entail a two-channel display worn on the arm. The display employs inertial tactors, actuating vertically, perpendicular to the site of contact. In our display, we mounted the tactors opposite one another, on the posterior and anterior sides of the forearm.

Given this configuration, we can produce two kinds of illusions depending on the signal. The first illusion occurs when the signals in each tactor are slightly offset from one another by frequency (<1 Hz), creating amplitude modulations from frequency beating. The second entails maintaining the same frequency in both channels but in changing the phase offset in one of the channels, also creating amplitude modulations. Given what we know about amplitude modulation from apparent motion panning, we might expect these modulations to evoke rapid linear trajectories between the output sources, but this is not the case. Instead, the effect is quite surprising.

Through an informal study, for the first stimulus, some subjects reported a phantom source in yaw rotation, around the axis of the forearm, accompanied by a sensation of pressure. The second effect is more complex, with some feeling a source in pitch rotation or a pressure pulling lengthwise along the forearm. We suspect these illusions are spatially bi-directional and some further informal studies with directional visual cues suggest there may be cross-modal influence here. We intend to develop these studies in future work.

As previously discussed in Section 3.2, we implemented these illusions in the publically presented study and demo entitled "A Vibrotactile 'Musical Sculpture' in VR Exploring Apparent Motion Illusions of Frequency Beating and Changing Phase."

5. CONCLUSION

The selection of work presented advances a new conception of spatial expression in music: one particular to somatosensation. To review, this conception can be taxonomized into two principle axes: 1) the operative domain for determining spatial expression (acoustics, computation, and perception), and 2) the referential lens and field where this expression resides (on the body or in the environment that surrounds it). The corresponding proofs-of-concept for as yet five of six of these resulting cells demonstrate the generative potential of this theoretical tool. This practically reinforced matrix is now poised to offer composers a path toward what the cognitivist Margaret Boden terms *exploratory creativity*. Creativity of this kind entails permutations through a given set of rules [56]. However, our greater objective with this tool is to afford vistas of larger horizons through finer or alternative distinctions, toward what Boden calls *transformational creativity*. This kind of creativity entails altering or eliminating rules to form new inventive spaces [56]. Our hope is that this generative tool is just the first step down a path through landscapes unimaginable until now.

Already, the spatial approaches here offer wider applications for exploration, particularly in the realm of creative spatial computing. These solutions may offer XR haptics an abstract and playful path forward, akin to non-diegetic music in cinema, outside more figurative, force-feedback simulations. Many of the allocentric virtual suggestions could apply to XR audio and other navigable musical implementations. More generally, the spatial theoretical framework here, one that arose out of the necessity to parse manifold somatic concerns, may have some transposable features for classifying and considering spatial audio approaches.

Our future work includes completing some work-in-progress tools in Max to facilitate some of these spatial approaches, conducting some more formal egocentric perceptual studies, and composing more artistic proofs-of concept with allocentric virtual and perceptual approaches. A far more extensive version of this paper will appear as a dissertation, forthcoming for the Université Paris 8. For images, see: https://youtu.be/b0-hwOCnFxM.

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