Computational Designing of Sonic Morphologies

DAVID WORRALL

Columbia College Chicago, USA
Email: dworrall@colum.edu

Much electroacoustic music composition and sound art, and the commentary that surrounds them, is locked into a materialist sound-object mindset in which the hierarchical organisation of sonic events, especially those developed through abstraction, are considered antithetical to sounds 'being themselves'. This article argues that musical sounds are not just material objects, and that musical notations, on paper or in computer code, are not just symbolic abstractions, but instructions for embodied actions. When notation is employed computationally to control resonance and gestural actuators at multiple acoustic, psychoacoustic and conceptual levels of music form, vibrant sonic morphologies may emerge from the quantum-like boundaries between them. In order to achieve that result, it is necessary to replace our primary focus of compositional attention from the Digital Audio Workstation sound transformation tools currently in vogue, with those that support algorithmic thinking at all levels of compositional design.

1. REPOSITIONING SOUND DESIGNING FOR ALGORITHMIC EXPRESSION: SYMBOLS AND MATERIALS

> Music is expressive, carrying us out of ourselves and beyond ourselves, into impersonal regions, into the stream of things; permitting us to feel the conditions under which objects exist, the forces playing upon human life. To live, to merge with the stream and become part of forces larger than ourselves, is to feel, to know something about the entire world. (Rosenfeld 1967: 225)

Two primary organising influences at play in musical structuring are the symbolic and the material. Syntactic meanings in tonal musics have been shaped by song, lyrical poetry and corporeal gestures that evolved through dance and the playing of musical instruments. These meanings contributed to the development of quasi-lexical (symbolic) logics based upon the repetition, evolution and, sometimes, mutation of cultural semiotic codifications such as rhetoric and dance forms (Beghin and Goldberg 2007; Zbikowski 2019). In the pitch-centred, increasingly disembodied West, this development was accelerated by notation and the systematising of functional harmonic relations, leading, in the early twentieth century, to a 'crisis' in tonal music and a search for other formal, non-harmonic means of organising musical structure.[1] Promoted as a viable way to continue this syntactic tradition, serial procedures were used as a means to develop new grammars to formalise musical expressions.

The combination of increasingly fluid harmonic structuring and the physical permanence and reproducibility of notated scores increasingly led to the tendency of theorists and commentators to consider the essence of a piece of music as being contained in the abstract notated representation of largely pitch-based syntactic 'lattice' structures (Wishart 1985: 4). Performances of increasingly complexly notated scores began to be thought of as imperfect realisations of notated Ideals, thus intensifying the development of notation away from an aide-memoire for performers, to abstract 'definitive' documentations of musical 'works' against or to which they interpretively react (Goehr 1994).

Until relatively recently, the sound material of musical compositions consisted of voices and human-initiated traditional musical instrument tones, with timbre playing only a minimal structural role, if at all. For example, timbral differences were sometimes used to assist in separating polyphonic lines. During the eighteenth and nineteenth centuries, printed scores became more widely available and ensembles grew larger and, proportionally, more fixed. This encouraged the development of instrumental orchestration as a somewhat codified translational practice; no better illustrated than in Hector Berlioz's slowly put together (1844–1905) technical study of Western musical instruments and instrumentation.[2]

[1]It is too simplistic to assert that the crisis was simply a result of over-chromicised use of functional harmony as the earlier non-crisis-inducing, sometimes extreme, use of chromaticism by Carlo Gesualdo, J. S. Bach and many other composers attest. Arguably, the 'breakdown' in the late nineteenth century could be ascribed to the unshackling of tonal planning, harmonic rhythm and temporal gesture from non-aural constraints, such as those imposed by dance forms, further emphasising the inherent formal lopsidedness of structures that over-emphasise frequency domain (pitch/timbre); something John Cage realised in his *Sonatas and Interludes for Prepared Piano* (1946–48).

[2]Prior to Berlioz's Grand Traité first publication in 1844, it had been serialised in many parts in the Revue et gazette musicale. He added a chapter on conducting in 1855 (Berlioz 1855) and in 1904, Richard Strauss updated the text to include some modern instruments and added musical examples from Wagner. The updated Treatise with a new preface by Strauss was published in German in 1905, translated into English in 1948 (Wikipedia 2019).

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In its physical dimension, music is rooted in the raw materials of sound; transmitted in all its timbral complexity to listeners through their skin and bones: precognitive, immediate and concrete. At the end of the nineteenth century, when metaphysics yielded to an empiricism based in material explanations of the physical world, and realist painters were producing impressionistic canvasses, some composers challenged the dominance of harmony as a structuring principle and began experimenting with the use of timbre as an alternative structural means. This led composers such as Claude Debussy to write music whose character was often formed by the specific timbral qualities of instruments, and others, such as Ferruccio Busoni, to dream of liberating music from the historical formalism of signs and syntaxes that had evolved from the idealisation of Pythagorean ratios, so as to produce musical structures that could accommodate an expanded palette that included the explicit use of microtones and glissandi, for example, as new forms of expression. Edgard Varèse's encounters with Hermann von Helmholtz, particularly his influential treatise *On the Sensations of Tone as a Psychological Basis for the Theory of Music*, supported his modernistic vision that 'In music, the auditive sensations themselves form the matter of the art' (Varèse 1938), and that music was an Art-Science in which the 'corporealization of the intelligence [is] in sound' (Varèse 1967).

An understandable extension of this impetus was the search for ways to liberate sounds to be themselves, free from the composer's overt decision-making and control. John Cage used indeterminate procedures and Iannis Xenakis, following Varese's lead, sought, unlike the serialists, to escape the language metaphor in which sensations are transformed into symbolic objects (1938/39) in favour of music as an *energetic* and *spatial* phenomenon, the experience of which, as Varése said, was not 'based on a conception but on the thing itself'. Pierre Schaeffer's rejection of the idealism of abstract symbolic notational representation in favour of *objet sonore*, and the use of sound recordings as 'reduced' or non-representational material for a musique concréte, together with the emergence of a new role for timbre in Spectralism and Minimalism in both electroacoustic and instrumental music, further promoted a materialist conception of sound.

It has thus become commonplace to consider some types of electroacoustic and contemporary instrumental music, and particularly sound art, as a shift towards this *sound-in-itself* materialism, in which each work calls for a new set of rules specific to the particular materials and circumstance under consideration. As Mohan Matthen (2019) has recently reiterated, such a position harks back to Aristotle's notion that color is a visible form, transmitted from an external object and received by a sense-organ; that sensing is a causal process that begins with an external object and ends in a sensory state. Such a characterisation finds its extreme expression in some contemporary sound art theory in which matter, being in a constant state of flux, is itself creative (Cox 2011: 153).

However, as Luc Döbereiner (2014) observes, this 're-enchantment of nature or vital matter-energy as a creative force, ultimately de-materializes matter by spiritualizing it'; matter itself has thus been idealised. If a sound is to not be identified as substantialised matter which is palpable, physical and creative (à la Cox), nor reduced to an Ideal, an immanent perceptual object, characterised by what the Scholastics of the Middle Ages called the intentional (or mental) inexistence of an object (Brentano 1995: 88), but to be regarded as the actualisation of some non-material ideal, we need to identify ways to move beyond these material and anthropomorphic dialectics. One way to do so is to give primacy to compositional *practice* – a somewhat circuitous and discursive form of thought that is continuously renegotiating the actions of eliciting sounds and their descriptions in notation, in software, through performances, and through recordings and manipulations. Sounds emerge from, or are induced through, these activities, just as written words arise from spaces between the arrangements of letters of an alphabet, movies from the gap between still images and sound source locations from binaural differences.

2. ABSTRACTIONS, NOTATIONS AND ALGORITHMS

The human inclination towards abstraction is encouraged by the capacity of our auditory processing to produce only weak cognitive bindings to unknown sound sources. For example, we can easily confuse the sound of a ticking clock with the sound of a dripping tap. However, once the sound source is identified as that of a dripping tap, we are able to aurally extract a multitude of characteristics: of the basin, for example – its material composition, size, the presence of content – and perhaps even some characteristics of the physical space in which it is situated. Similarly, our psychoacoustic ability to highly discriminate frequencies led to musics with complex pitch relations for which the instrumentation was often unspecified, or at least ambiguous. There is a parallel line of argument for temporal discrimination and rhythm, with notation being invented in an attempt to sufficiently accommodate evolving musical practices.

Abstract notation is a powerful tool, both for remembering and for concentrating thought (Iverson 1980). However, musical notation, on paper or in computer code, is not *just* an abstraction, a conceptual ideal, but a way of commodifying the transitory nature

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of sound to realise (lit. make 'real') music. It is a set of *instructions*, a description of relationships between resonators and actuators that, when set in motion, produce aural experiences. Thus, compositional practice is understood not as relying on (notated) abstract representational frameworks that access and release the real, material, creative forces of 'sounds-in-themselves', but the codification of a model of interactions between potential resonators and the sounds resulting from their various actuations. While the creation of form in connection to such compositional models might rely heavily on symbolic structures, it is not necessarily directed towards representing something external, or entirely non-representational. Such formalisations employ sounds as the real 'material' of musical composition; not just as physical substances or directly perceived phenomena, but as references to a space between resonators, actuators and activating agents. More broadly, quoting theoretical physicist Karen Barad's discussion of quantum mechanics: 'Reality is composed not of things-in-themselves or things-behind-phenomena but of things-in-phenomena' (Barad 2007: 140).

The world is overwhelmingly chaotic and complex, and the slower-than-expected rise in the effectiveness of artificial intelligence provided the impetus for a more critical examination of the ontological dimensions of perception and human knowledge. In the process of us orienting ourselves in the world, relations form as a result of our *awareness* of our temporal and spatial proximity to objects, situations and other beings. Events and objects manifest themselves to us as things, not just because they are 'there', but because of what they afford us: because of our capacity to use them. One consequence of understanding that this is how perception works was a developing understanding of the importance of another (older) form of truth which is not derived empirically but from meaningful action (Brooks 2002). Maurice Merleau-Ponty had anticipated this necessity in 1945 when he asserted that the process of getting a maximal grip on things in the world mirrors processes that are built into the fundamental structures of our perceptual systems:

> My body is geared into the world when my perception presents me with a spectacle as varied and as clearly articulated as possible, and when my motor intentions, as they unfold, receive the responses they expect from the world. (Merleau-Ponty [1945] 1962: 250)

The interaction between (idealised) compositional models (e.g., notated, communicated scores or algorithms), sound generation systems (e.g., musical instruments with real or virtual performers) and sound synthesis software (e.g., interactions between subjects and objects) are structures that both produce and result from this 'quantum' border of 'things-in-phenomena'. Thus, in keeping with what we now know about the direction-oriented, meaning-driven nature of perception, we can assert that, even on a very fundamental level, without composition there are no 'sounds in themselves', and music is not just the result of symbolic discourse, but the formalisations of procedures that occur in compositional practice between physical or virtual resonant potentials and the structures of their actuations perceived in continuous morphologies.[3]

In his work on the cognitive structure of music, Larry Zbikowski (2002) observes that all humans use three cognitive processes to make sense of the world around them: categorisation, conceptual models and cross-domain mapping. Categorisation is a fundamental cognitive mechanism by which we group sensory experiences, and conceptual models are simplified representations of the concepts or meanings we give to various elements of our experiences, so as to explain or better understand them. By connecting new experiences to existing knowledge, cross-domain mapping helps us make sense of experiences by understanding a (new) target domain in terms of a (known) source domain. Two important techniques we use to do this are metaphor and analogy (Fauconnier 2001). We frequently use metaphor, for example, to represent latent or unseen phenomena (such as temporal patterns) in terms of manifest phenomena (such as visuo-spatial layouts) or sounds in terms of material substances.

Fauconnier and Turner (2002) proposed that the blending together of concepts from separate, even heterogeneous, domains to create new concepts is a basic mechanism of human thinking. Conceptual blending theory (CBT) has recently been used to model creative processes computationally (Coessens 2013; Schorlemmer et al. 2014; Eppe et al. 2018; Zbikowski 2018). Much of CBT research to date seems to have focused on linguistic blending. However, music contains a greater diversity of repertoire and practices, as well as a broader range of subjective ways of listening and experiencing the world (Tuuri and Eerola 2012). Research into the application of these cognitive ideas to music composition, and sonic design more generally, is still in its infancy (Roddy and Bridges 2019; Worrall 2019). There are many outstanding issues to be tackled, including, as Danae Stefanou (2018) enunciates, the need to map conceptually fixed and objective spaces to the mutable subjective spaces of the sensing body. Most thought is inaccessible to direct conscious introspection. Humans mostly think using conceptual metaphors, that is, they conceptualise abstract concepts in concrete terms (Lakoff and Núñez 2000: 5). In this process, creative thought emerges through the process

[3]A reference to John Cage's description of musical form in his 1937 'Credo' as *the morphology of the continuity* (Cage 1961).

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of persistent exposure to, unfolding and de-automating of conceptual blends.

3. COMPUTATIONAL DESIGN OF AUDITORY TRAJECTORIES

Under algorithmic control, a subtler obverse to our proclivity to produce only weak cognitive bindings to unknown sound sources becomes possible: with refined temporal and spectral control of sound synthesis models and acoustic resonator-actuator interactions, hierarchically intricate transformations of musical form more easily lend themselves to symbolic thought at several levels simultaneously (Roads 2004; Farnell 2010). In order to achieve this, we need to evolve or replace our thinking and the Digital Audio Workstation (DAW) sound transformation tools we currently use in favour of those that support algorithmic thinking at all levels of compositional design. This involves designers adapting their generative, representation and translation practices from the designing objects for auditory engagement (musical compositions, data sonifications,[4] etc.) to the construction of systems of formally described relationships that define the *state space* from which streams of such morphologies can be drawn.[5] This shift from the crafting of individual sonic objects and streams to defining dynamical spaces of design possibilities is called *computational designing* (Menges and Ahlquist 2011). Such model spaces are inaudible, heard only through their instances, or the manifestations of particular *trajectories* through them. Approaching the design of auditory trajectories as computational tasks poses both considerable challenges and opportunities. These challenges are often understood to be technical, requiring scripting or programming skills, however the main challenge lies in computational design thinking: a meta-designing which is not simply an extension of established designing processes. This dichotomy is no better illustrated than in following Schaeffer's refusal in 1963 to use mathematics and the computer in the studio at GRM, which led Xenakis to establish EMAMu, later CEMAMu, specifically in order to undertake research into the application of mathematical ideas to music composition (Hoffmann 2009).

The intellectual foundations of computational designing rest at the confluence of multiple fields ranging from mathematics, computer science and systems science to biology, psychophysical and cognitive perception, social science, music theory and philosophy, and increasingly artificial intelligence (so called) as elaborated by McCormack et al. (in this issue). In exploration of how they might be applied to the construction of models for synthesised auditory designs, an outline of the fundamental concepts of design thinking based on seminal ideas from these fields follows.

4. DESIGNING COMPOSERS

Design is a messy business and the relationship between decisions made in the process of 'tweaking' the contribution of individual components in the final result is rarely the sum of simple linear combinations. So, being able to evaluate the effectiveness of a design for a clearly defined purpose is not the same as being able to determine what aspects of it are responsible for, or contribute to, that effectiveness. This is no different in form to being able to construct a neural-network to simulate an observable behaviour without being able to understand the complexity of the individual contributions to the network itself.

Many designers have spent hundreds of hours, not unusually from a very early age, in the case of composers, learning to listen intently and experiment intelligently. They have learnt to compose sound combinations that either crystalise into harmonically coherent complexes (harmonies) or individual streams of sound (musical lines) that maintain various degrees of independence from each other when sounded simultaneously (counterpoint). They learn to orchestrate, which involves both how, over hundreds of years, composers of different styles of music have scored harmonic and contrapuntal ideas to different effect. Such learning also includes searching for techniques for scoring abstract musical structures for performance by a wide variety of musical instruments for their own compositions.

Composers thus bring to the designing task a plethora of skills and experience that have been black-boxed into their individually developed Heuristic Auditory Environment Synthesis (HAES)[6] techniques. Many of the techniques they have acquired have their foundations in psychoacoustic principles even though they were developed, often over centuries, by composers who 'seekingly' listen, rather than by psycho-acousticians, cognitive psychologists or music theorists who infer the rules post hoc. There are a large number of such 'rules-of-thumb': those for maintaining linear integrity

[4]The term *data sonification* is used here in the narrower sense: an acoustic representation of data for relational interpretation by listeners, for the purpose of increasing their knowledge of the source from which the data were acquired.

[5]While being fully cognoscente of the multiple possible sometimes subtle differences between sound design, composition, sound sculptures, improvised performance and even polymedia installations, the broad encompassing terms *design* and *designing* are used here by the author to cover all such variations, unless making the distinction seems necessary in a particular instance.

[6]A term I invent here to distinguish the process from Computational Auditory Environment Synthesis (CAES), discussed later. The term Auditory Environment Synthesis is preferred to Auditory Scene Synthesis (ASS) as it emphasises the three-dimensional surrounding nature of sonically being in the world.

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by avoiding parallel fifths and octaves is a simple example, or for where in the tessitura of various instruments of different timbres the attack transient onset-times are similar, thus affording the smooth dove-tailing of multiple-octave scalar sweeps, or how to adjust relative onset times to ensure simultaneities (chords) are heard as such.

How designers attempt to achieve an effective communication solution with a design task is affected by many things, including an imagined range and clarity of possible solutions for the design (the state space), which in turn, is affected by the tools and methodologies employed, as well as the skills applied in using them. Attempting to evaluate the extent to which a solution is optimal, whatever that may mean in any particular circumstance, and how effective it is in achieving a goal, which itself may fall anywhere on an implicit–ambiguous–explicit communication continuum, remain open questions because the connection between the individual decisions that are made in the designing process and the way they interact in the solution space are non-linear. They are at best open to exploration and interpretation, and at worse a collection of individualised black-box heuristics.

5. SONIFICATION DESIGNING

Such a characterisation is rarely controversial, even by those calling for robust evaluation and scientific comparison of data sonification methods, as it is understood that:

> In the context of data exploration, what can be potentially learnt from a sonification is unknown, or at least not defined properly, and therefore it is very difficult to specify an objective performance measure. (Degara, Nagel and Hermann 2013)

Today, our increasingly artificial or designed worlds are also digital. In fact, they *rely* on digitisation. Yet, just as the designed world is rapidly replacing the natural world as the principal mode of (humans) being-in-the-world (after Heidegger), it is widely recognised that many design problems are ill-defined:

> They are not the same as the 'puzzles' that scientists, mathematicians, and other scholars set themselves. They are not problems for which all the necessary information is, or ever can be, available to the problem-solver. They are therefore not susceptible to exhaustive analysis, and there can never be a guarantee that 'correct' solution-focused strategy is clearly preferable to go on analyzing 'the problem,' but the designer's task is to produce 'the solution.' (Cross 1982)

There are some efforts to make sonification a well-defined scientific method, that is, the 'data-dependent generation of sound that uses systematic, objective and reproducible transforms' (Hermann 2008). However, the designerly production of a sonification obscures its methods of production, leaving an object that is resistant to analysis, or at best not conducive to it. This 'covering up' of the design process does not assist the development of better sonification practices. Nor does it promote the reproducibility requirement which has been declared by some as necessary for sonifications to be called scientific:

> (C3) The sonification is reproducible: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical. ... The definition claims reproducibility. This may not strictly be achieved for several reasons ... The use of the term 'structurally identical' in the definition aims to weaken the stronger claim of sample-based identity. Sample-based identity is not necessary, yet all possible psychophysical tests should come to identical conclusions. (Hermann 2008)

The more ubiquitous design has become the more it is apparent that it is neither free expression nor scientific engineering; it is in-between, that is, a 'third culture', sometimes fluxing more towards one than the other; the application of scientific *and other organised knowledge* to practical tasks.

If the computational design process is to be strengthened, made more flexible, more open to exploration, more teachable, decisions need to be derived from more explicit criteria than the crafted responses of designers with black-box skills. It is not just a question of the importance of user-centred interactive design replacing fixed-format audio files. What is needed is a deeper and more encompassing codification of the design process itself, including the processes and relevant contents that currently go into heuristic black-box decision-making processes, the translation of historical and current knowledge into computer-actionable knowledge banks, and the ability for such systems to both suggest novel solutions and to learn and adapt to individual designers' styles. This is a non-trivial task but one that is slowly being attempted in allied disciplines such as audio game engine design, which is discussed in section 8.

6. COMPUTATIONAL DESIGNING[7]

The dominant mode of utilising computers for audio design and production today is computerisation or compilation: sonic objects or processes that have been conceptualised in the designer's mind are recorded, manipulated and/or stored in a computer using a Digital Audio Workstation (DAW). Typically, a DAW consists of a computer with sufficient storage and processing speed to be able to mix multiple simultaneous channels of audio to which pre-programmed processes

[7]This section relies heavily on ideas developed through the synthesis of multiple authors in Kwinter (2008).

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are applied (often in the form of 'plugins') by software (such as *Protools*, *Abelton Live*, *Audacity*, *Logic* and *Reaper*), which is used to edit, mix, transform and store or simultaneously play back those audio channels for direct audition.

From a design perspective, this computer-aided, compilation approach does not allow the designer to take advantage of the *computational* power of the computer in the design process itself. Expressed simply, computational designing employs algorithms in the design process itself to *deduce* and place elements; for example, real-time synthesised sounds including microsound responsiveness to situational criteria, user input and the like. Computational design is different to computerised (or computer-aided) design, in which the computer is used to *compile* and arrange fixed design elements such as transforming pre-recorded sound samples to better fit the specific situation in which they are to be used:

> The manifest form – that which appears – is the result of a computational interaction between internal rules and external (morphogenetic) pressures that, themselves, originate in other adjacent forms (ecology). The (pre-concrete) internal rules comprise, in their activity, an embedded form, what is today clearly understood and described by the term algorithm. (Kwinter 2008, cited in Menges and Ahlquist 2011: 10)

Critical to understanding the difference between computerised design and computational design is that computerised design is based on a data model, whereas computational design relies on a procedural model. Computational design involves the processing of information and interactions between elements that constitute a specific environment. The final appearance of these elements, whether they be game objects, sonified information derived from data, or otherwise-induced compositional gestures, is rendered from the processing of intrinsic properties, such as the specific values of data points, important information beacons and formal morphological constraints, or extrinsic properties such as the positional rendering of the object in the acoustic environment in which it is being placed, taking into account the effect, salience and occlusion,[8] for example, of other objects that have already been or will be placed there. Computation provides a conceptual framework for highlighting the data being rendered according to the importance placed on it at the time by the designer and the interacting user, if any. Whereas computer-aided designs begin with *objects* (such as sound samples) and adapt them to specific situations, computational designs start with *elemental properties* of resonant objects and their actuators and environmental influences, and use generative rules to formulate (or proceduralise[9]) sounds synthesised for the specific environment into which they are placed.

Most of the detailed work of the computational designer involves explicitly defining and editing the definition of sets of variables such as psychoacoustic parameters, together with gestural and other constraints. In generating specific solutions, logical operations on these sets and their (often dynamically generated) subsets are performed without the designer necessarily being able to conceptualise the full formal implications of their relationships. This can be a positive consequence of such abstraction as it can produce state-space solutions that might not have been intuited, considered or imagined using non-computational approaches. Because the designer is freed from the requirement to produce a single 'masterful' solution, many instantiations can be produced and then evaluated for their effectiveness or incorporated into performer- or audience-initiated interactions.

6.1. Most music is composed procedurally

Adapting Schön and Wiggins' three types of seeing for architectural designing (Schön and Wiggins 1992) to listening, we have:

1. Literal aural apprehension of auditory objects – sensorially led appreciation.
2. Appreciative judgements of quality (tone, texture, timbre, pitch and duration), discovered by more intellectually led reduced listening, and 'deep' pattern recognition.
3. Apprehension of auditory state-space *Gestalts* which are not instantaneously heard or imagined. Such higher-order designs are well known to be important in music and include things such as beat, pulse, meter, swing, scales, modes and chords – higher-level perceptual groupings that afford memory retention, comparison and contrast, as well as symbolically initiated hierarchical formations.

Much designing undertakes these steps in reverse: general conceptual ideas and *Gestalts* such as melodies and harmonies precede thoughts about instrumentation and scoring. As we observed earlier in this article, this is in evidence in music that can be performed on multiple instruments: it is the structural organisation of the sounds that becomes primary, not the sensation of the tones used to 'carry' the organisation. This principle is also exemplified by the fact that, historically, many large-scale instrumental

[8]The salience of a sound is its attention-grabbing or distinctiveness (Delmotte 2012). Occlusion refers to the virtual hiding or masking of a sound by others. These characteristics can be altered using signal processing techniques such as filtering and reverberation.

[9]The terms *procedural design* and *computational design* are frequently used interchangeably. Procedural design is the more general term. When they are computed, procedural designs become computational.

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compositions were composed first into a keyboard score, with specific instrumental orchestration of these ideas being undertaken as separate and later processes.

Generative music composition has a long tradition, pre-dating the invention of the digital computer by several hundred years with a range of techniques employed. A few notable examples from Western Europe include:

- the extensive use of rhetorical conventions for translating both literal and figurative meanings of texts into musical gestures;
- Guido d'Arezzo's technique in the early years of the eleventh century for setting a text to music by varying the melody according to the vowels in the text;
- the use of the quasi-algorithmic isorhythmic techniques in the fourteenth and fifteenth centuries;
- the elaborate contrapuntal formulations culminating in the intricate interlacings of J. S. Bach;
- serial techniques of the Second Viennese School composers and their followers;
- music of the integral serialists and their protagonists of the mid-twentieth century.

The advent of the computer quickly enabled computational formalisation (Hiller and Isaacson 1959; Xenakis 1971). Procedurally equipping machines with the ability to play a vitally important role in achieving musical tasks, such as composition, improvisation and accompaniment, emerged in the second half of the twentieth century as an important development in innovative musical practices.

6.2. Digital sound synthesis

In addition to their use in compiling audio, computers can also be used to digitally generate or synthesise new sounds. Such computation has had a profound impact on our ability to produce conceptually simple sounds such as sine tones as well as sounds of great complexity such as stochastically controlled microsound-grains, as well as complex sounds using simulations of physical resonators such as acoustic musical instruments. Early work by pioneering composers and engineers such as Iannis Xenakis, Jean-Claude Risset, John Chowning, Max Mathews and Andy Moorer was seminal in establishing tools and techniques for exploring and understanding the dynamic nature of natural sounds and thus the design of 'lively' and interesting computer-generated tones and the multi-reverberant environments in which they are formed.

The synthesis of individual sounds is an intensely computational process and algorithms for doing so using granular, physical models, fixed-waveform and other hybrid techniques are available today in a number of mature, well-honed applications such as Csound, Supercollider and Pure Data. Such programs already contain the necessary sound-synthesis tools for supporting a computational approach. However, they are not sufficient in their current state of development to enable the design of sophisticated auditory environments, so, in order to produce computationally designed large-scale morphological transformations, there is a latent need to extend them in the manner discussed here.

6.3. Some advantages of using a computational approach to designing auditory forms

While there may be some circumstances in which auditory icons[10] and earcons[11] might be sufficient for creating a useful sonic environment, having to rely on them, with some general sonic smudging to attempt to smooth over the cutting-and-pasting, is not a recipe for the development of more sophisticated and responsive designs which are clearly needed when the understanding of the psychoacoustic and cognitive correlates of designing increases. As the complexity of an environment, and/or the number of 'objects' in it increases, the computational load of rendering all auditory objects becomes a critical defining feature of how many such objects can be rendered. In an audio-sample-based model, either the library of different audio samples for an increasing number of sonic objects has to be the generated and compiled, or the processing requirements for modifying a smaller subset of each object has to be increased.

In a computational design model, the rendered form of both individual auditory objects and general environmental factors – and the ways in which they interact – can be dynamic and highly flexible. This increases variety and reduces the reliance on the modification of decisions that need to be made in advance when using an audio-samples model. For example, whereas such sound samples might need to be modified according to situational salience requirements, in a computational model, the salience of objects can be made a feature of the synthesis of the objects themselves. In a sonic environment which is responsive to user-directed interests, for instance, this affords the production of a better balance between local and global reverberation requirements, resulting in a deeper sense of environmental continuity and morphology and sound-object integration. Another advantage of using a procedural approach is that, as the level of detail needed and the number of objects increases in the

[10]Auditory icons are 'sounds which mimic everyday non-speech sounds that we might be familiar with from our everyday experience of the real world' (Brazil and Fernström 2011).

[11]Earcons are 'short, structured musical phrases that can be parameterized to communicate information in an Auditory Display' (McGookin and Brewster 2011).

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rendered auditory environment, the overall computation time involved relative to that required to store, retrieve, compare and manipulate large sets of fixed samples significantly reduces.

7. A CASE STUDY: AUDIO IN COMPUTER GAMES

A game world is composed of discrete entities (objects) that have a set of properties (name, visual appearance, location, sound signature, etc.) and a set of behaviours and sounds associated with those behaviours as they interact in the world, and/or the world in which they exist interacts with them. Early games used generative techniques to produce sound-effects and musical accompaniment before computers became powerful enough to use sampling technology to deliver 'realistic' recorded sounds. Because a sound recording captures a digital imprint of a single instance of a sound and not the potential dynamic behaviour of the interacting (resonator, actuator) components, many clever tricks have been developed to blend, layer, filter, interpolate and time-warp these singular sound 'instances'. What this has meant for game audio over the last two decades is that, overwhelmingly, the auditory design approach has remained *event based*, that is, using sound samples:

> Traditional game audio binds each action to an event which triggers a sound sample. Some real-time modifications can be applied such as distance damping, or combining alternative samples in a random or granular way to get more variation. But none of these techniques is able to map the underlying physical behavior of an object and its sound ... an equivalent event-based graphical game would only be a series of static photographs ... In software engineering terms, games audio is badly coupled and inconclusive. (Farnell 2010: 318)

This event-based approach causes timing problems such as the aligning of sample loops with game movements, thus limiting visual and/or audio actions to a predetermined duration and raises the need to devise new methods, such as randomly selecting samples and subsamples, to alleviate the repetitive quality of a limited sample data set. What is somewhat surprising is that although the use of procedural generation of dynamic sound objects is being introduced to game design, the approach has not (yet?) made the huge comeback Farnell predicted. The most common usages seem to be in continuous and environmental sounds:

> Our procedural audio synthesis technologies use a minimal amount of samples to generate a great variety of high-quality sound events. More importantly, our synthesis engine comes with specially-designed controls for intuitive and instant sound manipulation. Currently available technologies include wind, rain, fire, electric sparks and space ambience synthesizers. Some more are coming. (Le Sound 2017)

Joe Cancellaro, composer and game design educator informally described the current state of sound design for gaming in this way:

> (procedural audio) did not make a huge comeback. Sampled audio is pervasive in the game industry. What has changed significantly are the audio engines that deliver the samples, processing them (samples) in real-time, and in many cases altering the original sample. This could be seen as procedural but is it not really. There are examples where procedural sound is used in games, but it turns out it is less effective, emotionally, than samples. It lacks a 'human' touch. For big pads and sustained environments procedural could work, but even then, I would go with a composed sample and let the non-linear audio engine chew it up and make something contained but random. It's all Stravinsky at that point. Shackles! (Cancellaro 2017)

Overtly emotive sounds have a more explicit functional role in developing and enhancing satisfying game experiences than they do in other design tasks. So, it will be interesting to observe if, as game worlds increase in size and complexity, the time critical interactivity requirements that gamers demand will eventually force designers to rely more on computational sound design. Perhaps the increasing computer power of the platforms on which games are delivered will be sufficient to permit game sound designers to continue using sound samples as a means of delivering satisfying user experiences in the foreseeable future.

8. NEW DIRECTIONS IN COMPUTATIONAL DESIGNING OF AUDITORY ENVIRONMENTS

While task-based analysis is understood to be an important step in developing many effective designs such as data sonifications, there is a need to develop larger solution state-spaces with an increased number of dimensions, incorporating both microsound and gestural levels and the intelligence to form multiple mapping and morphing solutions from correspondences between them to afford the production of both highly dynamic and situationally responsive individual sound objects and higher-order, perceptual experiences by systematically modulating the temporal flow, to produce swing, for example.

The ability for designers, and ultimately performers and listeners, to adapt a design to their developing aural skills can be important for satisfying experiences. This is supported by Jean Piaget's observation of an interesting aspect of the relationship between representational and perceptual space. During the development of an understanding of a representational space through experimentation (or 'play'), representational activity is 'reflected' or 'projected back' on to perceptual activity (Piaget and Inhelder 1956: 4) as exemplified in the way understanding of musical structures affects

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the way one perceives musical affect. This observation supports the hypothesis that for a listener, there is a dynamic relationship between their critical listening skills and the sonic complexity and variability of a sound mapping that can be understood. This emphasises both a potential need to have auditory designs which are responsive and/or able to accommodate different and developing listening skills and the need to develop the integration of the development of listening and sound mapping experiences in early childhood education curricula.

If perception is not solely a bottom-up process but incorporates inherited or acquired response biases related to stimulus characteristics and sensory systems that have evolved for multiple, integrated representations of certain features which are meaningful to the perceiver rather than for just single one-to-one reproductions of the physical world, it makes sense to generate multiple designs of any particular algorithm or data set according to the listener's developing sense of meaningfulness. In order to accomplish this, I suggest it is necessary for designers interested in creating dynamic auditory environments to shift their design representation and thinking efforts from creating bespoke hand-crafted solutions using just their own black-boxes to a dynamic system model approach in which design activity is supported by extended state spaces that incorporate psychoacoustic and cognitively informed transforms.

Because of the breadth and depth of detail required, sets of such transforms are more robustly developed collaboratively, using agreed-upon criteria. A community-based approach to developing these resources should go some way towards increasing the computational power of the computer as a design tool to *deduce* a wider variety of more effective sonic designs.

9. CODA

The expressive power of music that Rosenfeld refers to in the quotation at the beginning of this article can be understood as more than the experience of the play of abstract (notational) forms, or the textural *mise en scène* dramaturgy of *objet sonore.* It is the embodied experience, for example, of the actuation and environmental conditions under which sounds and their combinations are evoked, 'realised' and sustained in the processes of continual formation.

The rightful reinstatement of the use of symbolic logics in electroacoustic composition at multiple structural levels from microsound resonance generation and activation to corporally informed gesture models, offers the potential to stimulate and enable the creation of new alliances between the capacity of our auditory processing to produce only weak cognitive bindings to unknown sound sources and the metaphorical cognitive sub-conscious bindings to emerge.

If conceptual blending theory or other compositional paradigms are to be fully explored algorithmically, both for music composition and auditory design more generally, computational frameworks that are capable of accommodating more sophisticated techniques than simple montage are necessary. Such a framework would bring dynamic sound synthesis and symbolic structuring into metamusical interfaces with material in a multitude of simultaneous dimensions, including, for example, psychoacoustic transformation fields, physical (gestural) and psychosocial metaphors and multiple listening modes. This type of metamusical conceptioning could be ably supported by artificial intelligence techniques, such as those currently misapplied to the generation of deep fakes, for example, not just in a bricolage of 'sound objects' but in liminal transitions in the gestural symbolic discourse that reveal themselves through the (awareness of) mutable, permeable interfaces between resonators and the abstract representational and translational frameworks that call them into being.

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