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Addressing the Mapping Problem in Sonic Information Design through Embodied Image Schemata, Conceptual Metaphors, and Conceptual Blending

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Abstract:

This article explores the mapping problem in parameter mapping sonification: the problem of how to map data to sound in a way that conveys meaning to the listener. We contend that this problem can be addressed by considering the implied conceptual framing of data–to–sound mapping strategies with a particular focus on how such frameworks may be informed by embodied cognition research and theories of conceptual metaphor. To this end, we discuss two examples of data-driven musical pieces which are informed by models from embodied cognition, followed by a more detailed case study of a sonic information design mapping strategy for a large-scale Internet of Things (IoT) network.

Keywords: Auditory Display; Sonification; Conceptual Metaphor; Image Schema; Conceptual Blending; Sound; Data-Driven; Music; Music Cognition

Introduction: Sonic Information Design and the Mapping Problem

Sonic information design refers to the application of design research, as defined by Trygve Faste and Haakon Faste in 2012, to *sonification*, an auditory display technique in which data is mapped to non-speech sound for the purpose of representation or communication. In this context, design research is taken to involve "the process of knowledge production that occurs through the act of design" (Faste and Faste 2012). Where visual information design is generally concerned with the presentation of information in a manner that can be effectively and efficiently understood (Horn 1999), sonic information design "pays particular attention to user experience including physical, cognitive, emotional, and aesthetic issues; the relationship between form, function, and content; and emerging concepts such as fun, playfulness and design futures" (Barrass and Worrall 2016).

It is within this expanded context that a key challenge for effective parameter mapping sonification (PMSon) – *the mapping problem* (Worrall 2010) – might be addressed. PMSon is a sonification technique in which data is mapped to auditory parameters such as pitch, amplitude, duration, or timbre in order to communicate the data to a listener (Grond and Berger 2011). The mapping problem was first introduced by John Flowers (2005), who noted that, in his experience, meaningful information does not necessarily arise naturally when the contents of complex data sets are submitted to sonification. This point is echoed by Florian Grond and Thomas Hermann (2012), who point out that because certain sounds can be interpreted in a number of ways and sonifications tend to represent phenomena that have no natural sonic referent, the practice of sonification often runs the risk of

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producing a perceptual experience that is too arbitrary in its form and dynamics to be clearly understood. From this point of view, the mapping problem is framed as a question of how a sonification or auditory display conveys an intended meaning to a listener. It is this particular aspect of the mapping problem (i.e. the conceptual framing) that we are concerned with in this article. Successfully addressing the problem may therefore involve a process of reducing the level of arbitrariness in data to sound mapping strategies, considering whether certain parameter mapping approaches may imply framing relationships which actually work *against* the structural dynamics of a given data set. In this regard, David Worrall (2013; 2014) argues that the mapping problem is further entrenched by some of the software tools used for sonification research and practice. Many of these tools (e.g. SuperCollider, CSound, Max) are borrowed from the field of computer music and are designed to control sound in terms of the parameters of Western tonal music, which, as Trevor Wishart (1996) argues, reduces the rich multi-dimensional spectra of musical discourse to just three primary dimensions: pitch, duration, and timbre. These parameters, Worrall argues, fail to account for embodied aspects of sonic discourse which he sees as critical to meaning–making, such as the micro-level gestural inflections that instrumentalists employ to add layers of performative punctuation – and, hence, information around structural or dynamic features – to a musical performance. Much as a successful Western classical music performance is not simply a mechanistic rendering of the pitch and timing information from a musical score, successful sonic information design may involve consideration of how its data is framed by the performative punctuation of the mapping strategy.

Mapping as Conceptual Framing in Parameter Mapping Sonification

Standard approaches to PMSon can work quite well when the data represented contains a few *orthogonal* dimensions (i.e. each data dimension varies independently) and those dimensions are mapped to a small number of orthogonal sonic parameters. Guillaume Potard's "Iraq Body Count" sonification is frequently cited as an effective example (Barrass and Vickers 2011). It consists of three streams of data: military deaths, civilian deaths, and crude oil prices during the first year of the Iraqi invasion. The data for civilian and military deaths are mapped to short impulses with unique timbres, while the oil price is mapped to modulate the pitch of a continuous tone. While the mapping strategy here seems quite straightforward, the interaction between these axes produces a richly discursive sonic structure. Denis Smalley's (1997) theory of *spectromorphology* might shed further light on sonic dynamics at play in Potard's mapping strategy. Spectromorphology is a descriptive framework for electroacoustic music consisting of detailed categorization schemes deriving from basic gestural shapes (called primal gestures) that are extended to add a meaningful low–level organizational structure to musical domains. In Potard’s piece, the mappings for the civilian and military deaths result in two streaming (i.e. perceptually segregated) sound shapes defined by discontinuous textural motion. This textural motion takes the form of a turbulent growth process that is driven by a movement between *note*, when individual data can be heard, and *noise*, when the data values increase to create a cloud of sound. The oil price appears as a rich spectral contour whose internal texture contains multiple tonal centers which are not quite consonant with one another, giving this sound a sense of disharmony and instability. Adopting Gary Kendall's (2010, 2014) thinking on meaning-making in electroacoustic music, the listener’s embodied experience and cultural context come into play when interpreting such sounds. In the case of the “Iraq Body Count” sonification, the transient sounds representing deaths may sound, to the contemporary listener, like digital “glitches.”

The practice of making creative use of glitching (transients introduced due to errors in digital audio systems) emerged in the late 1980s and early 1990s in the works of electronic musicians (e.g. Oval and Pan Sonic) who, appropriating ideas from earlier experimental musicians such as John Cage, were exploring the concept of “failure” (Cascone 2000). We hear this exploration continued today with artists like Christian Fennesz and Ryoji Ikeda. In terms of the materiality of the medium, glitch’s sudden discontinuities point to a rupture, a sometimes–violent transition, possibly indicating failure, or, in more neutral terms, a “breaking” of continuity. The cultural framing of the affordances of a “cracked” or breaking medium (c.f. Kelly 2009) underlines the role of discontinuities in sound as related to a foregrounded sound event which “breaks out of” a comfortable continuity. In this context, the departure from a stable structure becomes both perceptually and structurally salient (and, hence, a useful aesthetic strategy in a sonification context) and, via the eruption of the apparent materiality of the medium and its cultural associations, might also contribute to an emotional narrative: a sense of growing failure and/or brokenness. From this perspective, Potard's mapping strategy is richer and more nuanced than it might sound on the surface.

AudioObject 1: “Iraq Body Count” (CLICK HERE)

In a medical care context, Tecumseh Fitch and Gregory Kramer (1994) developed an effective auditory display solution which allowed listeners to monitor and respond to indicators of complications across five continuous and three binary physiological variables. These medical complications can be identified on the basis of interactions between the streams of data. Rather than mapping this complex data to eight discrete sonic dimensions, the display instead featured two independent auditory streams with mappings which affected various aspects of their articulation. These streams were designed to act as realistic-sounding (and thus, familiar) sonic referents – 1) a heartbeat signal and 2) a breathing signal – and were mapped to heart rate and breathing rate respectively. The other variables were "piggy-backed" onto these base streams. Atrioventricular dissociation and fibrillation were mapped to modulate the heart signal in the same way these factors modulate a heartbeat in the real world. Four other mappings (body temperature to a filter applied to the heart beat sound, blood pressure to the pitch of the heart sound, brightness of the heart sound to CO2 level, and pupillary reflex to a high-pitched tone) were arbitrary and thus required learning on the part of the listener. Fitch and Kramer suggested that this approach allowed users to more effectively identify medical complications than a visual display, due to the parallel processing of the auditory streams. However, it might also be the case that having two streams of data based on such familiar (and associated) sounds, namely heartbeat and breath, made it easier for listeners to interpret the display. When there are no obvious sonic referents for the data that is to be represented in an auditory display, the mapping problem may become more pronounced, and the listener may find it increasingly difficult to interpret the system. We suggest that incorporating and addressing concepts from embodiment in general, and embodied cognition in particular, can help in the provision of such referents for auditory displays. The following section will explore some of these concepts and their implications in greater detail.

Connecting Embodied Cognition and Sonic Information Design

The modern embodied cognition research program in cognitive science shares some roots with 20th-century European continental philosophy (primarily through Merleau–Ponty). However, it is a distinctive research strand that is more closely identified with cognitive linguistics (Lakoff and Johnson 1980), American pragmatism (Johnson 1987), and more recently with neuroscience (Lakoff 2012). The central thesis of embodied cognition is that the cognitive processes and conceptual systems of the human mind are shaped by the physical and perceptual affordances of the human body (Varela, Thompson and Rosch 1991). When the terms "embodiment" and "embodied cognition" appear in relation to sound, there is sometimes an implicit assumption that for a sound to "be embodied," it must somehow relate directly to some physical gesture, pattern of movement, or phenomenological observation. Whilst the body is obviously the starting point for embodied cognition research, the final goal is to explain cognition in all of its nuance and variation. Embodied cognition aims to achieve this by rethinking the mind from a *bottom–up* perspective, departing from bodily experience. In pursuing this aim, embodied cognition, as it has matured as a research theme, has provided a number of theories of how more abstract, higher–level cognition may be conceptualized from a foundational perspective of embodiment. However, it would be a mistake to assume that these theories should refer back to physical experience at every turn or attempt to reduce all aspects of cognition to bodily experience.

From a theoretical perspective, embodied cognition can be seen as arising in response to the identification of a *symbol grounding problem* (Harnad 1991) within *computationalist* philosophy, which describes shortcomings in traditional *cognitivist* treatment of the human mind as a computer in the attempt to adequately describe how mental and perceptual symbols become meaningful (Varela, Thompson and Rosch 1991). The symbol grounding problem points out that the traditional cognitivist/computationalist model of the mind as a computer of mental and perceptual symbols treats mental and perceptual symbols as arbitrary tokens which have no implicit relation to the referents which render them meaningful. We see this replicated in the mapping problem where, as discussed earlier in relation to Grond and Hermann (2012), the sound materials and structures presented in a given sonification may run the risk of being perceived as too arbitrary in their relationship with a given data set, or in which the mapping may even contradict important dynamics within the original data set. The field of embodied cognition in its response to computationalism could be seen as primarily concerned with meaning–making, taking embodied experience to be the site of enaction for mental and perceptual symbols. Embodied cognition researchers have theorized a number of novel cognitive faculties that complement the more traditional models of cognition. Developments in embodied cognition have shaped research agendas in a number of important fields related to sonic information design, including computer science and artificial intelligence (Brooks 1991; Dourish 2004), visual perception (Noë 2009), aesthetics (Johnson 2008), music (Godøy 2003, 2006; Zbikowski 2002; Adlington 2003; Brower 2000; Larson 2012; Cox 2001; Leman 2008; Klemmer, Hartmann and Takayama 2006), and HCI (Imaz and Benyon 2007; Hurtienne 2009; Waterworth and Riva 2014; Bødker and Klokmose 2016). Recently, a number of auditory display researchers have begun to apply principles from embodied cognition to auditory display design (Diniz, Deweppe, Demey and Leman 2010, 2012; Dyer, Stapleton and Rodger 2015, 2017; Verona and Peres 2017).

An influential strand within contemporary embodied cognition research is represented in the interrelated theories of *image schemata*, *conceptual metaphors*, and *conceptual blending*, which relate to structural and formal models of how more abstract, logical, or propositional thought may be explained using embodied concepts.

> *Image schemata*, introduced by Mark Johnson (1987), can be conceptualized as basic building blocks of propositional or relational thought which are derived from physical gestures: commonly shared gestalt patterns of embodied experience

derived from sensorimotor experience, providing a commonly shared frame for organizing and enacting meaning and logical consistency to the chaotic patterns of raw perception prior to and independent of conceptualization. As such they provide the basic cognitive building blocks upon which meaning-making, language, reasoning, and imagination are erected.

Conceptual metaphor was introduced by George Lakoff and Mark Johnson (1980). It is another key embodied cognition theory. Its basic premise is that metaphor is a fundamental cognitive process and that humans make sense of new experiences and concepts using previous experiences and concepts as a frame of reference. A classic example is the "love is a journey" metaphor in which one frames love as a journey, allowing the listener to understand and reason about romantic relationships, drawing upon the concepts and logical structure associated with journeys. As such, a conceptual metaphor is a frame-to-frame mapping "with the roles of the source frame mapping to corresponding roles in the target frame" (Lakoff 2012). The theory postulates that the ultimate ground of all metaphors and frames is found in the image schemata of everyday physical experience.

Conceptual blending, introduced by Gilles Fauconnier and Mark Turner in 2002, involves "a blending of older concepts to give rise to new emergent properties" (Imaz and Benyon 2007). A conceptual blend involves the integration of two familiar concepts to create a novel concept which contains properties that were not present in either of the two concepts in isolation. The mythical concepts of the Pegasus and the Centaur have been described as blends between the concepts of bird and horse and man and horse, respectively (Martinez et al. 2012). Kendall's (2014) *feeling blend*, discussed earlier, describes the emergence of novel emotions, meanings, and affective states in electroacoustic music through the blending of familiar everyday sonic materials. One possible fruitful approach to sonic information design, which we wish to highlight here, is defined in Imaz and Benyon's (2007) *Designing with Blends.* They describe and advocate an approach to HCI design in which systems are analyzed and conceptualized in terms of image schemata, conceptual metaphors, and blends. The design discussed in the following sections is informed by this approach.

Embodied and Aesthetic Mapping Strategies in Data–driven Music Composition

Sonic information design, as noted earlier, is the application of design approaches to choices of sonification mappings, including a focus on relationships between "form, function and content" and user experience aspects, including accessibility and aesthetic and affective aspects (Barrass and Worrall 2016). As embodied cognition is, in part, a response to the symbol grounding problem, it could provide an important framework for sonic information design, addressing relationships between a sonification's form, its function, and its content. In addition, as embodied cognition has also been applied to music theory, it may also provide insights into aspects of aesthetics. It is in this context that Roddy and Bridges (2016) present and discuss the mapping strategy for "The Human Cost," a piece of data-driven music in which the mapping problem is addressed in the adoption of a design approach informed by embodied cognition principles.

AudioObject 2: "The Human Cost" (CLICK HERE)

Data–driven music composition is a subset of sonic information design which foregrounds aesthetic factors in a sonification with the aim of sustaining a listener's engagement. The concern for aesthetic factors in sound mappings may also encourage a listening strategy which prioritizes a search for correlation and causality within and between the different elements of the sonification. "The Human Cost" uses socio-economic data sets from the period preceding and following Ireland's post–2008 economic crash and recession. The piece is informed by Michael White's (2003) observation that we use the notion of a living organism as a conceptual metaphor for the economy. GNP is mapped to control a parameterized heartbeat sound, providing a rhythmic grounding for the piece. Deprivation, unemployment, and emigration are mapped to control parameters of three synthesized vocal gestures, created in CSound using FOF synthesis, a hybrid of granular and formant synthesis techniques (Clarke 1992). The data is mapped so that the leading voice (representing emigration data) takes the foreground, while the other two voices (deprivation and unemployment) provide a sonic backdrop. Data is mapped to control the pitch vowel shape in each vocal gesture so that, as the economy worsens, the open vowel sounds shift to closed vowel sounds, and pitch increases to communicate a sense of tension, providing an embodied association through the corresponding increased tension in the throat and facial musculature with closed/higher vowel sounds such as "e" and "i" (Durand 2005).

From a culturally–specific perspective, this is informed by a similar approach to the structure of pitch and prosody found in old Irish laments, a type of song sung at a *wake*, a social gathering which was often held to honor either a deceased relative or a relative who was emigrating with no prospect of return. The backing vocal sounds move around the stereo stage. As the economic data worsens, the speed of this movement increases. The piece adopts the concept of the lament as a conceptual metaphor for the data represented, utilizing synthesis parameters to evoke vocal emphasis and stress patterns which are similar to the pitch and vowel contours found in laments. Furthermore, for narrative purposes, the piece is broken into two sections. The first section is marked by dynamic filtering of the spectral content to alter the timbre so that it sounds more diffuse and "dream-like." This filtering is no longer present by the halfway point, as the 2009 data is heard. This aesthetic and narrative effect is intended to reference the painful realization, in the years directly after the financial crash, that the dream-like optimism and unrestrained growth of the "Celtic Tiger Era" was now a thing of the past.

AudioObject 3: "The Good Ship Hibernia and the Hole in the Bottom of the World" (CLICK HERE)

Roddy (2017) explores another embodied cognition approach to representing data from the Irish financial crash and recession in the data–driven composition "The Good Ship Hibernia and the Hole in the Bottom of the World." This piece makes use of soundscape recordings which are mapped to represent Irish GDP growth rate from 1979 to 2013. The piece is structured using the conceptual metaphor of a maritime journey where "smooth sailing" and "good weather" represent "good times" and "rough seas," and "bad weather" represents "bad times," a conceptual metaphor first discovered and studied by Izabela Zołnowska (2011). The piece is further structured on the basis of Johnson's (1987) *balance schema* in so far as data is communicated as a function of the balance between two soundscape elements in the piece. This balancing was achieved by simple amplitude mapping. Harmonic material, consisting of an improvised guitar performance in response to the shifting soundscape of the sea journey, is also heard throughout the piece. There are two distinct forms of harmonic material present a foreground melodic component and a background chordal accompaniment. The individual notes and chords are not directly determined by the data but are rather an interpretative response to the shifting soundscape. This was intended to provide a background context against which the changes in GDP might be rendered more obvious. The perceived audio fidelity, salience, and timbral character of the improvised material is also determined by the GDP data, with low GDP mapping to a noisy timbre and loss of amplitude (so that the harmonic material is overcome by the sounds of the storm). The piece was composed as a conceptual blend where the maritime weather metaphor provided the framing structure and the data was mapped to determine how the piece unfolds. The improvised harmonic material was intended to provide a baseline against which changes in the soundscape could be interpreted. This approach is illustrated here.

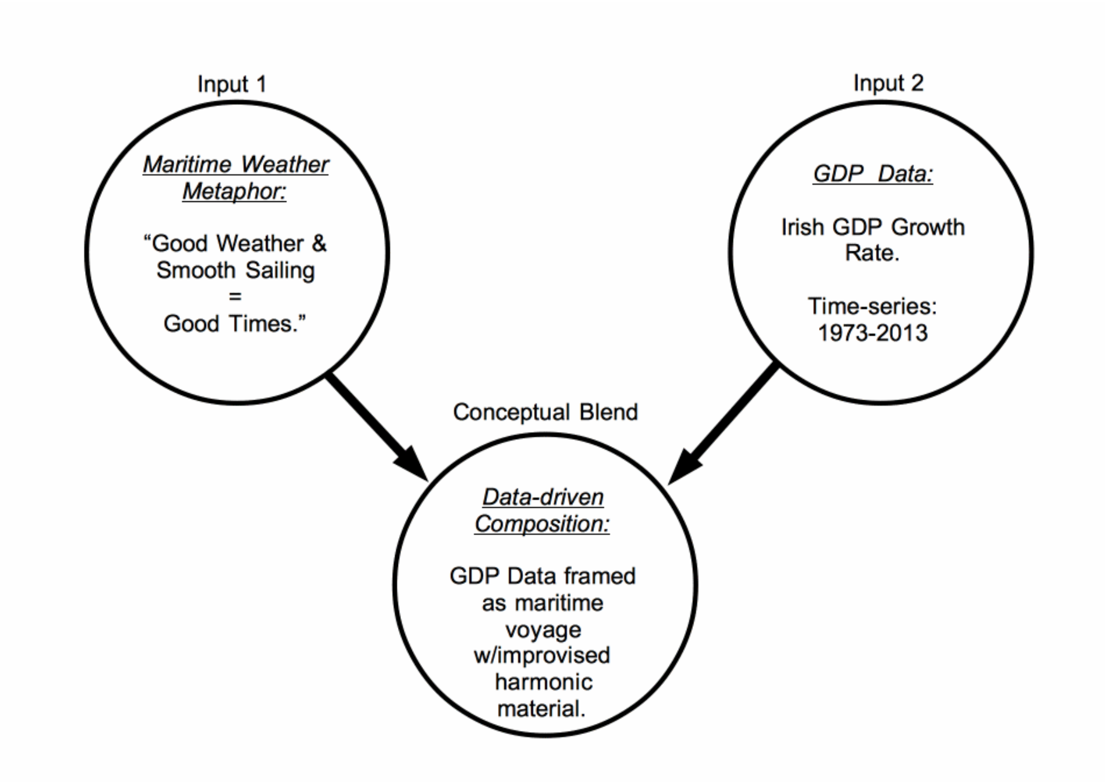


Figure 1: "The Good Ship Hibernia"

A Proposed Embodied Mapping Strategy for IoT Network Monitoring

In order to demonstrate how some of the parameters and approaches discussed thus far in data-driven music might be applied in a sonic information design context, we will now consider a recently devised mapping strategy for live monitoring of traffic activity in a large-scale internet of things (IoT) network.

Whilst Worrall (2015) has demonstrated how sonification could be successfully deployed for representing metadata in an organization's own internal network, there are a different set of factors at play in the sonification of IoT data. An IoT network is comprised of physical objects, machines and devices that have been enabled for Internet connectivity. The mapping strategy presented here is intended for use with the Pervasive Nation, Ireland's national-scale IoT test-bed. The network consists of a diverse set of devices spread across the country, monitoring everything from water levels for flood detection to agricultural applications. These devices relay data through a system of gateways (or base stations) spread around the country. A log of all messages shared across the network is maintained by the network server. Pervasive Nation is a Low-Power Wide-Area Network (LPWAN), which means that it operates at low throughput, processing very few data packets when compared to a modern cellular network. This is more than enough to support messages from IoT devices in which transfer speeds usually fall below 27kb per second (Adelantado, Vilajosana, Tuset-Peiro, Martinez, Melia-Segui and Watteyne 2017).

As a result, there are no continuous variables with IoT network data of this nature. However, given the number of devices online, the data can still become quite dense and complex.

IoT networks are generally concerned with *machine to machine* (M2M) communication and, as such, device payloads (sensor measurements) are encrypted and inaccessible. Network monitoring practices tend to focus on maintaining the overall "health" and integrity of the network. To this end there are a number of behaviors that need to be detected: devices that continually fail to connect to the network server, devices that exhibit irregular behavior (e.g. erratic switching across frequency positions, constantly reconnecting to the network server), and devices with low signal strength or bad signal to noise ratio. Monitoring for these anomalies generally consists of visually scanning large tables which describe the activity of each node over some predefined time period. If a problem is identified, a visual representation of the data from individual devices can be accessed. Given the large amount of data involved, this process can be slow and inefficient. Furthermore, this is all carried out after the fact, with the result that problems in the network can continue undetected for some time. These issues could be addressed by designing an auditory display to represent the data with sound in real-time.

> The future is not going to be people talking to people; it's not going to be people accessing information. It's going to be about using machines to talk to other machines on behalf of people. (Tan and Wang 2010)

A recurrent metaphor employed across the IoT literature to describe M2M communication, reflected in the above quote from Tan and Wang, is that of "machines talking to each other." Drawing from Imaz and Benyon's (2007) recommendations to structure HCI design on the basis of conceptual metaphors and blends, this metaphor can be adopted as a frame of reference for our auditory display design. The auditory display can be conceptualized as a blend between the data and sound, framed in terms of a conversation between machines (see figure 2). Designing this interpretation of M2M communication into our auditory display might help to make it more intelligible to the listener and support them in understanding and reasoning about the data. Other relevant work in fields related to embodied cognition can be called upon throughout the design process to further inform and refine design choices.

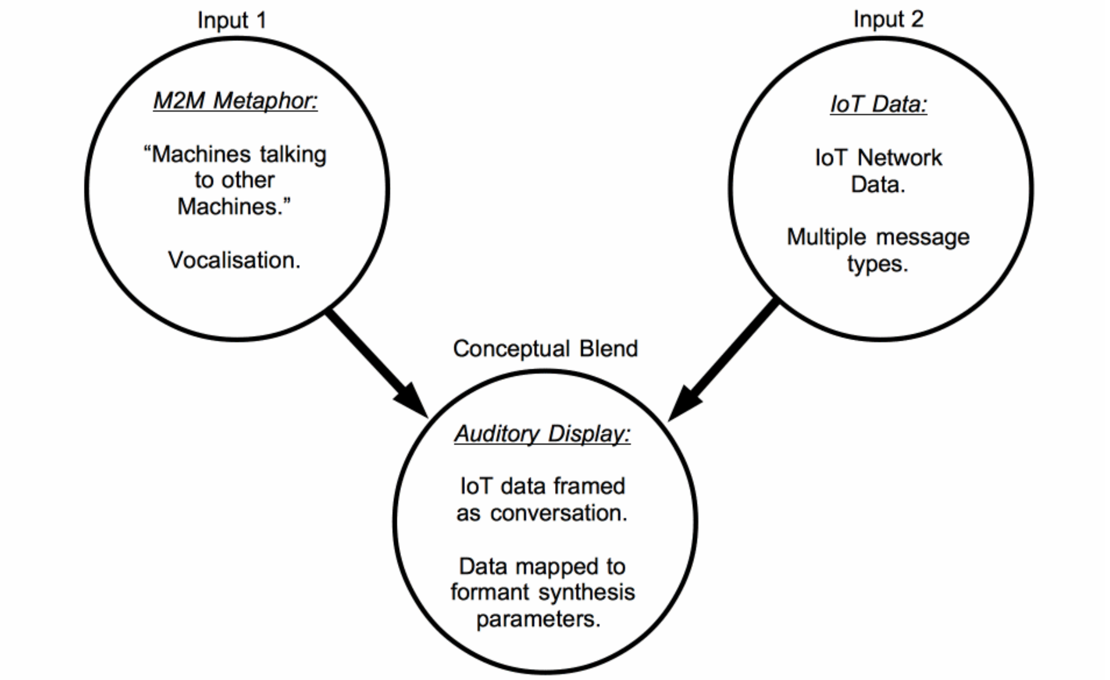


Figure 2: M2M Communication as Machines Talking to One Another

Formant synthesis (see figure 3) has been applied effectively in a number of auditory display contexts (Hermann et al. 2006; Chafe et al. 2013). This synthesis approach creates speech-like sounds using a source filter model in which the source simulates the action of human vocal folds, and the filter models the resonances of the vocal tract (Smith 2010). It was also the basis of the synthesis method used to create vocal sounds in "The Human Cost." Vocal sounds can communicate rich information to a listener because the auditory system has evolved to interpret and extract information from the human voice (Armstrong, Stokoe and Wilcox 1995; Armstrong 2002; Gentilucci and Corballis 2006; Fogassi and Ferrari 2007). This capability extends beyond language to the highly communicative prosodic dimensions of human speech (Hirschberg 2002; Juslin and Laukka 2003; Grieser and Kuhl 1988; Grandjean et al. 2005; Elordieta and Prieto 2012; Alba-Ferrara, Hausmann, Mitchell and Weis 2011).

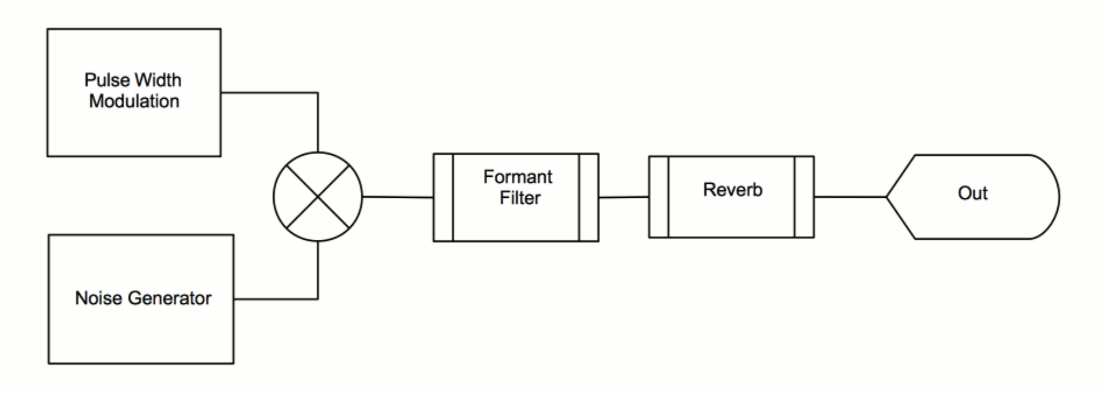
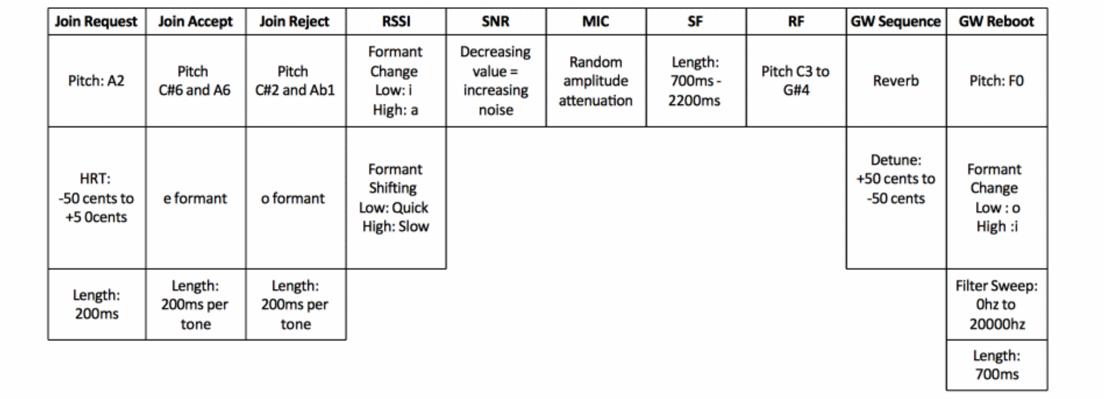


Figure 3: Formant Synthesis

The mapping strategy presented in table 1 was implemented in the Reaktor 5 audio programming environment using formant synthesis techniques. The mapping strategy was informed by the metaphor of M2M communication discussed previously.



Join Request	Join Accept	Join Reject	RSSI	SNR	MIC	SF	RF	GW Sequence	GW Reboot
Pitch: A2	Pitch C#6 and A6	Pitch C#2 and Ab1	Formant Change Low: i High: a	Decreasing value = increasing noise	Random amplitude attenuation	Length: 700ms - 2200ms	Pitch C3 to G#4	Reverb	Pitch: F0
HRT: -50 cents to +5 0cents	e formant	o formant	Formant Shifting Low: Quick High: Slow					Detune: +50 cents to -50 cents	Formant Change Low : o High :i
Length: 200ms	Length: 200ms per tone	Length: 200ms per tone							Filter Sweep: 0hz to 20000hz
									Length: 700ms

Table 1: Proposed Mapping Strategy for IoT Network Monitoring

There are a number of key message types relevant to the IoT network monitoring in the context of the Pervasive Nation network. Join requests are messages sent by devices when they are ready to share data across the network. They are met with an accept or reject message by the network server. To follow our "conversation" metaphor, we can adopt a call–and–response structure to represent this data. The application of an "a" vowel formant profile lends them a speech–like timbre. Each request message is 200ms in length. They move along a frequency contour from +50 cents above A4 to -50 cents below A4. This increase in pitch is a culturally dependent strategy (from variants of the English language) intended to simulate the high rising terminal (HRT) wherein speakers modulate their intonation so that the fundamental frequency of their voice rises in pitch from the beginning of the final accented syllable, especially when posing a question. Because the sounds involved are much shorter in length and different in nature to a full sentence, our mapping exaggerates the HRT by beginning to rise at the very beginning of the sound for maximum effect.

AudioObject 4: Join Request Message (CLICK HERE)

The *response messages* are designed to sound more machine-like in origin. They have a two-part structure, moving from C#2 to a Low A 1 for a reject message, while the *accept messages* move from a C#4 to a high A4.

AudioObject 5: Reject Message (CLICK HERE)

AudioObject 6: Accept Message (CLICK HERE)

Each tone is roughly 200ms in length. The vowel formant profile for the reject messages is an "o," intended to sound similar to "No," while the accept messages have an "e" formant profile, intended to sound similar to a "Yes". These mappings are influenced by Candace Brower's (2000) cognitive theory of meaning in music. She argues that on the basis of the "image schemas that lend coherence to our bodily experience," listeners experience a range of melodic "forces." One of these is a sense of tonal attraction, whereby a series of notes is experienced as achieving a "stable" state when it reaches its tonic, the harmonic center of attraction. Outside the tonic there are varying degrees of instability. In the above mapping, where the key is established in A major, the sound for the accept message resolves at the tonic, becoming stable, while the reject sound "misses" the tonic, landing on an unstable A .

Gateway status requests are sent to gateways to make sure they are online and functioning correctly. If the gateway is not in working order, it can be rebooted. In this mapping strategy, gateway reboots are signified by sweeping a vowel formant filter across the sound signal. The sound is 700ms in length and pitched to an F0. The data is redundantly mapped to modulate both the cutoff frequency and the vowel shape, which moves from an "i" when the filter is high to an "a" as it closes. The sweep moves down the frequency spectrum before coming back up, which is intended to simulate the process of a reboot where the system first closes down and then boots back up.

AudioObject 7: GW Reboot (CLICK HERE)

This pattern of cyclical closing down/booting up is informed by two image schemata, described by Johnson (1987) as the cycle schema, the topological pattern underlying experiences of cycles, and the up-down (verticality) schema, the topological pattern underlying experience of movement along a vertical axis, with different positions on the vertical axis corresponding to stability or instability. In this case, the higher/filter open position (in which the network is functioning normally or has booted back up) is taken to be the stable, nominal one (related to a metaphor of the network "standing upright").

The device data within this network is complex, consisting of the encrypted payload data from the device along with twenty or more additional parameters, depending on the number of gateways complicit in relaying the data. Fortunately for the present purposes, there are only a few messages relevant to the basic monitoring of the overall health of the network. The message integrity code (MIC) is used to authenticate the message; a MIC code that fails to validate can indicate a security problem. The Received Signal Strength Indicator (RSSI) and the signal and Signal to Noise Ratio (SNR) are somewhat self–explanatory, and frequency refers to the frequency band on which the message is received. Each message also contains information about the Spreading Factor (SF), an important variable, alongside bandwidth, in the determination of data rate: the rate at which devices transmit data. The SF determines the amount of time a device is allotted to send its message across the network. The further a device is from a gateway, the larger the SF, along a scale from 7 to 12. Radio spectrum is heavily regulated (Levin 2013/1971), and in Europe the total amount of "time on air" a transmission is allowed to take is regulated to a 1% device duty cycle per channel. For example, if a device sends data for 1 second every 100 seconds, it has a duty cycle of 1%. Radio frequency (RF) and bandwidth are also regulated, and in Europe LoRaWAN networks operate in the RF range of 868-870MHz with a channel bandwidth of 125-250khz. Legally, all nodes and gateways must be compliant with duty cycle regulations. They are thus quite important factors to monitor. Gateways and nodes, which exhibit suspect patterns of activity, need to be easily identifiable. Each of these messages also comes with information about the sequence of gateways that have relayed that particular message to the server. Pertinent information here includes MIC Code, SNR, RSSI, RF, and SF. In designing a mapping strategy for these messages, we return to our conceptual metaphor for M2M communication. Each message is broken into two "sections": the first section contains a single phrase which pertains to the node data while the second section will contain phrases relating to each of the gateways that the message has travelled through.

SNR represents a continuous variable that can be simulated in a direct manner with the addition of noise to the original signal. As SNR decreases the amplitude level of noise decreases, and as it increases the level of noise increases.

AudioObject 8: SNR Lo (CLICK HERE)

AudioObject 9: SNR Hi (CLICK HERE)

RSSI is also a continuous signal that, in this case, can be mapped sonically using vowel shapes and behaviors. This mapping strategy draws again from our conceptual metaphor for M2M as a conversation between machines. It is intended to represent strong RSSI with controlled and relaxed speech-like patterns and weak RSSI with chaotic and tense patterns.

AudioObject 10: RSSI Strong (CLICK HERE)

AudioObject 11: RSSI Weak (CLICK HERE)

The generation of an "i" vowel requires more tension in the throat and facial musculature of the speaker than the more relaxed "a" (Durand 2005), hence a straightforward conceptual link can be made between controlled, relaxed sounding speech patterns and stability, and chaotic, tense patterns of speech and instability. When RSSI is at its strongest, the vowel formant position is constant and has an “a” profile; when it becomes weaker, the vowel formant profile begins to transform into an “i,” and the position of a vowel filter rapidly shifts in a random fashion across a range of ± 12 semitones.

The MIC code is evaluated to test message integrity. A MIC code which fails verification can be perceptualized as an error in the message. Drawing from sonic representations of failure explored in our earlier discussion on glitching, the amplitude of a sound signal can be modulated by a randomized square wave generator so that it changes amplitude in a random and abrupt manner, switching itself off completely for short periods.

AudioObject 12: Bad MIC (CLICK HERE)

RF can be also be mapped in quite a direct manner to the fundamental frequency of the voice, representing each of the twenty-one possible frequency bands between 868–870MHz (i.e. 868.0, 868.1, 868.2, 868.3, etc.). This data is mapped to a chromatic scale, extending from C3 to G#4, keeping it distinct from the other harmonic material used.

AudioObject 13: RF Lo (CLICK HERE)

AudioObject 14: RF Hi (CLICK HERE)

SF also contains 6 levels: SF7 to SF12. Given that the spread factor is a measure of the length of time taken to send a message, we created another more direct mapping strategy. The length of the sound is controlled to reflect SF: longer SF factors correspond to longer phrases. The Just Noticeable Difference (JND) for a tempo change in speech is estimated at roughly 5%, which suggests that a listener will detect a change between a 500ms vocalization and a 525ms vocalization (Quené 2007). The timings used here fall well within those limitations. SF7 is assigned a length of 700ms, and each following SF is incremented by 300ms, up to 2.2 seconds for SF12.

AudioObject 15: SF 7 (CLICK HERE)

AudioObject 16: SF 12 (CLICK HERE)

This increment was chosen to support the listener in distinguishing timings while adhering to the JND for tempo in speech and not exceeding the limits of echoic memory, roughly 4 seconds (Darwin, Turvey and Crowder 1972).

The second section of each message, which represents the gateway data, uses the same mapping strategy as the first phrase with the addition of a descending pitch contour and reverb. The descending contour is intended to help listeners discern gateway messages from device messages, while reverb indicates the position of the gateway in the original relay sequence. Reverb tails decay at 10ms to avoid interfering with other messages. The first gateway is represented with 100% wet level reverb, while the most recent are represented with no reverb.

AudioObject 17: GW Far (CLICK HERE)

AudioObject 18: GW Close (CLICK HERE)

Furthermore, these messages have a descending pitch contour from +50 cents above their designated pitch level at the beginning of the message to -50 cents below at the end. This is to distinguish them from the other message types. The entire mapping strategy is formalized in Table 1 (see above).

Conclusion

The above mapping strategy is intended to give listeners an overall sense of the health of the Pervasive Nation network at any given time. As such it is designed to help the listener to easily determine normal (read "healthy") patterns of activity from abnormal patterns of activity.

AudioObject 19: Good Network (CLICK HERE)

AudioObject 20: Bad Network (CLICK HERE)

As the prevalence of noise increases, SNR ratios decrease for more and more nodes. As reverb increases, nodes are transmitting their payloads through an increased number of gateways, indicating connectivity problems. High SF factors, indicated by long message lengths, suggest the same problem. As pitch tends towards randomness, nodes are displaying increasingly erratic patterns of RF switching. The increased "glitching" of messages indicates bad MIC codes, suggesting possible security issues. Continual reboot sequences indicate problems with gateways, and continual rejection messages indicate problems with devices attempting to connect to the network. The mapping strategy aims to render each of these problematic patterns of activity understandable to a listener by using a relevant conceptual metaphor – machines talking to other machines – to frame the auditory display in terms of vocal communication. The auditory display is thus less arbitrary for the average listener skilled in the interpretation of patterns in speech vocal communication.

Conceptual blending and conceptual metaphor, as applied to design in HCI by Imaz and Benyon (2007), provide overarching guidance for the IoT mapping strategy presented above. This approach helps to address the mapping problem by advancing design frameworks which result in less arbitrary and more conceptually relevant mapping strategies. We believe that this approach provides a meaningful grounding that prevents sonification and auditory display solutions from becoming so arbitrary that they are difficult to interpret. The example presented here is currently under active development, and future empirical testing will be used to guide further refinements. It is presented here as a demonstration of how principles from the field of embodied cognition (in particular, conceptual metaphor, image schemata, and conceptual blending theories) might be applied to sonic information design.

To summarize, the application of an embodied sonic information design process, such as the present one, begins with a consideration of the metaphors used to discuss and reason about the domain under study. The chosen metaphor should result in the use of a recognizable sonic referent that is compatible with and effectively represents the data set. The conceptual blend is then considered as an aid in thinking about how features in the data space might be mapped to features in the metaphor space. Consideration is finally given to the technical implementation (i.e. parametric mappings) so as to flesh out the general approach to the mapping strategy.

One shortcoming of this approach is that there may not always be an obvious or dominant metaphor to draw upon in representing the data source. For example, different aspects of a single phenomenon might be conceptualized using a number of different metaphors, and this in turn would require a more complex data to sound mapping strategy. Furthermore, some metaphors will have no obvious sonic associations and metaphors can change between languages and cultures, making this approach culture-specific. Another limiting factor at play here is the level of difficulty in synthesizing and controlling the sounds suggested by the guiding metaphors. Whilst our example was designed to exploit established techniques for synthesizing human vocal sounds, such straightforward approaches to sound synthesis are not feasible in every case. Therefore, the approach presented here cannot act as a universal solution for designing meaningful data to sound mapping strategies. We suggest instead that designers consider data–to–sound mapping strategies informed by embodied cognition principles. Image schemata, conceptual metaphors and conceptual blends open up radical new ways for thinking about sound and can help designers to create better mapping strategies.

In the context of sonic information design, considering the representation of data with sound through the lens of conceptual metaphors, conceptual blends, and image schemata can open up possibilities for the use of new sonification parameters beyond pitch, duration, and timbre. In the examples explored here, prosodic features, environmental sounds, perceived audio fidelity, and formant profiles become important parameters for representing data. While these might not exemplify groundbreaking new parameter sets in and of themselves, as important as the question of *what* parameters should be used is the question of *how* they should be applied. This is addressed in the example of the IoT network where the framing metaphor of M2M communication acts as a guide not only for *what* parameters should be used (speech–like parameters), but also *how* they should be used, namely as organized around logical rules of conversation. This is also reflected in the structure of "The Good Ship Hibernia and the Hole in the Bottom of the World," where the mapping strategy is largely defined by a conceptual metaphor. The conceptual metaphor offers a mechanism for reducing the perceived arbitrariness in a data to sound mapping strategy by grounding the design in a familiar and interpretable domain of experience.

If the mapping problem can be addressed, as we in fact believe possible, by reducing the arbitrariness in a data–to–sound mapping strategy by considering it using the framework of conceptual metaphors, then how is this to be achieved when the data represented has no clear sonic referent and no implicit link to any particular sound source or process? We argue that, as demonstrated in the previous examples, designing a mapping strategy using sound processes that can be related to the data (or data source) through shared image schemata, conceptual metaphors, and conceptual blends can help to reduce arbitrariness in the sonification's framing, allowing the listener to consider the data in terms of other (similarly–structured) domains with which they are familiar. In this context, even relatively generic embodied metaphorical associations (the tension/relaxation axis of the vowel sounds and the verticality schema of the "reboot" sound gesture in the Pervasive Nation IoT mapping) may provide a sufficient element of "grounding," based on familiar embodied experiences, when encountering an unfamiliar or relatively abstract data domain.

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