TITLE: Mapping for Meaning: the Embodied Sonification Listening Model and its Implications for the Mapping Problem in Sonic Information Design.

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1 Introduction: Sonic Information Design and the Mapping Problem

Sonic information design refers to the application of design research, as defined by Faste and Faste [1], to *sonification*, an auditory display technique in which data is mapped to non-speech sound to communicate information about its source to a listener. A key challenge in sonification is *the mapping problem*, first introduced by Flowers [2], who stated that meaningful information does not necessarily arise when complex data sets are submitted to sonification. In fact, due to cognitive–perceptual dimensional entanglement (such as the ecological intermingling of what had traditionally been considered to be discrete auditory dimensions, e.g. pitch and amplitude), this may rarely be the case [3]. Similar concerns have been raised within sound studies and practices, notably Truax [4], who criticised the overreliance on the ‘energy transfer model’ of sound (asserting that a psychophysical approach does not account for many aspects of sound’s communicative affordances), O’Callaghan [5], a philosopher of sound, and sound artists and sound studies theorists Kahn [6], LaBelle [7] and Cox [8]. The relationship between arts practices and the sonification mapping problem is further discussed by Roddy and Bridges [9,10]. From a design–centered perspective Worrall [3,11,12] presents a similar argument: that the software tools used in sonification parameterise sound using the basic parameters of Western tonal music (pitch, duration, loudness and timbral identity/difference), an example being the *PMSon* mapping of pitch, loudness, duration and timbre to unique data [13]). These parameters, Worall argues, fail to account for the embodied aspects of sound and sound production, which he sees as critical to meaning–making in the context of sonification.

From this perspective, then, the mapping problem becomes a design challenge that must be addressed anew whenever one attempts to create a sonification. The sonic parameters we choose when designing a sonification determine how well the sonification communicates information and how well the listener can interpret it. As Ryle [14], Searle [15] and Harnad [16] have variously shown, meaning cannot be generated for a listener without providing sufficient context because, as Dreyfus [17] and Polyani [18] point out, objects of meaning require a background context against which their meaning can be assigned, and, as such, auditory display solutions must be designed with this critically important constraint in mind. We argue that the mapping problem can be addressed by adopting models of sound which draw from contemporary theories of embodied cognition to refine the more traditional perspectives of psychoacoustics and formalist/computationalist models of cognition. This, in turns may provide designers with new higher-level parameter mapping strategies that allow them to map data in ways may be better suited to providing sufficient context by which the symbolic component sounds of sonification might become meaningful and informative to a listener.

2 Embodied Cognition Guiding Sonic Information Design

Embodied cognition researchers approach the problem of how to describe cognitive processes and conceptual systems from the perspectives of the physical and perceptual affordances of the human body [19]. To this end, the field has introduced a number of theoretical cognitive faculties that complement our traditional computationally–based understanding of cognitive faculties. *Image schema theory* [20] posits that the building blocks of thought are derived from frequently–encountered structures within sensorimotor experience; according to this theory, we draw upon image schema to lend structure to both our thinking and perceptual activities. One way in which we may do this is through conceptual metaphors. A *conceptual metaphor* [21] is the cognitive process by which image schemas in a familiar domain of thought are leveraged to make sense of an abstract domain of thought. A common example is highlighted in the phrase "Love is a Journey". In that phrase the familiar logical structure of a 'journey' is mapped to frame the more abstract domain of 'love'. Inferences can then be made about the concept of 'love' on the basis of this logical frame. For example, it can be inferred that, just like a journey, love has a beginning, middle and end and is typified by forward motion along that linear path. The image schema involved here is the *SOURCE-PATH-GOAL* schema [20]. In addition to providing a structure for logical inference, conceptual metaphors, within this theory, are also assumed to structure experience on the perceptual and sensorimotor levels. Here they frame an unfamiliar perceptual or sensorimotor domain in terms of a more familiar one. For example the desktop metaphor in human computer interaction (HCI) frames what would otherwise be an unfamiliar and abstract virtual space in terms of an office desk space. This structures how a user understands, reasons about and interacts with the virtual space.

Conceptual blending is another process by which familiar conceptual content is integrated to generate new hybrid conceptual content [22]. Conceptual blending and its relationship to sonic information design is explored elsewhere [9], and design approaches informed by embodied cognition have been successfully applied in the context of HCI [23, 24, 25, 26] In a similar fashion, embodied approaches to interactive sonic information design have been developed, informed by Dourish's [27] introduction of the concept of embodied interaction; see (Serafin *et al*., 2011). In recent years, more broadly embodied models of sound have become increasingly prevalent in sonification. Diniz *et al*. [28, 29] apply principles from embodied music cognition to the design of a multilevel interactive sonification and Dyer *et al*. [30, 31], drawing from similar principles in the design of sonification mapping strategies for motor skill learning. Peres *et al*. [32] explore embodied approaches to sonification in the design of a real-time sonification for surface electromyography (EMG).

Whilst these approaches have provided productive connections between theories of embodied cognition and mapping strategies, we argue that a consideration of embodied perspectives drawn from music theories and practices may be helpful in further extending sonic information design. There is an extensive body of literature which has investigated the structures of Western tonal music in terms of embodied image schemas, conceptual metaphors and blending [33, 34, 35, 36, 37]. In particular, these models provide perspectives on the *temporal dynamics* of listening via embodied metaphors. A crucial factor for our present purposes is that the strategies which underpin music's evocation of apparent causality may inform more complex and dynamic sonic information design approaches. Beyond pitch–based musical structures, a number of researchers within the field of electroacoustic music have investigated embodied theories of timbre and sound–structural organisation. Kendall [38, 39] describes electroacoustic music on the basis of image schemas, conceptual metaphors and conceptual blending, and Graham and Bridges [40, 41] describe how Smalley's theory of spectromorphology [42, 43], a model of how sound textures and 'gestures' within electroacoustic music may relate to one another, can be seen as compatible with image schema and conceptual metaphor theory. Similar work by Godøy [44] highlights the implied embodied underpinnings of Pierre Schaeffer's concept of the sound object (itself an antecedent of Smalley's theories [42, 43]). Further work in this domain [45] argues that an influential three–dimensional parametric model of timbral relationships—[46], with primary dimensions for spectral centroid, synchrony of start times, and presence/absence of attack transients—is compatible with dynamics drawn from embodied image schema and conceptual metaphor theory (verticality schemas, tension/projection/linearity dynamics of movement and spatial presence/diffusion).

3.1 Theoretical Frameworks and the Embodied Sonification Listening Model

The mapping problem could be said to arise when we fail to account for the idiosyncrasies of human perception and cognition. Sonification designers are broadly aware that they must work within the limits of human perception and that psychoacoustic constraints have a very large impact on how we represent data to a listener using sound. Furthermore, beyond the psychophysics of perception, we must account for the cognitive constraints of the listener in terms of working memory and cognitive load, etc. Embodied cognition suggests that there is both another layer of constraints for which we must account and another layer of possibilities that we can exploit in the design of effective sonification and auditory display solutions. The theory posits that we think, reason and understand, at least in part, on the basis of image schemata, conceptual metaphors and conceptual blends and as such we must account for them in our design solutions. The problem is that we do not yet have the theoretical tools with which to analyse, discuss and address these in the context of sonification listening. We present one such theoretical model below.

The *Embodied Sonification Listening Model* (ESLM) aims to describe the role of conceptual metaphor in the listeners' interpretation of a sonification. A model of the embodied meaning-making faculties active in sonification listening might help to guide the design of communicatively effective sonification mapping strategies.

Vickers and Hogg [47] make a similar argument: that the modes of listening proposed by thinkers like Schaeffer [48], Chion [49], and Gaver [50] are insufficient in describing sonification listening, and calls for a new paradigm that is exclusively focused on describing the richness and diversity of the sonification listening experience.

The Embodied Sonification Listening Model (Figure 1) was originally introduced by Roddy [51] but is formalised and described in greater detail here. It uses Lakoff and Johnson's [21] conceptual metaphor theory to provide a theoretical description of how meaning might emerge in sonification listening, from an embodied perspective. Typically, a listener does not have direct access to the data or the original data source being represented during sonification listening. As a result, they must construct an imaginary model of the data on the basis of the cues provided by the sonification. In the same way that a sonification designer creates a mapping strategy from data to sound, the listener must create their own cognitive–perceptual mapping strategy from that sound back to an imagined data source. The embodied sonification listening model provides a theoretical explanation of the embodied meaning–making faculties involved in this process. It relies on the embodied meaning–making faculties discussed previously to describe the sonification listening process. The ESLM involves two novel *conceptual evaluation* schemes: the *embodied sonic dimension* and *embodied sonic complex*. These were devised to account for traditional dimensions of sound such as pitch, duration, amplitude and timbre, and also to account for the dimensionality of sonic aesthetics, and their role in framing and associated meaning–making in the context of sonic information design. These dimensions tend to be, generally speaking, too complex to be adequately described in terms of simple interactions of the traditional dimensions of pitch, duration, amplitude and timbre alone.

Examples of such dimensions might be a sense of narrative development over a sequence of sounds, felt emotional qualities conveyed by a sound, such as a sense of foreboding, tension as communicated in prosodic information of human vocalisations or the unique sense of place established by a specific soundscape. Smalley's spectromorphology framework [42,43], mentioned earlier, also describes a number of similar sonic dimensions such as motion and growth processes, behaviours and structural functions.

These conceptual evaluation schemes are also intended to address the perceived need for dedicated theoretical descriptors for sonification [52]. (They were motivated by Koestler's concepts of the *holon* and the *holarchy* [53], a holon being something which is simultaneously a whole and a part of a larger whole while a holarchy is a hierarchical arrangement of individual holons). An embodied sonic dimension is defined here as any individual sonic aspect that a listener can attend to as a meaningful perceptual unit which remains identifiable while evolving in time along a continuous bi–polar axis. An embodied complex is defined as any perceptual grouping that contains multiple embodied sonic dimensions and can also be identified by a listener as a meaningful perceptual unit.

$$f(t)\text{: } ((\mathrm{sC} \rightarrow_{\mathrm{m1}} \mathrm{dP}) + (\mathrm{sD} \rightarrow_{\mathrm{m2}} \mathrm{dM}))\mathrm{eK}$$

Formula 1. Formalization of the Embodied Sonification Listening Model

At a given time *t* a listener attending to a sonification *f(t)* will associate the sound they are hearing (the sonic complex sC), with the phenomenon of which they imagine the represented data to be a measurement (the data phenomenon dP). This constitutes the first metaphorical mapping (m1).

The second metaphorical mapping (m2) involves the association of changes along dimensions within the sonification (sonic dimension, sD) with changes in the original dataset (measurement dimension, dM). These mappings are further constrained and modulated by the listener's embodied knowledge, eK. This contains the listener's understanding of the sound, the data, any instructions or training they have received regarding the sonification and any associations, conscious or unconscious, the listener draws between or to these elements. More broadly it encompasses a listener's everyday knowledge of their physical, social and cultural environments. This knowledge determines the cognitive mapping strategy a listener employs to map the sound back to an imagined data source during sonification listening. (A more detailed description of how embodied knowledge mediates a listener's interpretation and understanding of a sound is presented by Kendall [38, 39].)

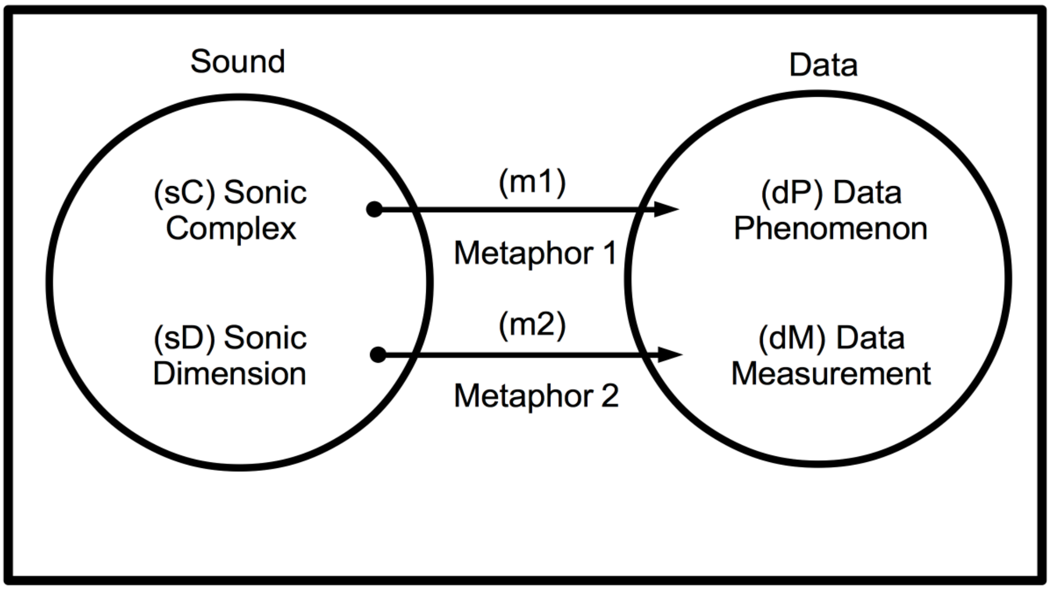

Figure 1. The Embodied Sonification Listening Model

As previously pointed out, there are two metaphorical mappings within the ESLM. In the first metaphorical mapping (m1) the listener maps, or identifies, the sonic complex with the source of the data. That is to say that they associate the sounds they are hearing with the source from which the original data was recorded or measured. In the second metaphorical mapping (m2), the listener maps or identifies changes in attributes of the sonic complex to the data set. This simply means that they associate changes in different attributes of the sound with changes in the data.

3.2 Applying the Embodied Sonification Listening Model

To better illustrate the operation of the ESLM let us consider a number of design strategies that a sonification designer can employ to present different kinds of data. For example considering a sonification developed for a flood monitoring and alert system the key data in question is water level. This is usually measured in meters and centimetres. For the sake of this illustrative example let's imagine that a designer chooses to represent this data using a pitch-mapped sine tone and that the polarity of the mapping is such that as the water level increases the pitch rises and as the water level falls the pitch falls too. This is a clear and direct mapping strategy.
In this context the sine tone is the *sonic complex* (sC) of the sonification. It acts as a metaphor (m1) for our *data phenomenon* (dP). In this case the data phenomenon (dP) is the 'water', the level of which has been measured and recorded in the dataset.

This representation or substitution of the water with the sine tone is our first metaphorical mapping (m1). The second metaphorical mapping (m2) is between the *sonic dimension* (sD) and the *data measurement*(dM). In this example our sonic dimension (sD) is pitch and our measurement dimension (dM) is water level as recorded in metres or centimetres in the dataset. In this example the designer has mapped increases in water level to increases in pitch, and *vice versa*. (Whilst they could have inverted the polarity and mapped increases in data value to decreases in pitch, the original mapping polarity is in line with common practice in pitch-mapping sonification, one reason for which will be discussed below).

Our model suggests that these mappings are mediated by the listeners' *previous embodied knowledge* (eK) and that generally speaking, listeners come to a sonification with their own unique and vast history of such knowledge (eK).
This raises some important additional issues:

(a) Which aspects of previous embodied knowledge do listeners draw upon when interpreting a sonification?
(b) How do we design a mapping strategy that a listener can understand on the basis of their previous embodied knowledge?

We suggest that designers focus on the data here, and choose the strategy that best reflects the real-world, physical behaviours of the data phenomenon *and* the data measurement. In doing so the designer is leveraging the listeners' previous embodied knowledge of the data being represented. In the example above, the data phenomenon is water and it is probably safe to assume that from previous experiences the average listener knows that when you add water to a vessel, the overall level of the water within the vessel 'rises'. The polarity of this 'mapping' is therefore grounded within our direct, real-world experience of water. On this basis we can reason that when a listener perceives a rising pitch contour in a sonification of water level data they will interpret it as a rise in water level.

We can approach a sonification of a phenomenon like wind in a similar manner. For example, consider a sonification where wind speed data is mapped to the control the cutoff frequency of a filtered white noise generator. The white noise in this example is the sonic complex (sC). This provides a metaphor (m1) for the original data phenomenon (dP), which is the wind. The cutoff of the filter is the sonic dimension (sD) and this in turn provides a metaphor (m2) for the data phenomenon which is the set of recorded changes in wind speed. Again, one might assume that, on the basis of past embodied knowledge (eK), an increase in cutoff frequency would be interpreted as an increase in wind speed. The reasoning here is that filtered white noise provides a good analogue for the sound of wind and increasing the cutoff increases the amount of perceptible activity in the frequency spectrum. As wind produces sound through friction when in contact with a surface, the higher the wind speed, the higher the frequency (e.g spectral centroid) of the resulting sound. As such, higher filter cutoff frequencies might coincide with higher wind speeds and *vice versa*, and the dimension and polarity of the sonic mapping is thus consistent with eK.

An interesting, but more demanding, example which nonetheless conforms to this model is the sonification of population data. Whilst still a measure of a physical phenomenon, population data (unless we are dealing with very small populations) is somewhat less immediately accessible than physical data like water levels and wind speed. However, if we consider a sonification where population data is mapped to control the number of individual grains in a grain cloud, the grain cloud (sC) becomes the metaphor (m1) for overall population (dP) and the density of the cloud (sD) becomes a metaphor (m2) for increases in the number of people in the population (dM). In this case, one might assume that on the basis of previous embodied knowledge (eK) increases in the density of the grain cloud would be interpreted as increases in the population number. The previous knowledge at play here can be quantified in terms of basic arithmetic or, from an embodied point of view, from simple everyday experience of adding and removing individual members from larger collections of physical objects; a conceptual metaphor of spatial *coverage* and *density versus sparseness*, which relates to Talmy's [54] 'states of consolidation' (whereby spatial coverage may be compact or diffuse). Thus, in this example, the mapping is informed by a familiar, real–world, physical model (in this case, the behaviour of crowds), but is reinforced with reference to a more generic conceptual metaphor of spatial coverage/density.

The key point here is to focus on various aspects of common physical experiences that we can assume a listener is familiar with when designing a mapping strategy, and, furthermore, to design mapping strategies that are congruent with these familiar embodied experiences based on simple, directly–observable physical relationships (the first two examples) and, potentially, their reinforcement by more generic spatial conceptual metaphors (the third example).

Metaphor 1 (m1)			**Metaphor 2(m2)**		
Sonic Complex (sC)		*Data Phenomenon (dP)*	*Sonic Dimension (sD)*		*Data Measurement (dM)*
Sine Tone	>>	Water	Pitch	>>	Water Level
Filtered White Noise	>>	Wind	Filter Cutoff Frequency	>>	Wind Speed
Grain Cloud	>>	Population	Grain Density	>>	Pop. Number
Heartbeat (sound)	>>	GDP	Heart/Pulse Rate	>>	GDP Changes

Table 1. Example mappings based on prior embodied knowledge (eK)

However, not all data have clear connections to physical experience. For example, consider changes in the gross domestic product (GDP) of a country. We cannot experience an economic phenomenon like GDP in the same direct manner that we can experience physical phenomena like water and wind. When representing data of this type, we don't have previous embodied knowledge of the data source that we can draw upon to inform our sonification mapping strategy. In these cases we suggest choosing *sounds* (sC) which themselves have proven to have familiar embodied associations for a listener. If we cannot derive a suitable background of embodied knowledge from the original data, we can import one by representing and framing the data with sounds for which the listener has sufficient previous embodied experience, developing a new 'narrative' through this new metaphorical connection which are nonetheless based on established metaphors from eK.

An example of this type of approach would proceed as follows.

(1) Identify linguistic conceptual metaphors which are associated with the data set. White [55] argues that there is a clear conceptual metaphor underpinning the concept of an 'economy': that economies are often conceptualised as living organisms and are thought and reasoned about in those terms.

(2) As such, a sonification designer would consider a biologically–inspired sonic complex (sC) in order to represent changes in an economic metric such as GDP. For example, a heartbeat sound could be used as a paramaterised auditory icon to represent the data phenomenon (dP) in question: GDP.

(3) The sonic dimension (sD) in this case could be the pulse or heart rate and the data measurement (dM) could be the changes in GDP, whereby increases would map to an increased pulse/heart rate and decreases could map to a decreased pulse/heart rate. (These types of mapping example are summarised in table 1, above.)

It must be noted here that we are making some assumptions about embodied knowledge in the previous examples. In practice, embodied knowledge is a critical aspect of this model as it mediates how exactly a listener will interpret a sonification, this is complicated by the fact that embodied knowledge (eK) can vary wildly from person to person and from culture to culture. Such factors must be taken into account during phases of design by adopting user-centric design and evaluation methodologies to produce systems which are better adapted to the specific embodied knowledge (eK) of expected user groups.

As discussed previously, the listener's background of embodied knowledge contains their understanding of the sound, the data and any instructions or training they have received for the sonification. This knowledge is grounded in the listeners' embodied experience through embodied schemata and these embodied schemata determine how the embodied sonic dimensions are mapped to data. A similar phenomenon is referred to by Walker [56] as *polarity*. For example, when the speed of a train is mapped to the sound of flowing water, an increase in the speed of the water flow (embodied sonic dimension) is likely to coincide with an increase in the speed of the train as both share a common measure, speed, which is structured by the Fast–Slow schema [20]. When the depth of a submarine is mapped to pitch, a decrease in pitch (embodied sonic dimension) is likely to correspond to an *increase* in depth. This is because both depth and pitch are structured by a common Up–Down (*verticality*) schema [20, 36]. For depth however, an increase in the data means downward motion and so a decrease in pitch might be interpreted as an increase in data. In this case, the listener's embodied knowledge of the data determines their experience of the sonification.

3.3 Sonification Metaphor and Culture.

Lakoff and Johnson [21] argue that all linguistic cultures that they have considered employ embodied knowledge and create and use conceptual metaphors based on embodied experience; however, the metaphors created are often specific to that culture. Taking this a step further, Kövecses [57] illustrates a class of conceptual metaphors that, while still rooted in embodied experience, have a predominantly cultural basis. As an example, he points to the idiom 'Time is Money' and argues that it can only result from, and make sense in a capitalistic culture in which profit can be equated with the time required to produce a product. This is an important point for sonic information design and suggests that when applying a model like the ESLM, which relies heavily on conceptual metaphor, the designer must be aware of the culture in which the listener is embedded and base their design on metaphors with which these users are accustomed. Consider the sonification of economic data. Since its inception sonification has proved a useful tool for representing economic and market data [3]. However, research by Chung [58] has suggested that Chinese, Malay and English speakers use different conceptual metaphors for markets. The results show that Chinese and Malay speakers tend to use more metaphors based on 'competition' than English speakers when conceptualising markets. By contrast metaphors used by English speakers tend to focus on the 'fall' of a market. A related study compared the use of conceptual metaphors across financial reports written by native English speakers with those written by native Spanish speakers [59]. The results showed that while both groups conceptualised the economy as an organism (similar to our earlier GDP example), Spanish reports used more metaphors based on psychological mood and personality while reports in English showed a tendency towards more nautically based metaphors. These differences in the conceptualisation of markets and economies across cultures are important and they call for unique approaches to the sonification of market and economic data for the groups in question. Accounting for these differences can result in systems that are more inclusive overall as well systems that are developed specifically for users of a certain culture.

How listeners interpret the meaning of a given sound in a sonification context is, undoubtedly, highly dependent on cultural factors. Polli [60] points out that approaches to sonification reliant on the Western harmonic music system fail to account non-Western listeners. She argues that listening to the soundscape is an experience more commonly shared across cultures, though the content of those soundscapes can differ radically over time and geographical space. Jeon et al. [61] showed that in the representation of emotional state data in auditory display, Koreans listeners showed a stronger preference for either auditory icons (real-world sounds) or earcons (Westernised musical sounds), whereas U.S. listeners showed more distributed preference between the two categories. These results are suggestive of cultural differences between listeners. Vickers and Hogg [47] also comment on cultural differences in auditory display suggesting that spectromorphology (discussed previously), has the advantage of being less culturally specific than some Westernised alternatives as it is chiefly concerned with the sonic gestures discussed earlier.

The ESLM has been consciously designed to accommodate a broad range of sounds. The sonic complex can just as easily be a soundscape, or a section of a raga, as it can be a sine tone, melodic pattern or rhythmic pulse. They key point is to choose a sonic complex and sonic dimension that creates the right conceptual metaphorical mapping for a given listener allowing them to interpret the sonification on the basis of a familiar domain of embodied experience for them. It is critical that designers account for cultural factors, taking care to choose sounds and mapping strategies that are consistent with the metaphors employed by the user, whilst also seeking to better understand how cultural factors may be at play in the construction or modification of these metaphors.

3.4 ESLM Re-iterated

To summarise in plain English, listeners attend to the sound as though it *were* the data during sonification listening. Thus, the sound is experienced as a metaphorical representation of the data. There are two metaphors involved in this process. In the first, the sound heard is identified with the original data source. In the second, and arguably more critical, metaphorical changes in the sound are identified as changes in the data recorded from the original source. Crucially, this entire process is mediated by the listener's background of embodied knowledge, which determines how exactly metaphorical mappings take place. However, where the data is more complex, more broadly embodied models of sound, through which multivariate data series can be represented using conceptual metaphors, blends and a wider range of timbral/textural changes (informed by the treatment of timbre's component dimensions via embodied dynamics), may be helpful.

The ESLM is proposed as a tool for guiding the design of sonifications that can exploit the embodied aspects of meaning–making during sonification listening. The ESLM connects a number of research strands in embodied cognition, sonification and music composition to describe how sonifications can be paramaterised in terms of image schemas, conceptual blending, and conceptual metaphor theory. Research of the kind explored in this article is important for sonic information design because it shows that both sound and music can be modelled in terms of embodied cognitive processes. Rather than parameterising sound and music on the basis of listeners' abilities to discern changes in pitch, amplitude and timbre, the present article proposes the parameterisation of sound on the basis of their ability to detect, track and interpret changes based on image schema and conceptual metaphors and blends. This is arguably crucial to sonic information design because it allows the designer to map data to more complex sonic dimensions (and combinations of dimensions) that are far better suited to communicating information to a listener, and to which the listener, based on ecological–embodied experience, is adapted to making sense of.

4 Discussion and Concluding Remarks

The ESLM has far-reaching implications for the field of sonic information design. There are strong cultural and historical precedents in the West for conceptualising sound in either psychophysical terms, (i.e. pitch, loudness and timbre) or Western musical terms (i.e. rhythm, melody etc.). This approach has proven to be less useful for sonification, where the mapping problem imposes hard limits on how data can be represented with these auditory dimensions. The ESLM provides a novel framework for thinking about and working with sound in the context of sonification. It differs from standard approaches in that it is specifically intended to account for sonification and it provides this account in terms of conceptual metaphor theory so as to address some of the embodied aspects of sonification listening. In doing so the ESLM serves as an explanatory framework for how given groups of listeners might interpret a sonification. Crucially, it provides a framework for thinking about, and better understanding, the processes by which listeners might relate a specific sound to a data source when listening to and interpreting a sonification. The ESLM allows a designer to work with sounds from a wide and varied range of sources in a systematic manner. The model can be applied if a sound can be paramaterised with a sonic complex (sC) that can represent the data phenomenon (dP) and a sonic dimension (sD) that is mapped to the data measurement (dM) in the original data set via a relevant conceptual metaphor informed by, and adapted to, the listeners previous embodied knowledge (eK). This model, with its novel sonic and conceptual dimensions, introduces more degrees of freedom for representing data with sound. This expanded possibility space gives the designer the opportunity to choose sounds and mapping strategies which might better represent their data to the listener. The conceptual metaphors involved in the model, and the need to choose metaphorical mappings from data to sound that make sense to a listener, help to constrain this possibility space to only those mapping strategies that are meaningful and can be interpreted by a listener. In doing so, the ESLM provides a useful tool for addressing the first design challenge posed by the mapping problem: the question of how to design a meaningful data to sound mapping strategy [2]. The ESLM also helps to address another design challenge posed by the mapping problem: the issue of dimensional entanglement encountered in traditional approaches to sonification as the use of a sonic complex (sC) to represent a specific data phenomenon (dP) and a sonic dimension (sD) to represent changes in the measured data (dM) allows the designer to make clear delineations between different sounds in a sonification and the data sources they represent. Another crucial component here however is the embodied knowledge (eK) that a listener draws upon to interpret a sonification.While this doesn’t unequivocally solve the mapping problem, which remains a design problem that must be solved each time a designer creates a sonification, it does offer a framework in which to address it.

Adopting approaches informed by embodied cognition may support designers in more efficiently investigating and devising solutions to this problem. Frameworks such as the ESLM can help a designer to account for some of the embodied cognitive aspects of cognition involved in a listeners interpretation of a sonification.

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