Embodied Auditory Display Affordances

Conference Paper · August 2015

2 authors:

Stephen Roddy
Trinity College Dublin

Dermot Furlong
Trinity College Dublin

EMBODIED AUDITORY DISPLAY AFFORDANCES

Stephen Roddy
Trinity College Dublin, Dublin 2, Ireland
roddyst@tcd.ie

Dermot Furlong
Trinity College Dublin, Dublin 2, Ireland
dfurlong@tcd.ie

ABSTRACT

The current paper takes a critical look at the current state of Auditory Display. It isolates naive realism and cognitivist thinking as limiting factors to the development of the field. An extension of Gibson's theory of affordances into the territory of Embodied Cognition is suggested. The proposed extension relies heavily on Conceptual Metaphor Theory and Embodied Schemata. This is hoped to provide a framework in which to address the problematic areas of theory, meaning and lack of cognitive research in Auditory Display. Finally the current research's development of a set of embodied auditory models intended to offer greater lucidity and reasonability in Auditory Display systems through the exploitation of embodied affordances, is discussed.

1. CURRENT STATE OF FIELD

The field of Auditory Display (AD) is in crisis. After a strong and promising start with the establishment of the International Community for Auditory Display and many years of groundbreaking research, the program struggles for momentum. Data sonification has not reached the same level of innovation or mainstream acceptance, as visualization. This is often dismissed as a symptom of a visually biased Western culture. The AD corpus is littered with open questions and dead ends that require innovative solutions if this discipline is to continue to evolve past its current state. Walker and Nees [1] call for an all-encompassing theoretical framework in which to position AD research. Neuhoff and Heller [2] suggest that future research needs to leverage intuitive mental models in the design of AD technologies. Gossman [3] suggests an embodied cognition approach towards AD design and Walker and Kramer [4] propose focusing on general cognitive processing as a key concern in the development of the area. These examples are reflective of the general thinking across the community on the future of AD. This trend tends to reference the need for a theoretical framework more cognitively based research and a deeper understanding of the place of meaning in AD technologies.

2. AUDITORY DISPLAY THEORY

The status of AD as a collaborative research program at the intersection of science, technology, cognitive science and the arts is often considered a disadvantage across the literature [1]. This perception drives the search for some solid theoretical foundations upon which to lie AD. There are general theoretical arguments to be made against this approach. Gardner [5] points out how valuable and positive inter-disciplinary collaboration has been to the establishment and development of cognitive science. Modern cognitive science exists at a junction between Psychology, Philosophy, Artificial Intelligence, Linguistics, Anthropology and Neuroscience. It has been this mixture of different kinds of theory and practice that have led to the success of cognitive science as a research program. To date AD has benefited from contributions across a large spectrum of research areas, to move away from this knowledge sharing community would be a mistake. The general spirit of foundationalism (whereby one endeavours towards a single unified theory) in science, academics and the arts has been heavily critiqued by thinkers such as Dewey, Rorty, and Popper [6, 7, 8]. They have shown that the pragmatic interrelation of diverse and sometimes opposed theories presents a more useful context in which to pursue scientific, academic and artistic goals. Severing AD from its rich and innovative background context necessarily reduces the potential for a cross-pollination of new ideas. This limits the relevancy of AD to outside research fields and erodes the potential for benefit from future developments within these fields. This may not be the best approach for overcoming the current stagnation and could have dire consequences for the innovation and development of the discipline in the future. In light of these considerations, the march towards a monolithic theory of AD seems misgiven. Rather multiple theories of AD, both competitive and complementary, should be encouraged. This in turn may give rise to a form of Adhocracy whereby AD theories can be pragmatically applied to solve a specific problem.

3. TOWARDS A PRAGMATIC DESIGN THEORY

As previously discussed AD exists in a state of flux at the intersection of myriad other complimentary research fields including but not limited to Cognitive Science, Computer Science, Music, HCI, Sound Design, and Psychology. The fractured and dynamic nature of the research program is simultaneously its strength and its weakness. Eldridge [9], while recognizing the need for theoretical underpinnings for AD has suggested the development of generic principles of AD design informed by perceptual and psychoacoustic research rather than the development of a single unified theory. It is conjectured here that such an approach is valid in attempting to address stagnation within the field. Where the possibility of a fundamental theory is a meta-issue that applies to the overall state of AD, the most pressing internal issue within AD is the question of meaning. The creation of meaningful and intuitive sonifications that rely more on users innate cognitive capacities than previous learning is a key issue in sonification. The question of meaning is extensively dealt with in the literature (e.g. [1, 2, 3,9, 10, 11]) and will be explored in detail later in this paper. A third problem area within AD is the deficit of cognitively based research. This is highlighted repeatedly across the literature (e.g. [2, 12, 4]). This will be explored in greater detail later in this paper also.

In summary three main problem areas in the study of AD are:

1- The need for theory.
2- The question of meaning.
3- The need for more cognitively oriented research.

4. GIBSONS AFFORDANCES

The ecological approach to perception pioneered by J.J. Gibson [13] puts forward a model of perception where the possible number of actions an organism can execute within its environment is limited by the affordances (opportunities for action) the environment offers to organism. This theory has been widely employed across a number of prominent research projects in AD [4, 14, 15, 16, 17, 18, 19]. This approach is bound up with the philosophical notion of naive realism; the idea that the human senses offer direct perception of an objective world. This is a notion that fails to take into account the features of the human body within which perception takes place, and also the cognitive processing that is by now known to be an inherent facet of perception. It is here speculated that this approach has contributed to the stagnation of AD by downplaying the role of both cognition and embodiment and misinterpreting the status of the auditory domain by treating sonic phenomena as wholly objective events to which human perception grants unmediated access. For auditory display to truly embrace modern (second generation) cognitive science, a fundamental shift in how researchers think about sound is required. It is here argued that the ecological approach provides only half of the picture when it comes to auditory phenomena. In order to remedy this, AD research must begin to acknowledge the role of cognition in parsing the auditory environment and its affordances. At present this is not the case. By embracing the notion of Enaction (cognition as guided action) [20] a wider view comes into focus, where the environment and affordances are organised and explained not only in physical terms but in terms of common cognitive capacities uncovered by second generation cognitive science. In this way affordances are shaped by the interplay of cognition and the physical world. This grants the notions of an embodied auditory environment that can be extended to AD design allowing for the exploitation of entirely new cognitively based affordances as well as their physical counterparts.

5. COGNITIVISM

Where AD and auditory research more generally doesn't directly embrace Gibson's ecological perspective or naive realism it tends towards a cognitivist model of the mind. This model defines the mind as a computer. The objective world is represented to this computer, via perception, in an array of arbitrary symbols. Thinking is the manipulation of such symbols [20]. Cognitivism acted as the dominant conceptualization of the human mind until the emergence of second-generation cognitive science in the early 1980's. As a field AD has yet to part from this model and truly embrace the implications of modern cognitive science. According to Harnad's Symbol Grounding Problem [21] cognitivism cannot explain meaning (or the process of meaning-making). This is because it defines cognition as the relation of arbitrary symbols to a coresponding objective reality, entirely omitting the role of meaning. Any serious attempt to address the question of meaning in the field of AD must at the very least acknowledge its existence, if not offer a satisfying account of its genesis in relation to auditory perception and cognition. It could be argued that the stagnation experienced by the field may at least be partially resultant from the research and developments of AD solutions that adhere to the by now defunct notion of the cognitivist mind. It is here argued that in the development of theory and design guidelines for the field of AD, careful consideration needs to be paid to the implications of ones theoretical assumptions on the status of cognition, perception and critically, meaning. The assumption of the cognitivist mind must be corrected if we are to avoid the symbol grounding problem. If not, a true account of both meaning and cognition will be forever beyond the reach of AD. With the application of rigour and a serious reconsideration of the role of the mind in AD, new solutions and pragmatic theories can be devised.

6. TOWARDS EMBODIED AFFORDANCES

Embodied affordances are here described as affordances offered by the interplay of cognition and the environment where cognition is defined in terms of second generation cognitive science, more typically known as Embodied Cognition (EC). This theoretical school (EC) may help to inform solutions to the three main problem areas in the study of AD visited earlier. When extended to the auditory domain, the recognition of embodied aspect of affordances allows for design solutions that are better rooted in our cognitive capacities and more implicitly meaningful as a result. Such an approach could potentially address all 3 problem areas in AD simultaneously. This topic shall be discussed in greater detail after a brief account of EC as it currently stands in the field of AD.

7. EMBODIED COGNITION

An alternative theory of mind put forward in the formative years of second generation cognitive science, which has since found scientific validity and wide application [22], is Embodied Cognition. Embodied cognition (EC) presents a new paradigm for thinking about the perception and cognition of both music and sound [23, 24]. It provides an answer to the symbol grounding problem recognizing meaning-making as a key cognitive task and is said to offer a more accurate view of cognition than cognitivism [25, 26, 27, 22]. Rather than remaining of purely theoretical worth it also provides a comprehensive account of human cognitive competencies, the mental faculties by which a mind cognizes, understands, imagines and reasons. EC researchers concern themselves with topics such as affective/kineasthetic dynamics, conceptual metaphor theory, sensorimotor mimesis, embodied schemata and conceptual blending. Each of these cognitive capacities arises from activity in the sensory-motor system. As a result, they are thought of as being embodied and have been show to organize our cognitive experience in terms of our embodiment. They are intimately bound with the process of meaning making in audition [24] and the other sense domains [16]. The EC framework provides theoretical guidelines for cognitively based research into the question of meaning in auditory display. In so doing it provides a framework in which we can address the three problem areas in AD as they are presented in this document. It has been decided to focus on Lakoff and Johnson's [25, 26] conceptual metaphor theory, and embodied schema as a means to extending Gibson's theory of affordances. These explicit mechanisms have been chosen as not only are they theoretically relevant to meaning-making, but a strong body of empirical research documents their operation [22]. Before outlining a theory of embodied affordances the contribution of EC to AD must be considered.

8. EMBODIED INTERACTION

To date, notions from EC theory have been applied to the field of AD in number of successful ways. Much of this application has been on the side of interaction. AD technologies and systems have been developed on the basis of Dourish's theory of embodied interaction [28]. In embodied interaction, the physical world is treated as the medium for interaction with digital technology. The primary focus of the theory is conversion of action into meaning. It bridges the gap between social and tangible computing and allows for the generation and sharing of meaning through interaction with tangibles. This allows the designer to leverage EC theory in the design of interaction within AD technologies. This theory has provided the basis for research into continuous sonic interaction as an embodied interface [29, 30], sonic interaction design [31] and embodied interaction in auditory display [32, 33]. In order to move beyond interaction design in AD, and to tackle the three questions stated above a broader understanding of EC as it applies to AD is required. Theory based purely on embodied interaction does not allow for applications in the exclusively auditory sub-set of AD.

9. COGNITIVE CAPACITIES

Rather than being simply a theoretical research program, the EC literature offers us detailed descriptions of the cognitive capacities and their workings. Some of these previously listed capacities will now be considered in relation to AD. Conceptual Metaphor Theory (CMT) and Embodied Schema theory are two complementary and scientifically valid streams of thought within EC research [25, 26, 22, 35, 36]. CMT illustrates a cognition in which concepts are composed of cross-connections from source to target domains. A source domain is an intelligible human experience and the target domain is the conceptual space. Meaning is connotative and results from the correlations between these domains referred to in EC as cross-domain mappings. A concept then is a conglomerate of other inter-related aspects of human experience, be they concepts, memories or perceptions themselves. At their root, concepts are grounded in the human experience of embodiment within physical and socio-cultural environments. Certain repetitive patterns or schemata emerge from this embodiment. These schemata provide the logical rules by which concepts and their transformations are governed. Cognition, reasoning and perception are organized in terms of these schemas [37]. According to the invariance principle in CMT target domains retain the image schematic structure from the source domains that inform them [26]. It is the invariance of embodied schematic structure across all domains of human experience that enables the mind to understand abstract and seemingly arbitrary concepts. The embodied mind lends concepts intelligible structure, by projecting logical organization into a conceptual domain from domains of repetitive embodied experience. In working from the point of conceptual structure back to embodied experience, the embodied mind achieves understanding and applies meaning to a concept. The mechanism here simply relies on mapping logical structure in terms of embodied schemata from abstract to more familiar domains where all mapping paths find an ultimate grounding in embodied experience. In EC to reason is to reason about one thing in terms of another where both elements share embodied schematic organization. Understanding and meaning-making work similarly. For example we can reason about balancing a balance sheet in the same way we would balance a see-saw. The common schema here is the twin-pan balance schema. We can understand what it means for one's heart to be inside our chest from our experiences of placing clothes in a drawer. The common schema here is the container schema. The mind can make a musical experience meaningful by relating galloping bass line to the galloping of horses. This notion is richer and contains many embodied schemata (e.g. Source-path-goal and force schemata.) Metaphor has long been acknowledged in the field of linguistics [25]. CMT differs by extending the notion of metaphor so that it is situated as the mechanism by which thought is possible. As discussed above to think is to think in terms of something other than the original thought. In another example above a musical bass line is described as galloping. This represents a metaphorical projection where music is reasoned about and understood in terms of the movement of a horse or similar animal. CMT claims (and offers empirical support) that this isn't just a linguistic mechanism but describes how people think, imagine and reason. The mind actually reasons about the bass line in terms of prior experiences of galloping. The mind takes the schemata present in ones experiences of galloping and uses them to make sense of a bass line.

10. EMBODIED COGNITION IN AUDITORY DISPLAY

The worth of embodied cognition in furthering the field of auditory display has been acknowledged to a degree by researchers working in the area. Embodied schemata and CMT are beginning to find application in the field. They've been used as a framework for designing auditory feedback systems that a user can better understand and reason about (using a balance schema) [38]. Embodied music cognition has been considered as a framework [39, 23] along with more purist approaches that focus on the work of Lakoff and Johnson as well as Varela, Thompson and Rosch's [20] enaction [19, 35]. CMT and embodied schemata theory are being employed in auditory display as a design framework for salient feedback in auditory display environments [38] where an embodied schema is leveraged as a model by which users can reason about and understand the auditory display. This is being employed in the context of interaction. Springboard is one such AD system, which is specifically designed for human cognitive capacities. This approach has been repeated in the field. CMT and embodied schema provide an excellent design framework for intuitive understanding especially in the realm of audio [36, 38, 40, 41, 42, 43, 44]. It is hoped that this approach can be extended to the exclusive auditory domain in the future. CMT and embodied schemata also prove to be well suited to the design of more meaningful auditory displays, where audio signals are of a higher level of salience [26]. Antle et al. [45] have developed AD design guidelines grounded in CMT and embodied schemata theory, which support a listener reasoning and understanding in an interaction context. The application of metaphors in sonification mapping has been a topic of interest for numerous researchers [46, 47, 48]. Design patterns, have been suggested to guide the development of solutions to commonly encountered sonification problems by reusing previously effective sonification metaphors and strategies [49, 50, 51]. There is an excellent body of research testifying to the usefulness of embodied cognition as a framework for the design of auditory display. The projects reported on here are not only concerned with embodied interaction and embodied interfaces, but also integrate AD into the embodied interaction process. The current research maintains an interest in how human bodily nature provides certain cognitive affordances, which may be leveraged for the interpretation of elements of an auditory display. As such, it is necessary to consider some of the cognitive capacities discussed earlier in order to establish how exactly a project of this type may be executed. The applications of EC considered thus far share a common oversight. EC solves the symbol-grounding problem by rooting meaning in embodied experience, and this fact has not been exploited to offer satisfying answers to the question of meaning in AD. It is here proposed that by focusing on the role of cognitive competencies in meaning making, a cohesive account of embodied affordances can act as a design framework. It is here argued that such a framework would be well suited to developing solutions to the three problem areas in AD. Lawrence Zbikowski [24] demonstrates how CMT and embodied schematic transformations drive the process of meaning making in audition at an extremely low level. The very mechanisms by which the mind organizes auditory perceptions make such perceptions meaningful. On the level at which auditory perceptions come to conscious awareness they are instantly meaningful. Zbikowski grounds this meaning making empirically offering it as an explanation for musical experiences. This is an important fact that the current research aims to exploit.

11. EMBODIED AFFORDANCES

Gibson's naive realism argues that we perceive the world directly. This does away with the notion of cognitivism, where the world is represented to cognition in symbolic form via the senses. Concurrently, naive realism fails to offer any satisfactory account of meaning. Rather than answering the symbol-grounding problem, it simply ignores it. As Varela et al. [20] demonstrate that our experience of color in a visual scene arises from the interplay of embodiment, cognitive competencies and the environment. Smallman and John [52] demonstrate the inadequacies of naive realism as a guiding framework for the development of visual displays due to its severe underestimation of both the difficulty and accuracy of visual perception. It is here argued that the same is true for auditory perception. A final argument against naive realism is its disqualification of cognitive capacities in acts of perception. As mentioned earlier it fails to account for meaning by sidestepping the symbol-grounding problem. At the same time, it prevents any cognitively based account of meaning arising through its dismissal of the role of embodied cognitive capacities in perception. In order for AD to tackle the questions of meaning and cognition and to generate sound and useful theory based on these enterprises it must overcome the pitfalls of both naive realism and cognitivism. By reconsidering Gibson's affordances in the light of EC (most specifically CMT and embodied schemata) we are presented with the notion of embodied affordances that overcome the disconnects of both naive realism and the symbol grounding problem thrown up by cognitivism. An embodied affordance can be thought of as any affordance that is open to a user as a result of the users cognitive meaning-making capacities. The notion of the embodied affordance opens up new areas in which to design AD solutions. In order to appeal to these embodied affordances we require AD tools that can better interface with a users cognitive capacities. The current study is concerned primarily with developing such tools. It focuses solely on the auditory portion of auditory display. It does not deal directly with the question of interaction; rather the focus is on designing sonic models to aid understanding and reasonability in AD. This is an attempt at contributing to the three problems areas in AD discussed in this paper. It is hoped that the wealth of EC research in AD has been faithfully represented here and that the need for an exclusive focus on meaning, cognition and the purely auditory element of AD has been communicated. It is expected that this project will offer tools for designing more intuitive and user-centric AD systems. The development of a design framework based on embodied affordances will expand the breadth of cognitively based research in the area as well as promoting a non-foundational theory that can be pragmatically applied across the field.

12. DESIGNING FOR EMBODIED AFFORDANCES

In order to capitalize on the role of human cognitive capacities in meaning making for the enrichment of the AD field the current project focuses on the modeling of internal logical structures of select embodied schemata and the codifying of these models in the auditory domain. These models make subconscious embodied schemata conscious through metaphorical projection of embodied schemata into the auditory domain. A user can understand and reason about these auditory signals in terms of those schemata by which they are organized. It is hoped that these embodied auditory models will offer the user new cognitive affordances by which they can understand and reason about an AD. A framework of theoretical design guidelines will be drawn up from the development and testing of these auditory models. These models are based on CMT and embodied-schemata principles and represent a first attempt to design elements of AD to offer the user embodied affordances. The first model under development is the twin-pan balance model where dual data inputs are mapped to individual sound objects at equidistant location across both X and Y axes in and auditory space. Changes in the magnitude of the two data inputs may map to salient audio dimensions such as pitch or timbre. Such a model can communicate relational changes between two variables. For example X is larger than Y or Y is decreasing while X increases. Each embodied schemata and each configuration of multiple schemata is conductive to a different form of reasoning and imparts a different meaning. Where the twin-pan balance schema is useful for conveying relationships between two values, the source-path-goal schema is more useful in conveying temporal changes in a single variable. By extending a schema into the auditory domain in this way, an unconscious reasoning strategy is made conscious and offered to the user as a tool by which to more clearly understand and reason about an auditory phenomenon. It is intended to develop a set of such auditory models for deployment in AD systems while also documenting their development and implementation in order to inform a design framework. The proposed theory of embodied auditory models that leverage embodied affordances differs from past AD research in its focus on meaning making. Such a theory is also freed from strict ties to interaction. Embodied affordance design guidelines, should be chiefly concerned with meaning, understanding and reasonability in AD due to theoretical the underpinnings. This allows innovative new solutions to the three problems areas in AD selected at the start of this paper.

13. APPLICATION OF FRAMEWORK

Some experimental evidence is presented here in order to support the idea that embodied schemata can be modeled in the auditory domain using sound synthesis techniques. An embodied schema is gestalt-like pattern. In order to realize that pattern it must be applied to a specific sonic domain. The domain chosen for this experiment is that of vocal synthesis. Being gestalt-like patterns, individual elements of the schema are defined relative to one another, rather than in relation to some external benchmark.

A good analogy for explaining this dynamic is presented by alphabetic letters. For example the letter ‘H’ is a pattern where two equal length parallel lines are bisected by a third perpendicular line. ‘H’ can be presented using many different fonts e.g. ‘*H’*&‘**H’** but as long as the internal logic of the pattern is maintained a reader will recognize it as ‘H’. Embodied schema too can be presented in many different kinds of sound, but as long as the basic pattern is in place the schema will be recognized. In defining an embodied schema then, each individual element must be described in relation to the other elements of the schema rather than in reference to external measures.

13.1 Hypothesis

This experiment was intended to test the hypothesis that amplitude, frequency profile, pitch level, vowel profile, envelope attack speed, reverb level, compression level and stereo image width could be used, to make a sound seem either Big or Small thus modeling the Big-Small schema discussed by Johnson [36] in the auditory domain. The Big-Small schemata is basic to a listener’s embodied experiences of any sound that communicates a sense of size relative to the object or process that created it, the space in which the sound is located, or the sound in itself.

13.2 Design and Materials

The experiment had a 2x4 design with repeated measures on both factors.

The sounds for this experiment were created using additive synthesis techniques to which different degrees of processing mentioned previously. 4 stimuli were given a noisy timbre and 4 a clear vocal like timbre. Both sets of stimuli were then assigned a set of cues to create a Smallest, Smaller, Bigger and Biggest version for each timbre type.

The two stimuli with the Smallest cues are given a low amplitude, a boost in the higher end of the frequency range, a high pitch level, the vowel formant profile for an ‘I’, a quick amplitude envelope attack speed, a small amount of reverb, little compression and a narrow centrally panned stereo image.

The two stimuli with the Smaller cues have higher values than those of the smallest cues.

The two stimuli with the Biggest cues are given a high amplitude, a boost in the lower end of the frequency range, a low pitch level, the vowel formant profile for an ‘A’, a slow amplitude envelope attack speed, a large amount of reverb, much compression and a wide diffuse stereo image.

The two stimuli with the Bigger cues have lower values than those of the smallest cues.

13.3 Experimental Procedure

Listeners are presented with each stimulus once and asked to rate the stimulus on a 5-point Likert scale from Very Small to Very Big afterwards. Participants are allowed to listen to the stimuli as many times as needed to help rate them.

13.4 Results

A repeated measures ANOVA was performed on the size schema measures with the design 2(tone: clear vs. noisey) x 4 (size: Biggest Cues vs. Bigger Cues vs. Smaller Cues vs. Smallest Cues) with repeated measures on both factors. There was no main effect of tone $F<1$, but a significant effect of size $F(3, 414)= 19.77$, $p=.000$, $\eta p^2= .125$, and the two variables did not interact $F(3, 414)= 1.56$, $p=.2$.

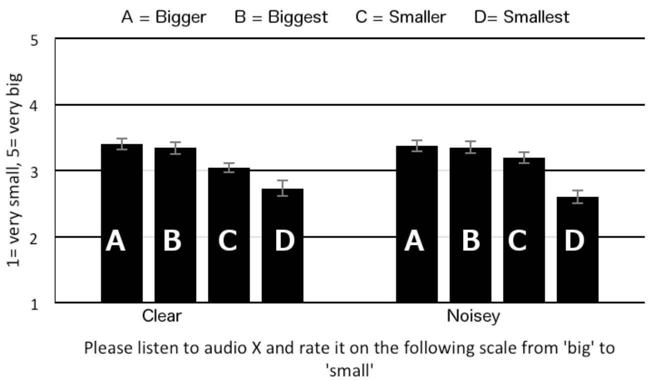

Figure 1. Experimental Results

13.5 Discussion

The results showed that participants accurately identified the stimuli with the smallest and smaller cues but identified stimuli with the bigger cues as slightly larger than those with the biggest cues across clear and noisey timbres. This indicates that the synthesis parameters used to model the Big-Small schema in the auditory domain are effective and that although listeners found it easy to distinguish between sounds modeled after the big and small poles of the schema they found it harder to distinguish between two individual sounds towards the larger end of the schema. This lack of distinction between like sounds may indicate that stimuli should be exaggerated to better enhance distinction. Regardless, the dimensions tested proved useful for modeling the Big-Small schema in the auditory domain. Table 1 presents the parameters required to model both poles of the Big-Small schemata. As discussed in section 13 each of the parameters are defined in relation to one another.

Parameters	Big	Small
Amplitude	Lower	Higher
Energy Profile	LF Energy	HF Energy
Pitch Level	Low	High
Attack Speed	Slow	Fast
Vowel Profile	“a”	“i”
Reverb Amount	Most	Least
Dynamics Range	Small	Large
Stereo Image	Wide	Narrow

Table 1. Parameters for Big-Small Schema in Vocal Synthesis.

14. EXPANDING THE FRAMEWORK

The aesthetic merits of the framework have received some acknowledgement through the well-received performances of data-driven pieces composed within this framework at national (Ireland) and international level. These pieces are intended to evoke a qualitative understanding of the human cost associated with Ireland’s recent economic crash. A broader review of the aesthetic and philosophical factors associated with this approach to sonification and the constraints they impose upon individual technical implementations is available elsewhere [53, 54, 55]. It is hoped that in the future, this framework (and those similar) will become more commonplace in the world of AD and can continue to open up new avenues for designing meaning rich data sonifications that speak to a listeners perceptual and cognitive faculties in the same language in which they understand both themselves and their world.

15. REFERENCES

[1] B.N. Walker and M.A. Nees. “Theory of Sonification” in *The Sonification Handbook*. 1st ed., vol.1. T. Hermann, A. Hunt & J.G. Neuhoff Eds. Berlin: Logos Publishing House, 2011, pp.9-39

[2] J.G. Neuhoff and L.M. Heller. “One small step: Sound Sources and Events as the Basis for Auditory Graphs” in Proc. of ICAD, 2005, pp.1-3.

[3] J. Gossman. “From metaphor to medium: Sonification as extension of our body” in *Proc.* ICAD, 2010.

[4] B.N Walker, and G. Kramer. “Ecological psychoacoustics and auditory displays: Hearing, grouping, and meaning making”. Ecological Psychoacoustics, pp150-175, 2004.

[5] H. Gardner. *The mind’s new science: A history of the cognitive revolution*. Basic books, 1987

[6] J. Dewey. *Art as experience.* Perigee Trade, 1934.

[7] R. Rorty. *Objectivity, relativism, and truth: philosophical papers (Vol. 1)*. Cambridge University Press, 1990.

[8] R. Swinburne. *Objective Knowledge: An Evolutionary Approach*. Philosophical Books, pp.17-20, 1973

[9] A. Eldridge. "Issues in Auditory Display". *Artificial Life*, vol. 12, pp.259-274, 2006

[10] S. Serafin, K. Franinovic, T. Hermann, G. Lemaitre, M. Rinott and D. Rocchesso,. 2011. "Sonic Interaction Design" in *The Sonification Handbook,* 1st ed., T. Hermann, A. Hunt and J.G. Neuhoff. : Logos Publishing House, 2011, pp.88-110.

[11] S. Barass. "Personify: a toolkit for perceptually meaningful sonification" in *Proc. ACMA,* 1995.

[12] J.G. Neuhoff. "Perception, Cognition and Action in Auditory Displays in *The Sonification Handbook*. 1st ed., vol.1. T. Hermann, A. Hunt & J.G. Neuhoff Eds. Berlin: Logos Publishing House, 2011, pp.63-81.

[13] J.J. Gibson. *The ecological approach to visual perception*. Psychology Press, 1986.

[14] P. Sanderson, J. Anderson and M. Watson. 2000. "Extending ecological interface design to auditory displays" in P*roc. Australasian Conference on Computer-Human Interaction*, 2000 pp.259-266.

[15] S. Saue, S. "A model for interaction in exploratory sonification displays*" in Proc. ICAD,* 2000.

[16] P. Sanderson and M. Watson. "From information content to auditory display with ecological interface design: Prospects and challenges" *in Proc. Human Factors and Ergonomics Society Annual Meeting*, 2005, pp.259- 263.

[17] T.C. Davies, C.M. Burns and S.D. Pinder. "Using ecological interface design to develop an auditory interface for visually impaired travellers" *in Proc. 18th Australia conference on Computer-Human Interaction: Design: Activities, Artefacts and Environments,* 2006, pp.309-312.

[18] M. Mustonen. "A review-based conceptual analysis of auditory signs and their design" *in Proc. ICAD*, 2008.

[19] E. Brazil and M. Fernstrom. "Investigating concurrent auditory icon recognition" *in Proc. of ICAD*, 2006 pp.51-58.

[20] F.J. Varela, E. Thompson and E. Rosch. *The embodied mind: Cognitive science and human experience*. MIT press, 1992

[21] S. Harnad. "The symbol grounding problem" *Physica D: Nonlinear Phenomena*, vol. 42 pp.335-346.

[22] G. Lakoff. " Explaining Embodied Cognition Results" *Topics in Cognitive Science* vol. 4 (4), pp.773-785, 2012.

[23] M. Leman. *Embodied music cognition and mediation technology*. Mit Press, 2007.

[24] L.B. Zbikowski. *Conceptualizing music: Cognitive structure, theory, and analysis,* US: Oxford University Press, 2005.

[25] G. Lakoff and M. Johnson. *Metaphors We Live By*. Chicago: Univ. of Chicago Press, 1980.

[26] G. Lakoff and M. Johnson. *Philosophy in the Flesh: The Embodied Mind and it's Challenges to Western Thought.* New York: Basic Books, 1999, pp.3-602.

[27] W. Freeman and R. Nunez. *Reclaiming Cognition: The Primacy of Action, Intention and Emotion*. USA: Imprint Academic, 2000, pp.1-262.

[28] P. Dourish. *Where the Action Is: The Foundations of Embodied Interaction*. USA: The MIT Press, 2001, pp.1-210.

[29] M. Rath and D. Rocchesso. "Continuous sonic feedback from a rolling ball" *in Proc. Multimedia, IEEE*, 2005, pp.60-69.

[30] D. Rocchesso, P. Polotti and S. Delle Monache. "Designing continuous sonic interaction" *International Journal of Design*, vol. 3 pp.13-25, 2009.

[31] A. Dewitt and R. Bresin. "Sound design for affective interaction" in *Proc. Affective Computing and Intelligent Interaction*, 2007, pp.523- 533.

[32] R. Wakkary, M. Hatala, R. Lovell, and M. Droumeva. "An ambient intelligence platform for physical play" in *Proc. ACM international conference on Multimedia,* 2005, pp.764-773.

[33] M. Droumeva and R. Wakkary. "Understanding aural fluency in auditory display design for ambient intelligent environments" in *Proc.* ICAD, 2008.

[34] M. Droumeva, S. De Castell and R. Wakkary. "Investigating Sound Intensity Gradients as Feedback for Embodied Learning" in *Proc.* of ICAD, 2007, pp.26-9.

[35] S.C. Peres and M.D. Byrne. "The Interactive Behavior Triad and Auditory Graphs" in *Proc.* ICAD, 2005.

[36] M. Johnson. *The Body in the Mind: The Bodily Basis of Meaning, Imagination, and Reason.* Chicago: University of Chicago Press, 1987.

[37] B. Hampe and J.E Grady. *From perception to meaning: embodied-schemas in cognitive linguistics.* Ber-

lin: Mouton de Gruyter, 2005.

[38] A.N. Antle, G. Corness and M. Droumeva. "What the body knows: Exploring the benefits of embodied metaphors in hybrid physical digital environments", *Interacting with Computers: Special Issue on Physicality*, pp.66-75, 2009.

[39] N. Diniz, P. Coussement, A. Deweppe, M. Demey and M. Leman. "An embodied music cognition approach to multilevel interactive sonification", *Journal on Multimodal User Interfaces*, pp.1-9, 2009.

[40] A.N. Antle, G. Corness and M. Droumeva."Human-Computer-Intuition? Exploring the cognitive basis for intuition in embodied interaction", *International Journal of Art and Technology,* vol. 2, pp.235-254, 2009.

[41] A. Macaranas, A. Antle and B.E. Riecke. "Bridging the gap: attribute and spatial metaphors for tangible interface design", in *Proc. International Conference on Tangible, Embedded and Embodied Interaction*, 2012, pp.161-168.

[42] J. Hurtienne and L. Blessing. "Design for Intuitive Use-Testing image schema theory for user interface design" in *Proc. International Conference on Engineering Design*, 2007 pp.1-12.

[43] J. Hurtienne. "Cognition in HCI: An ongoing story", *Human Technology*, vol. 5, pp.12-28, 2009.

[44] J. Hurtienne, K. Weber and L. Blessing. "Prior experience and intuitive use: embodied-schemas in user centred design", *Designing inclusive futures*, pp.107-116, 2008

[45] A.N. Antle, G. Corness, S. Bakker, M. Droumeva, E. Van Den Hoven and A. Bevans. "Designing to support reasoned imagination through embodied metaphor", *in Proc. Conference on Creativity and Cognition*, 2009, pp.275-284.

[46] K. Vogt and R. Höldrich, R. "A metaphoric sonification method-towards the acoustic standard model of particle physics" in *Proc. of ICAD*, 2010.

[47] N. Schaffert, K. Mattes, S. Barrass and A.O. Effenberg. "Exploring function and aesthetics in sonifications for elite sports" in *Proc. of ICoMCS2*, 2009, pp.83-86.

[48] S. Barrass" EarBenders: Using stories about listening to design auditory interfaces" in *Proc. APCHI*, 1996.

[49] S. Barrass, S. "Sonification design patterns" in *Proc. ICAD*, 2003.

[50] C. Frauenberger and T. Stockman. "Auditory display design—an investigation of a design pattern approach". *International Journal of Human-Computer Studies*, vol. 67, pp.907-922, 2009.

[51] M. Adcock and S. Barrass. "Cultivating Design Patterns for Auditory Display: in *Proc. ICAD*, 2004.

[52] H.S. Smallman and M. John. "Naive realism: Limits of realism as a display principle" in *Proc. Human Factors and Ergonomics Society Annual Meeting*, 2005, pp.1564-1568.

[53] S. Roddy and D. Furlong. 2014. "Embodied Aesthetics in Auditory Display". *Organised Sound*, vol. *19*(01), pp.70-77, 2014.

[54] S. Roddy and D. Furlong. 2013. "Embodied Cognition in Auditory Display" in *Proc. ICAD*, 2013.

[55] S. Roddy and D. Furlong. 2013. "Rethinking the Transmission Medium in Live Computer Music Performance". Available at: http://issta.ie/wp-content/uploads/ISSTC-2013-RODDY.pdf [June 2015].