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The Use of Sound to Represent Data and Concepts as a Means to Engender Creative Thought: Some Thoughts on Implementation and a Research Agenda

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ABSTRACT
This paper poses the question: How can sound be used to function analogously to the function of the images in a graph in order to create the conditions for creative thought and insight to occur and thus to facilitate the synthesis of new knowledge? It uses this to develop further questions and a research agenda. In particular, it is concerned with the use of sonification of the non-audio data and concepts represented in a diagram or graph and the techniques that might be used to foster a creative research environment using sound. The ultimate goal of the research agenda is to go beyond sonification and to use sound pro-actively in a Virtual Research Environment in order to create the conditions for creative thinking and insight to occur with the hope that this may then lead to the synthesis of new knowledge.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *auditory (non-speech) feedback, standardization, user-centered design.*

General Terms
Design, Human Factors, Standardization, Theory.

Keywords
Sound, Cognition, Emotion, Meaning, Creativity, Knowledge synthesis, Virtual research environment.

1. INTRODUCTION
It would be a truism to state that, speech and music apart, humankind is ocular-centric particularly in the field of the metaphorical representation of data and knowledge. Humankind has developed a complex system of graphical signs that, while it sacrifices detail and precision, in the best examples is capable of representing vast amounts of data and advanced concepts with remarkable efficacy and efficiency. In this paper we leave aside speech and music (both systems of sound signs that have proved invaluable signifiers of data, thought and emotion) to concentrate on sonic analogies to visual graphs and other diagrammatic forms, sonic representations whose purpose is not only to represent data and concepts but also to facilitate innovative and creative thought directed towards the synthesis of new knowledge.

If image-based representations (of ideas, data, emotion, knowledge and so on) can be grossly and simply divided into text, art and diagrams/graphs, then we equate (while being cognizant of the many differences, major and minor) speech with text, music with art and the under-developed area that we are interested in viz. nonverbal, non-music sound with diagrams/graphs. Such a gross simplification ignores several sub-categories that may be made. For image: TV news; films; documentaries; photography; fashion; ornamental gardens, for example; and, for sound: radio bulletins; soundscape design; industrial sound design; and so on. The area's under-development is pointed to by the lack of a concise and precise term as there is for speech and music. Perhaps the closest is the term 'sonification' that Kramer et al. define as "the use of non-speech audio to convey information" [1]. More specifically, "sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation."

Hermann refines the specific requirements of a genuine sonification, insisting that: the sound must reflect "objective properties or relations in the input data," the transformation from numerical data to waveform must be systematic, and the overall sonification system must be both reproducible and flexible in that "[t]he system can intentionally be used with different data, and also be used in repetition with the same data" [2]. Barrass and Kramer contribute further specification within their definition that describes the output of a sonification system as *synthetic-nonverbal*, however their precise definition of synthetic within this context is unclear [3]. In response to the belief that a sonification is a functional construct, designed to fit a purpose, Barrass rejects the *representation of information* definition in favour of *tool*, a descriptor that relates closely to their assertion that a genuine sonification must have significant practical value and should not be simply a gimmick or embellishment [4].

Despite variations within the fine detail, there appears to be a general consensus between researchers as to the meaning of sonification and such a definition has been widely used to explain sound design in a variety of circumstances. For example, Grimshaw asserts that a computer game audio engine is, in essence, a sonification engine [5]. Further connection between the sonification concept and contrasting disciplines can be observed when considering the two primary branches of the construct; analogic representation and symbolic representation, respectively defined by Barrass as "an immediate and intrinsic correspondence between the sort of structure being represented and the representation medium" and a categorical, non-intrinsic denotation of the data being represented [4]. These terms form a core aspect of practical sound theory within a range of disciplines, including digital games [6], web design [7] and cognitive neuroscience [8]. However, sonification as a definition does not capture all that we wish to pursue here, most notably the creation of a sonic environment that not only sonifies data and concepts, but also uses sound pro-actively to synthesize new knowledge.

In this paper, we wish to concentrate on one fundamental question: How can sound be used to function analogously to the function of the images in a graph in order to create the conditions for creative thought and insight to occur and thus to facilitate the synthesis of new knowledge? Such a question raises many more (not least, *can* sound be used in such a manner?) but we return to these later.

One question that must be dealt with here, though, is this: "Why would we require sound to function in this manner – to be able to rapidly convey information as to amount, size, decrease or increase, rate, relationships and so on when image alone appears to do a perfectly reasonable job? There are many answers to this and, in order to answer some of them within the context of tools for creativity, we turn first to a brief description of a software program developed by Grimshaw (co-author of this paper) since 2003.

WIKINDX[1] is a Virtual Research Environment (VRE) designed to capture, store and make available via the World Wide Web to groups of researchers data such as bibliographies, quotations, paraphrases in addition to thoughts about the data and knowledge contained therein. Among its many tools are bibliography conversion utilities, personalization, keywords and categories, file storage, cross-referencing, search and the automatic formatting of citations and bibliographies to chosen styles within the built-in word processor. It is, then, at heart, a repository of data and knowledge that is ignorant of the research field any particular wikindx is focussed upon. Although it is widely used[2] to perform precisely this function, the ambition is to turn it from a passive, but responsive, collection to a pro-active research tool designed to create the conditions that facilitate creative thought and leaps of insight and, thus, for new syntheses of knowledge to occur.

WIKINDX is currently a text-only tool accessed through a web browser. Much of its interface is form-based and this is how users search for or select bibliographic items and their associated resources. Keywords, categories and subcategories, and user-defined tags (to name some of the tools available) provide the means to associate and group resources and thus to initiate and define complex cross-relationships. Certainly it is possible (and will be done) to create graphs and other diagrams that, at a glance, map these relationships and point to new associations in the researcher's mind. However, much of the use of *WIKINDX* requires the researcher to type in terms or to select keywords and categories from a text-based form where there would be no place or space for such images. Our hearing is always active and sound can be heard even if the source cannot be seen. This, then, is part of the thinking behind our reasoning that sound might be combined with *WIKINDX* user operations to provide the ideal means to accomplish the goal of a pro-active research tool that is an aid to innovative thought and the creation of new knowledge. Sound, though it can be combined perceptually with image and other modes, exists in a distinct sensory space and thus can complement information displayed on the screen without disturbing or obscuring the space that information is displayed within. We have other reasons for wanting to assess the efficacy of sound for such a research tool that we describe below.

[1] http://wikindx.sourceforge.net/

[2] e.g. by NASA, the CNRS and a variety of university and multi-national research groups.

2. SOUND AND DATA REPRESENTATION

As previously mentioned, in Western culture at least, there exists a well-developed system of image-based signs that can be used to represent data and concepts. If not representing such data and concepts in all their inherent precision and detail, such signs, in the form of diagrams and graphs, are perfectly capable of presenting enough of the general outline and concept of the thing being represented to allow the viewer a good grasp of the basics (if not the salient details). Typically, such graphs are static but moving image technology allows a level of dynamism and thus allows for aspects of change over time to be represented.[3]

Such a system can be theorized further – through semiotics and later variants, for example – but, at heart, it is metaphorical. A variety of simple graphical elements combine to create a more complex representation that, with regards to meaning, is greater than the pictorial sum of its parts. Such elements, depending on the graph type being used, might include lines and arrows, circles and ellipses, numbers and figures, colours and shading, and scale and direction. Each of these signifies something in the given context – a line moving upwards across the page from left to right might represent an increase in amplitude over time – and it is with a practiced eye and the combining of these elements that the viewer is able to grasp the outline of the data and comprehend the concept contained within the graph. Here, the term 'practiced eye' is very important and we return to it later.

It might seem utterly irrational to attempt to metaphorically recreate through sound such a synthesis as images appear effortlessly to provide (particularly when we require the system to lead to creative thought and new knowledge), yet it is our contention that sound can provide such a function. When considering the acquisition of information, it could be asserted that an exact and objective knowledge is unattainable due to the limited capacity of the tools (such as language) we use to gain such knowledge [9]. Recent research has proposed that the finite value of visualization representation techniques is becoming apparent, in that "we are approaching the limits of users' abilities to interpret and comprehend visual information" [1]. In addition to the clear limitation of visual representation techniques for individuals with visual impairments [10], particular scenarios

[3] Change over time can, of course, be represented on a static graph.

exist in which the use of visualization(s) is inappropriate, such as vehicle operation. In such cases, the eyes are required to provide continuous attention upon a specific point and visual representations may distract the user, create a bottleneck in performance or even compromise safety [11]. The widespread development of mobile devices also presents a limitation of visual representation techniques, in that increasingly compact viewing screens with limited spaces for visually displayed information restrict the quantity of comprehensible information that can be presented to the user [12].

The use of sound to convey information is by no means a modern novelty; seminal designs such as the Geiger counter clearly demonstrate a practical application in which a sonification system provides genuine improvement of functionality over a visualization equivalent. Kramer et al. note that alongside this device, vital tools, including sonar, the stethoscope, and the auditory thermometer, all predate the term sonification [1]. Fitch and Kramer, using systematic experimentation, discovered that during a simulated operation, medical students performed significantly better when eight relevant data variables were presented as to them as sonifications, in comparison to both visualizations and a multi-modal display [13]. This reinforces the notion that in scenarios where constant visual attention is required, display systems must provide ancillary information by way of an alternative modality to ensure high performance.

Flowers et al. advocate multi-modal data presentation techniques as a superior path to knowledge through increased potential for information recall and recognition and state, in relation to sonification, that "the addition of data descriptive sound to presentation graphics in instructional settings may be of considerable benefit" [14]. Flowers et al. further contend that sonification utility may extend beyond efficiency and accessibility of information to display patterns, classifications, features and trends within the datasets that cannot be clearly perceived by way of a visual equivalent. Kramer documents a notable example of this when, in 1979, data from the Voyager-2 spacecraft raised concerns [15]. A visual analysis of the data could not identify the source of the problem but a sonification technique (in which the data was routed through a synthesizer) enabled successful diagnosis.

With the development of increasingly powerful computers, sound can now be dynamically manipulated in real-time by a range of acoustic parameters. This enables current sonification systems to represent samples of data, reveal distribution properties and display patterns of covariation between two variables [14]. As technology develops, the future of sonifications appears substantial. Barrass and Kramer argue that many visual displays will be replaced with sonification equivalents and describe a range of encouraging applications, from presentation of forensic evidence within a courtroom to the audition of a user's own internal health [3].

We argue that the very illogicality of the concept (of using sonification techniques to facilitate creative thought and to synthesize new knowledge) may prove especially useful if we take Karl Popper's words to heart: "[t]here is no such thing as a logical method of having new ideas [...] every discovery contains an "irrational element"" [quoted in 16].

Even single sounds can be used to represent complex situations and ideas. Sonic alarms, for example, are probably heard every day by the majority of people in the Westernized world. From the mobile ringtone to the honk of a car, from the bedside alarm clock to the ambulance siren, each of these can potentially signify and bring to mind a host of concepts both general to society and highly personal depending upon context. *Wake up and get to work!* Or: *That's my daughter's ringtone – there's still two hours before she's due home from the party so I hope nothing has happened.*

Other sound systems in addition to alarms exist and computer user interfaces are a particularly fertile area of study. Modern personal computers come with a range of auditory icons [see 17] to represent and/or confirm computer or user actions such as the trashing of a document or the arrival of email. Such sets of sound, and their usage, can often be customized according to user preference. Computer games likewise contain a variety of sound FX that are specific to the game and that aid players in interpreting game events and in placing themselves within the gameworld. The artificiality and arbitrariness of many of these sounds is evidence that sounds and sound systems can, within specific contexts, acquire quite precise meaning through the learning of associations.

The discipline of sonification is analogous to that of visualization. The *Sonification Report* sets out an agenda for research into such representation of non-audio data and, in particular, states the need for a study of the relationships between acoustic properties and events, or at least attending to those events [1]. Attending to events is a common use of sound particularly with the computer-based auditory icons described above. Yet, our fundamental question is related not to the attending of events but, rather, to the use of sound to create the conditions for creative thought and insight to occur and to facilitate the synthesis of new knowledge.

Academic research concerning creative environments is primarily concerned with our direct interactions within the environment and most commonly, interpersonal relations [18, 9]. The principal requirements for creative thought are most commonly introspective, personal characteristics that exist within the creative individual [19] including openness to new experiences, confidence, self-acceptance and a genuine love of the undertaken task [20, 21].

Indirect or subconscious interactions with the environment itself are less commonly referenced and are more likely to be documented within articles concerned with interior design or child education, within which the specific exploration of environmental factors upon creativity is underrepresented. We assert that documented variables such as employee hiring policy and prestige [19] are incidental and that, instead, a core emotional response drives creative thought and innovative design, and such an emotional state is not wholly dependent on context-specific variables. Singer, for example, suggests that "a psychological condition that excites and masterfully activates the central nervous system" might be one route to creative thought [22]. The question remains, however, as to whether sound can manufacture an environment capable of stimulating creative thought in a way comparable to that of the variables documented above. It is in pursuit of the answers to this question that we now turn our attention to other related questions.

3. SOME QUESTIONS

Before the fundamental question can be answered, other, more specific questions must be asked and the answers attempted. It is not our intention here to provide those answers but we will be attempting to map out a research agenda on the basis of the questions. Similarly, it is not our intention to define all questions that may be asked but to outline those we think most important to answer as a means to reach our goal.

Perhaps the most important question here is that of mapping. How does one map in a meaningful way acoustic parameters to data and thus, in the combination of such mapped representation with context, represent concepts? Acoustic parameters commonly associated with music such as pitch, tonal timbre and volume are established approaches [23]. If we take as a simple example the ascending line (linear or a more complex shape), one might suppose that the most logical (that is, the most obvious) sonic analogy would be a single sound of ascending frequency. The assumption here is that the ascending frequency is analogous to the ascending line and that this, therefore, represents something increasing, its quantity or quality rising. This assumption can be found in operation in a number of areas not least the isomorphic sound FX of many cartoons and animated films – as a character goes up some steps, there often is an accompaniment of a rising melodic scale. Similarly, as the character then falls down the steps, there may be a descending melodic scale to the accompaniment of percussive sounds accenting each painful bump of that descent.

As pitch rises according to our hearing perception, frequency certainly also increases (according to the scientific representation) yet the period of the waveform decreases. One theory of pitch perception maps frequency directly (and more or less linearly) to pitch while another theory maps pitch inversely to period. This example is used to illustrate the arbitrary nature of some mapping systems and to demonstrate that some of the apparently most obvious decisions are open to question. An *increase* of some value may well be best represented by an *increase* in frequency but can it not be equally logically represented by an *increase* in period (and thus decreasing frequency) and, why not, growing volume or a movement of sound in space that traces the shape of the graph?

Pitch as a representative of some variable is further limited if changes do not occur in a smooth, connected sequence. If pitch variations are separated by periods of silence then the listener cannot follow the curve of the signal but must instead attempt to differentiate the tones in a manner equivalent to musically determining melodic intervals. This itself is a skill that many would require training in to become proficient [23].

Localization (placing the sound at a distinguishable angle in relation to the listener by way of digital signal processing) may have great potential as a parameter for sonification yet, there remain practical concerns and most notable are those linked to current hardware. Franklin and Roberts document the limitations of conventional headphone and speaker setups, noting that listeners are subject to the minimal audible angle (MAA) problem that reveals the restricted ability human ears have to distinguish between varying degrees of the sound localization [23]. Furthermore, listeners wearing headphones have found it difficult to even distinguish between sounds placed in front of and behind their position [24].

As documented above, many current computer software programs and electronic hardware devices employ both auditory icons and earcons to good effect. It must, however, be acknowledged that in most circumstances, these soundsets are either embellishments to the primary visual indicators or learned associations that have become established to the user only after repeated exposure [3]. Whilst learning such associations can be encouragingly efficient when dealing with small quantities ("novices are able to learn 4-6 symbolic sounds within minutes"), larger numbers of earcons can take substantially longer to learn and the task may even be impossible for some individuals [25].

Throughout this paper, we have asked a question about using sound analogously to a graph. One question that arises from this is what properties of sound or hearing that image and vision do not have can be used to advantage? One quite obvious property is that of time. Unlike (static) image, sound only exists in time; it requires time in order to be perceived. Of course, there are moving images and it is the case that graphs, given the appropriate technology, can be made dynamic in order to bring in the concept of something happening to the data set over time. However, as the *Sonification Report* states, hearing is more sensitive to temporal change than vision [1]. Other differences exist such as: the field of hearing is wider than the field of vision; and the fact that our hearing cannot be turned off by closing our ears (although it can be affected by damage or through artificial means). Our hearing system is always sensing and always perceiving and this has been used to great effect using sonification techniques in projects such as the network monitoring of the now defunct *Project Peep*[4] not to mention that it is the reason why bedside alarm clocks function.

We have previously used the term 'practiced eye' to describe how viewers interpret a graph. There is little if any meaning inherent in the images of a graph. In order to ascribe meaning from such, in order to divine the graph creator's intentions, in order to convert meaningless image to meaningful symbol, we must first learn the language of graphical symbols and much time is devoted in our education to this. We learn that ascending lines on the graph typically mean an increase in something. Furthermore, this system must be one based on a widespread consensus or acceptance and must also be one that accommodates stylistic variation whilst retaining general meaning. For example, the wide variety of symbolic arrows in use all represent a general meaning in that they point to or connect things while in their thickness, their shape, their shading or colour, they add to that base meaning another layer of meaning within the context they are used.

How, then, to arrive at a consensus for a metaphorical sound system while at the same time accounting for the human ability to ascribe one general meaning to such a wide range of sounds as alarms? One could say that a consensus need not be sought and that the system may be imposed on its users. This is what has happened in some computing and related areas. In most computer games, for example, players must learn the given sound symbol set and the individual sound's meaning in the particular context in which it is used. Conversely, one need not impose but also one need not achieve consensus at all, instead allowing users of the system to define their own sound-meaning combinations that become ingrained over time. We can, for instance, spend hours deliberating over which mobile ringtone to use. In addition to a user-determined association matrix, such a sonification system could facilitate the full flexibility of bespoke user-generated audio content or even provide preset options that reflect a variety of applications (much in the same way as a reverberation plugin within a digital audio workstation program might offer parameter presets such as hall or plate).

The final question that we wish to deal with here brings us back to the motivation for this paper. How can sound be used to facilitate

[4] Last retrieved May 12, 2003, from http://peep.sourceforge.net/docs/peep_proposal.html

inspiration and to create the conditions for creative thought and insight to occur in the context of a VRE? We first start with a summary of what the functionality of a VRE should be; using *WIKINDX* as an example, we summarize what it *is* capable of and what we would like it to be capable of. We then proceed to a brief analysis of how sound might be used in this regard, both to sonify what can already be represented through other means and to create the aforementioned conditions that we are aiming at.

A VRE should provide the means to collect, store, organize and retrieve research materials through as efficient a mechanism as possible and should be usable either by a single researcher or a group of researchers. The research materials *WIKINDX* manages include bibliographies, relevant file attachments, external resources, and pertinent quotations, paraphrases and user-generated ideas. These can all be organized, grouped and cross-referenced through the use of categories and subcategories, keywords, personal user tags, and user bibliographies. Research material can be selected according to these parameters or can be searched through using free-form search phrases. The use of a web browser to access the VRE expands its use to geographically dispersed research groups. Finally, although this need not be the case for all VREs, a VRE such as *WIKINDX*, is agnostic as to the academic discipline or research field it works within; it is entirely up to the researcher(s) as to what is placed in the VRE. This has particular implications for the support of interdisciplinary and, intriguingly, transdisciplinary research methods regardless of whether such research is conducted by an individual or by a research team.

The visualization of such materials is a relatively trivial matter using well-established diagrammatic and graphing conventions. A hyperlinked map of cross-referenced materials can be produced whereby lines of various thicknesses or colours represent particular aspects of the cross-referencing relationship or pie charts can be devised to immediately explicate the relative distribution of certain keywords. To some extent, *WIKINDX* already has visualization of materials in its use of simple bar graphs showing quantity of publication type or its 'tag clouds' where the size and colour of font refer to the frequency of occurrence within the wikindx of authors, keywords, publishers and so on.

More challenging is to represent the examples given above not through image (or image alone) but through sound. Past research has developed sonification systems that duplicate the functions of various types of graph. Flowers and Hauer created a system for the sonification of histograms, using note lengths and tones on a chromatic scale to represent frequency distributions [26]. Franklin and Roberts present a range of alternative techniques for sonification of a pie chart, including one design that utilizes localization to place the listener in the epicentre and display the segments around them [23]. The technical process of sonification itself is relatively simple; more complex is arriving at the decisions underpinning that process and that must be made with a view to their providing a comprehensible and meaningful result. We have mentioned mapping before; the decisions to be made as to how to map fundamental acoustic parameters (frequency and amplitude, for example) to parameters of the VRE materials and how meaning might then be ascribed to such mapping for the user's comprehension. Other parameters in our acoustic arsenal might include reverberation, changes in equalization, tone timbre, aggregation of sound, and spatial location.

We could impose such mappings, such pre-defined sound-meaning relationships, but perhaps more fruitful would be to devise a system that allows the users themselves to decide such mappings and then to apply them to the VRE's data. This system has the benefit of being reasonably culturally aspecific and of making efficient use of the user's prior experience and expectation of associated meaning. There is precedent for this. The *Sonification Sandbox* [10] utilizes the java programming language to construct an accessible graphical user interface that allows users to associate numerous auditory parameters (including pitch, timbre, volume and pan) to datasets. Similarly, Liljedahl and Fagerlönn devised a sound synthesis interface to allow drivers to design the alarm sounds that they themselves found most appropriate for the auditory display of external driving conditions [27]. Such systems, however, are potentially impractical as an initial adjunct to the VRE given the number of parameters and mappings to be catered for. As an initial step in our investigation into how sound parameters can be generalized such that they can be ascribed meaning in the way that symbols in a graph have, we can find simpler and more immediately fruitful ways that we discuss further below.

As with graphs, none of this sonification would have any purpose were users not able to go a step beyond interpreting sounds as representative of data to grasping the significance of the data and the underlying concept(s) behind its representation. Going further yet, can the user generate new ideas that have been sparked by this novel use of sound? As diagrams and graphs can lead to insight into the fundamental nature of the universe, can sound do likewise and, importantly, can the unique properties of sound and the peculiar nature of hearing perception lead to insights and new thinking that would not otherwise be available through vision alone? As yet, we have no answers to this; we merely pose the challenge and, below, map out a research agenda in order to make a start in attempting that challenge.

4. CONCLUSIONS AND RESEARCH AGENDA

It has been our contention throughout this paper that, as a means of representing data and concepts, sound may be employed to function in a manner similar to diagrams and graphs and furthermore, in some cases, that it may be a superior mode due to the differences between image and sound and between vision and hearing. There is nothing new in this contention and such claims and several implementations of them have been detailed here. However, we additionally contend that such sound use may be taken further to achieve the conditions for insight and creative thought to occur and, thus for new knowledge to be synthesized. Such a goal, if it can be achieved, has particular implications for the design and use of VREs such that they may become pro-active research tools guiding the researcher(s) to hitherto unthought of research directions and conceptual thinking.

We have posed a number of questions related to this goal and, here, map out a research agenda that we believe must be followed in order to achieve that goal. Some of the work involved in this agenda will contribute to the research agenda already mapped out in the *Sonification Report*. In particular, such work concentrates on defining a semantics of sound similar to the semantics already achieved in the use of diagrams and graphs. Other aspects propose theoretical and empirical approaches to the use of such sonification in achieving the primary goal; that of a sonic environment that facilitates insight and creative processes such that they may then lead to the synthesis of new knowledge.

- Continue investigations into the semantics of sound and, in particular, how sound may be used to represent non-audio data and complex concepts. Issues to be dealt with here include:

- how to map parameters of the data to parameters of sound such that comprehension of that data is maintained and perhaps even enhanced;
- how such sonic mapping, when combined as the elements of a graph combine, allows for the grasping of fundamental concepts regarding the data thus represented;
- how to achieve a comprehensive and easily comprehendible sound language that is applicable across different types of data set. As the interpretation of graphs is taught in schools, the development and use of such a language is similarly likely to require widespread education. Barrass and Kramer posit that sonification could be taught within a general curriculum pending a more widespread acceptance of the concept [3]. Kramer et al. revisit this notion, stating that there remains a clear need for a consolidated curriculum of sonification [1].

- Investigate the utility of user-centered design in the development of a widespread common language of sound. Such an approach has the benefit that any language thus developed is likely to be more experiential and universal in its genesis and application as opposed to imposed and artificially created according to the dictates of its designer(s). Conversely, but following a similar user-centered ethos, this approach could lead to VREs wherein sound parameter to data variable mapping may be designed by the user to make use of personal experience of, and preference for, particular sounds and aggregations of sounds. Elsewhere in this paper, we have suggested that the personalization of such mapping militates against the development of a sound language consensus that operates analogously to a language of graphical symbols. Intriguingly, an empirical study of sound mapping preference may reveal a culturally specific yet hitherto hidden consensus.
- Investigate further the deictic use of sound, its abilities to point to other information in the wider context. This has particular implications in the potentially interdisciplinary context of a VRE. We imagine, for example, a VRE that, upon noting that the user has entered a certain search term, is able to use sound to point out to the user other related materials in the VRE that the user, following a typically narrowly discipline-oriented research path, may be unable to otherwise find. This leads to the possibility of the connection (in the researcher's mind) between previously unrelated concepts. Such unexpected connections and combinations, along with the provision of a novel, sound-based research strategy, will aid in the promotion of the creative environment we intend to achieve.
- Investigate new technologies, especially those that promote emotion states, as an aid to achieving the creative environment we seek in *WIKINDX*. Of particular interest to us, given work we are already undertaking [see 28, 29], is the use of biofeedback technology in engendering those emotional states in the user that are most likely to promote creative thinking and an exploratory frame of mind. If we can use such technology to synthesize or process sound in a computer game environment such that it promotes certain emotion states in the player, perhaps we can contribute further to the semantics of sound by classifying those sound parameters and variables most likely to engender those states. If we can do that, then perhaps we can create VRE sound environments conducive to creative and exploratory thinking.
- Investigate which audio synthesis system to use. *WIKINDX* is a web-based system making use of PHP and MySQL and, historically, audio capability on the web has lagged behind text and image capability. HTML 5 and new javascript functionality improve the picture somewhat but, while it is possible to synthesize sound on the fly, it is not then possible to manipulate that sound in real-time as the user navigates the VRE. It may be that java offers better audio functionality in this respect but unfortunately raises cross-platform compatibility problems and requires users to maintain a compatible java environment beyond the standard web browser functionality that *WIKINDX* strives for.

In this paper, we have posed the research question: How can sound be used to function analogously to the function of the images in a graph in order to create the conditions for creative thought and insight to occur and thus to facilitate the synthesis of new knowledge? We have defined a number of other related questions and mapped out the research agenda that we believe is required to attain that goal implicit in the research question. We do not doubt that such an agenda requires a long-term and high-risk research strategy that involves much experimental investigation from multiple directions (it is not necessarily the case that new knowledge will arise from the creative environment). However, even should our goal prove to be ultimately unattainable, we believe that the journey will be worth the effort in its potential to contribute further to the understanding of sound and our relationship to it.

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