REIMAGINING HUMAN CAPACITY FOR LOCATION-AWARE AURAL PATTERN RECOGNITION: A CASE FOR IMMERSIVE EXOCENTRIC SONIFICATION

Ivica Ico Bukvic

Virginia Tech,
SOPA, DISIS, ICAT,
24061 Blacksburg, VA, USA
ico@vt.edu

Gregory D. Earle

Virginia Tech,
Electrical and Computer Engineering,
24061 Blacksburg, VA, USA
earle@vt.edu

ABSTRACT

The following paper presents a cross-disciplinary snapshot of 21st century research in sonification and leverages the review to identify a new immersive exocentric approach to studying human capacity to perceive spatial aural cues. The paper further defines immersive exocentric sonification, highlights its unique affordances, and presents an argument for its potential to fundamentally change the way we understand and study the human capacity for location-aware audio pattern recognition. Finally, the paper describes an example of an externally funded research project that aims to tackle this newfound research whitespace.

1. INTRODUCTION

Human interfaces to the natural world are inherently multisensory [1]. In simulated environments we often mimic our interaction with the natural world by combining sensory mechanisms to broaden cognitive bandwidth [1], [2], as well as to reinforce comprehension [3] and learning [4], [5]. A 1997 report to the National Science Foundation [6] defines sonification as "the use of nonspeech audio to convey information". In this paper the authors refine this definition only slightly, using the term sonification to describe *the process of using sound to convey information that is not inherently auditory*.

Despite decades of concerted research, sonification remains vastly underutilized. In 1999 Hermann and Ritter suggested that sonification is an "underused perceptual channel for man-machine-interaction" [7], and in 2007 Nasir and Roberts stated "that researchers have not fully utilized the maximum potential of spatial sound" [8]. More recently, a 2014 paper by Thomas Hermann suggests that sonification is still in its infancy [9]. This continued challenge presents us with a seemingly obvious question: after decades of rigorous research, why is sonification still in its infancy? There are many facets to this complex issue. By leveraging the aforesaid immersive exocentric approach this paper proposes a path forward.

2. THE EXOCENTRIC ENVIRONMENT

Central to this paper is the idea of creating and exploring an exocentric environment through sonification. This naturally leads to the question: what is the working definition of the term "exocentric environment"?

The term "exocentric environment" has its origins within the context of immersive environments where it suggests an out-of-body experience [11], or an immersive environment that completely encompasses the user [17], [18]. What is particular to this definition is that the observer is not considered the center of the experience (as would be the case if we were to observe the immersive environment through their point of view), but rather as one subject with a unique and adjustable vantage point. In the context of sonification an exocentric environment does not treat the listener as the center of the listening environment. Instead the listener is a mobile actor who can navigate the space and adaptively interact with the real world to enhance their capacity to localize and discriminate various concurrent sounds. This specific meaning of "exocentric environment" is used throughout this paper. We will return to it at the end of the paper where we propose a new set of guidelines for studying the human capacity for location-aware audio pattern recognition.

3. LITERATURE REVIEW

To better understand the current state of sonification research and its limits we present a cross-disciplinary review of 21st century literature in the field of sonification in a number of scholarly communities, including the Association for Computing Machinery (ACM), the Audio Engineering Society (AES), the Institute of Electrical and Electronics Engineers (IEEE), and the International Conference on Auditory Displays (ICAD). The overall goal is to identify similarities, patterns, obstacles, and promising areas for future studies.

The Association for Computing Machinery (ACM) science cohort's early research has yielded promising results hinting at sonification's potential both as an independent form of representing data and, when coupled with a visual feedback, as a means of broadening cognitive bandwidth [2], [10]. Since 1999 the entire community has produced 28 publications on the topics of sonification and spatialization [11], a number of which mention spatialization in contexts outside of audio environments. Most of these reduce spatial data to a single-dimensional output [12], or rely on approaches (e.g., headphones) that decouple aural perception from other sensory inputs [13]. This is unlike any other domain of human sensory perception. For example, in studying visual perception, even if the experimenters immobilize the user's head, the user still retains the ability to create a spatial image through eye movement. Some research has gone as far as to suggest that sound is an inherently non-spatial medium [14], although this argument is easily refuted.

http://doi.org/10.21785/icad2018.021

Recent areas of research include assistive technologies [15]–[20], reflective practice [21] and biofeedback that all but ignores our human auditory spatial capacity [22]–[28], or implements a spatial component in an egocentric way [29]–[31]. Studies of this type often yield discouraging data [32]. A few researchers have focused on studying infrastructure for the delivery of spatial information [33]. There are notable exceptions [34]–[36] that focus on perception and cognition of spatially delivered stimuli, and even go as far as simulating elements of an exocentric environment [34]. However, none of these studies focus on spatial aural perception in a true exocentric environment.

Similarly, a review of the Audio Engineering Society (AES) community's output over the past 6 years offers three notable publications on the topic of sonification [37]–[39], none of which utilize the exocentric environment. A number of publications [37]–[45] either do not concern themselves with audio spatialization, or study it in isolated scenarios not directly related to sonification. Recent Institute of Electrical and Electronics Engineers (IEEE) literature echoes the ACM and AES trend. Topics can be categorized as fundamental studies [46]–[49], aggregators [50], [51], contextual spatialization algorithms [52], spatially sonifying data using virtual solutions [3], [26], [53]–[55], or sonification without any spatial component [56]. The best resource for sonification and spatialization research is found in the International Conference on Auditory Displays (ICAD) community, which annually publishes 50-70 papers that focus on sonification, spatialization, or both. Below we cite those most relevant to our theme.

The reasons for the apparent disparity between research and broad adoption are undoubtedly numerous and not yet fully annotated. Gregory Kramer talks about "clear parallels between the composer's role in [auditory displays] and the graphic artist's role in data visualization." He goes on to state that "Improved aesthetics will likely reduce display fatigue" [57], suggesting that part of the challenge in sonification processes is the ability to deliver content that is not tiring. Solving it will in great part depend on context-aware case-specific solutions.

There are other more pervasive challenges in the current sonification literature that are inherently tied to human ecology [58], or the ways in which we perceive our environment. Studying how we perceive spatial sound in a natural environment makes it difficult to decouple different sensory mechanisms, so the results of such studies may differ significantly from outcomes in which such mechanisms are studied in isolation. Despite this apparent bias, a vast majority of sonification projects and studies focus on simulating virtual environments, often by relying on an implementation that decouples the user from their immediate environment and eliminates input from other senses [59]. The most common examples of this are studies that rely on a headphone-based delivery system that utilizes discrete [60], stereo [26], [28], [61]–[63], or some form of head-related transfer function (HRTF)-based implementation [5], [54], [64]–[67], [68].

The aforesaid citations represent a snapshot of a larger volume of examples, so they should not be considered exhaustive. Instead, they are meant to offer examples of each of the aforesaid categorizations. A considerably smaller number of research projects explore spatial sound [55], [69], with a majority continuing to be linked primarily to kinematic data [70]. Interestingly, one paper [55] considers spatialization approaches like Vector Based Amplitude Panning (VBAP) [71] to be inadequate because of implicit assumptions that data perception should be decoupled from the perceiver's vantage point. In contrast, spatialization studies can be approached as an opportunity for users to traverse a simulated exocentric environment akin to the way they interact with the real world [34], [72], using their vantage point in a natural way to attain greater clarity. For instance, a user approaching one part of an audio display can naturally generate and process amplitude disparities in the overall image, allowing them to more easily separate sources of particular interest. The result is akin to the cocktail party effect [73], in which we tend to stand in proximity to key points of interest, facing them to ensure we have a clear understanding of their locus and that they stand out above the environmental noise floor.

4. DISCUSSION

The aforesaid literature review offers two noteworthy observations. First, there appears to be little overlap in institutional knowledge between different scientific communities. This limits the impact of the ensuing scholarship and leads to inefficiency and redundancy. This issue is certainly not limited to the sonification research, and it undoubtedly stifles progress.

Second, of all the extant research only a small subset is concerned with studying human spatial aural perception. This is surprising considering how integral the immersive spatial component is to human auditory perception. Further, of those projects that do explore the spatial context, virtually all focus on some form of simulation of spatial content, most commonly utilizing HRTF or similar approaches to spatializing sound. In doing so, such implementations are hampered by idiosyncrasies. For example, headphones restrict the ability to convincingly place sound in front of the listener, and in and of themselves are unable to address the front-back confusion. These issues are naturally mitigated by head movement in real-world applications, yet in many studies they are rendered ineffective by the delivery methodology. Because simulations often do not account for head movement, such ambiguities may be compounded. Finally, the addition of other simulated spatial sound perception (e.g. head tracking) may create its own idiosyncrasies, such as those stemming from latency.

The vast majority of research in sonification is focused on placing the listener at the center of a space with optimal loudspeaker distances and phasing. The goal is often to identify limits of human perception when the audio component is decoupled from the other senses. This kind of foundational knowledge is essential to understanding the core capacity of human auditory perception, but it is hardly representative of the way in which humans interact with auditory cues in the real world. Humans naturally process data concurrently from different senses to mitigate limitations that stem from one sensory input. For instance, head movement is a simple kinematic approach that can help minimize the impact of the cone of confusion and/or front-to-back ambiguity in spatial auditory perception. One's location and orientation can help to identify critical details that may stimulate a more comprehensive understanding of the surrounding environment and its stimuli. Instead of placing the listener in an egocentric environment where they are ideally equidistant to every loudspeaker around them, allowing user to move and disrupt the loudspeaker distance equilibrium recontextualizes such a space into an immersive exocentric environment where user's interaction with the surrounding stimuli is more similar to the way we naturally perceive the world around us. To date, only one study [74] has shown interest in exploring such an exocentric environment, and it has yet to provide any tangible or reproducible data.

5. A CASE FOR IMMERSIVE EXOCENTRIC SONIFICATION

We posit that studying the way we perceive the world through sound should be inherently holistic. It is worth noting that the spatial dimension of human hearing capacity is inextricably linked with stimuli perceived using our other senses, particularly sensations related to head rotation, head position, and visual cues related to location awareness. For instance, to minimize the so-called cone of confusion for sounds to the left and right of our head where there pinna is unable to create filtering variance, we commonly rotate our head to change our perspective relative to the sound source and better pinpoint a sound. Inability to do so vastly limits our capacity to locate sounds, and may result in errant conclusions. For example, studies that do not account for this capacity may conclude that our spatial hearing capacity seems lower than it actually is.

Even in a reductionist approach to studying human sight, we do not prevent users from moving their eyes or head. These are, after all, critical elements that enhance our ability to see because our eyes only have a very narrow area where we can clearly perceive details; the edges of our field of view are blurry, but still sensitive to motion and change. It is the brain that constructs a holistic image as our eyes scan our surroundings using eye muscles, and this process is further enhanced by our head and body motion. In studying aural perception it therefore makes sense that we should allow and encourage movement, particularly in immersive three-dimensional environments, thereby encouraging ecological validity of the ensuing research data. By moving within the space we refine and improve our ability to locate sound sources. For example, those of us who have placed calls to our cellphones in order to find them in cluttered environments can vouch for the advantage of walking around while listening for its ring. As we search, the ability to move throughout the space enables us to use the loudness of the ringtone, as well as any potential reflections to our advantage.

Coupling head position, body movement and position awareness with our hearing perception enhances the way we interact with our environment, and it comes naturally to us. We don't have to train for it. We simply interact.

Now, consider a walkable High Density Loudspeaker Array (HDLA) environment with loudspeakers all around you, including above and below. As you move around the space, you are able to get closer to a particular sound, thereby naturally attenuating the perception of other sounds while concurrently using your spatial memory to generate a comprehensive spatial map. In such an environment you can interact with sonified data in the same way you interact with the real world. The ensuing immersive exocentric environment offers unique opportunities for immersive exocentric sonification. Here the sonification emanates from the space perimeter and does not require the user to remain in one location to explore the volume and phase characteristics of the immersive sound field.

When considering exocentric sonification, it is worth noting that the varying distance between the loudspeakers and a listener navigating the space is not detrimental. Rather, it is an advantage that more closely resembles the way we interact with the world. There may be phasing artifacts and other unforeseen interactions. Yet, the same are commonly experienced in the real world and while they may adversely affect the overall aural image, the advantage of cross-pollinating sensory input, as well as the ensuing amplitude differences are likely to offset any such shortcomings by significantly improving our spatial resolution. Consider the way we perceive movies on traditional cinema screens that, depending on where we sit, may be too large to fit within our peripheral vision. Under such circumstances, some of the areas on the edge of the large screen are much farther from our eyes than others, leading to unusual distortions to the image's perspective in respect to our vantage point. Yet, our brain understands this is a flat image and we happily reconstruct it as such in our heads without any concern for its observed physical distortion. By extension, akin to Layer Based Amplitude Panning algorithm (LBAP) [75], in the exocentric environment speakers within the same horizontal layer share the same elevation, much like a row of pixels on a screen. Once we have the overall awareness of the visual (e.g. TV) or aural (e.g. HDLA front defined by its loudspeakers) canvas, our brains are capable of compensating for such physical inconsistencies in favor of maintaining consistent relationship between the individual loudspeakers, or, as is the case with its visual counterpart, between the pixels on a screen.

The immersive exocentric environment and, by extension, immersive exocentric sonification focuses solely on the space's perimeter where the loudspeakers are located. While there are ways of simulating sounds within the space, particularly when using the wave field synthesis (WFS) [76] and the ambisonics [77], they are prone to idiosyncrasies that limit the human ability to move and study such sources from different vantage points. If we were to consider the ensuing speaker front or perimeter as one canvas, we could project and move data across it. For initial studies the most obvious data choices may be inherently spatial data, such as geographical or geospatial data that limit the need for arbitrary assignment of variables to the spatial component. We posit that immersive exocentric sonification presents an opportunity to enhance and consolidate sonification research. This approach has not been adequately studied, and it has the potential to change the foundation of our understanding of human spatial aural pattern recognition.

6. REAL-WORLD APPLICATIONS

Studying human auditory perception in isolation is an important step towards understanding the limits of human sensory mechanisms and is a critical precursor to the immersive exocentric sonification. Yet, the application of such findings in real-world scenarios without considering other complementing sensory dimensions may lead to misleading conclusions, including lower perceived human spatial auditory perception capacity. As such, one could argue that studying human spatial hearing without incorporating head and more importantly body movement and location may be just as misleading as studying human vision while disallowing head, body, and eye movement. The immersive exocentric approach to sonification described above aims to address this potential pitfall and is rooted in the way we interact with our world. As a result, it feels natural and intuitive.

Its applicability can be seen both on micro and macro scales, as well as in natural and human-made environments. Let us return to the aforesaid example of how we may want to search for a misplaced smartphone in our home. Commonly we resort to calling it to hear the source of its ring. As the smartphone rings, rather than standing in one place we move around and typically closer to the source to improve our spatial resolution that is often impeded by physical and acoustic obstacles. We may want to consider this a micro scale natural environment.

Now imagine a large space equipped with a cutting-edge technology capable of monitoring human presence, motion, location, and user input, while offering a multisensory immersion in a complex dataset. Such an immersive environment is commonly referred to as the "decision theater" [78]. This macro scale human-made environment presents another case scenario where both the spatial aural and multisensory data immersion can take place and where listener location, motion, and orientation can help amplify their understanding of the data and the ensuing patterns. For instance, as they move closer to the edge of the space populated by an aural (e.g. a loudspeaker array) display, listeners attain greater spatial resolution and can effectively amplify specific sources of interest and consequently the perceived signal (source of interest) to noise (other sounds) ratio due to change in their proximity and orientation.

As evidenced by the literature review, virtual immersive spatial sonification has greatly benefited from the advances in immersive technologies, allowing for the incorporation of head rotation. Its utilization is steadily increasing. Yet, even in virtual immersive auditory environments that focus solely on the head rotation, it is worth considering that rotation also includes translation, allowing for ears to be closer to the source. If such scenarios were to utilize virtual sources placed in close proximity to the listener's head, such an aural spatial image stands to benefit from the increased spatial resolution due to head movement. This, arguably micro-scale human-made environment could have a far-reaching impact from spatial aural cues in operating equipment (e.g. cars and airplanes), to data rich environments and "decision theaters" that provide multisensory feedback with the goal of broadening cognitive bandwidth.

The immersive exocentric sonification may have applications in a number of scientific domains, both as a novel methodology for data analysis and as a teaching tool. To determine the extent of its utility the initial research needs to focus on using physical, real-world environments and inherently spatial datasets to the extent possible, thereby minimizing reliance on the virtual and its limitations and idiosyncrasies. Such an approach requires an immersive HDLA facility. One such facility is Virginia Tech Cube. It is a configurable immersive studio measuring 50x40x32 feet. It is equipped with 24 motion-capture cameras and 149 of individually addressable loudspeakers distributed over the ceiling and walls to create a flexible and powerful immersive audio environment. Since its introduction in 2013, the facility has been used in dozens of research projects, ranging from scientific to artistic.

To assess the impact of the proposed immersive exocentric sonification, the authors are currently leveraging the said Cube through an externally funded effort to study its utility for scientific data analysis, as well as to compare its capacity to the existing approaches, including virtual counterparts. Of particular interest is the capacity of the immersive exocentric sonification and its unique affordances to reveal correlations and inter-relationships between measured variables that are not easily revealed by conventional analysis techniques, such as visual inspection of standard two- and three-dimensional graphs. Our project title is SADIE, an acronym for Spatial Audio Data Immersive Experience. The main objectives of the study are to experiment with various sonification techniques, to uncover differences in spatial aural perception between the traditional egocentric approaches and an immersive exocentric environment, and to determine whether test subjects within the exocentric environment can experience an enhanced ability to detect subtle relationships between variables that represent real-world data.

7. SADIE

The SADIE project utilizes inherently spatial data representing an esoteric realm in Earth's geophysical environment, the ionosphere. We focus on the altitude range occupied by satellites in low-Earth orbit (LEO), where satellites, suborbital rockets, and ground-based radars have accumulated data since the dawn of the space age. This medium is inherently complex, consisting of three distinct particle populations: neutral gases, ions, and electrons. All three gases occupy the same volume of space simultaneously, and they interact with each other via collisions, pressure gradients, and electromagnetic forces. These forces affect the temperatures, velocities, densities, and global distributions of all three species. In addition, the geomagnetic field constrains the motions of the charged particles, but does not affect the neutrals. All of the physical parameters described above vary as functions of season, location, solar activity levels, and time. The result is an extremely complex domain that is only partially understood despite decades of research.

The dataset is inherently four-dimensional, and is commonly represented with latitude, longitude, altitude, and time as the independent variables. By initially restricting our study to a specific range of altitudes we collapse the 4D space into a 3D domain that can be represented as sounds in the Cube. A test subject immersed in the environment hears sounds from all directions that represent the ion, electron, and neutral gas densities and temperatures. These are generally enhanced in areas where sunlight is most intense, so in a simulated (and temporally accelerated) 24-hour day a user standing at the center of the Cube hears the sound field representing these variables rotate around his/her observing point. In addition, the medium has natural variations in the fundamental variables that change significantly with latitude. For example, auroras occur primarily at high latitudes, while other geophysical phenomena are restricted to mid and equatorial domains. Naturally occurring changes in solar radiation fluxes, coupled with seasonal and diurnal variations of the polar axis relative to the ecliptic plane, provide a continually varying environment that is inherently complex, and difficult to analyze with conventional techniques.

Since the data maps naturally onto the 3D space represented by the Cube, we limit potential idiosyncrasies that could arise due to arbitrary spatial mapping. Our approach mimics as closely as possible the human interaction with real world stimuli, which can emanate from any direction with minimal technology-induced idiosyncrasies. SADIE users are free to navigate the ensuing immersive exocentric environment, and by doing so they fundamentally change the amplitude relationships between spatially distributed aural stimuli, as well as azimuth and elevation relationships with the patterns of interest. By moving within the space users modify and enhance their natural interaction with the environment—they build a location-aware image of the sonified data and use motion to improve their ability to pinpoint specific sources. We see this initial case study as a fundamental step in uncovering the extent of the human capacity to perceive and process exocentric sonification of data, and we look forward to reporting on the outcomes at the next conference.

8. CONCLUSION

In this paper the authors have presented a review of the 21st century sonification literature from the several key scholarly communities. By reviewing similarities and differences among the cited research, the authors have presented a case for a new vector in sonification research—immersive exocentric sonification that leverages the way humans interact with the real world while minimizing any potential idiosyncrasies that may arise from interacting with the real world through egocentric technology (e.g. head motion and location). Further, by clarifying its purpose and potential, this paper presents immersive exocentric sonification as a holistic and potentially unifying approach to studying human spatial aural perception. We anticipate that this approach may challenge and redefine the traditional understanding of its limits. Lastly, we briefly describe an example project designed to investigate advantages in data analysis and understanding that may accrue from using a unique facility conducive to the newly proposed approach.

9. ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. 1748667.

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