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REVIEW

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Listening to life: Sonification for enhancing discovery in biological research

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Abstract

Sonification, or the practice of generating sound from data, is a promising alternative or complement to data visualization for exploring research questions in the life sciences. Expressing or communicating data in the form of sound rather than graphs, tables, or renderings can provide a secondary information source for multitasking or remote monitoring purposes or make data accessible when visualizations cannot be used. While popular in astronomy, neuroscience, and geophysics as a technique for data exploration and communication, its potential in the biological and biotechnological sciences has not been fully explored. In this review, we introduce sonification as a concept, some examples of how sonification has been used to address areas of interest in biology, and the history of the technique. We then highlight a selection of biology-related publications that involve sonifications of DNA datasets and protein datasets, sonifications for data collection and interpretation, and sonifications aimed to improve science communication and accessibility. Through this review, we aim to show how sonification has been used both as a discovery tool and a communication tool and to inspire more life-science researchers to incorporate sonification into their own studies.

KEYWORDS
auditory display, data visualization, sonification, sound design

1 | INTRODUCTION

Sound is a natural information medium, and the use of nonspeech sound to communicate information is commonplace in our day-to-day experiences through car horns, text notifications, and fire alarms. When nonspeech sound is generated from datasets, this process is termed sonification (Hermann et al., 2011a). A straightforward example of this process is assigning each nucleotide base pair in a genome data set to a piano key and playing the DNA sequence note-by-note to listen for repetitions or other patterns indicative of structural elements such as beta-sheets (Hayashi & Munakata, 1984; Ohno & Ohno, 1986). While astronomers and particle physicists have been using sonification for decades in complex ways ranging from pattern discovery (Diaz-Merced et al., 2012; Hughes, 2003) to science communication (Mohon, 2020; Zanella et al., 2022), its potential to broadly impact biological research is yet to be fully realized.

In 2010 one of five grand challenges proposed by the National Academies for research at the intersection of physical and life sciences was to predict an individual organism's characteristics from their genetic data (National Research Council US Committee on Research at the Intersection of the Physical and Life, 2010). With the advent of rapid sequencing tools, novel ways to derive valuable information, patterns, and phenotypic associations from genomic data were desired. Sonification has enhanced progress toward this grand challenge through creative approaches to interpret and analyze large datasets generated from nucleotide sequencing and -omics data. One such example is the Gene Expression Music Algorithm (GEMusicA), which sonified gene expression data as an alternative to conventional visual approaches to characterize and discriminate between cancer cell lines (Staege, 2015). By comparing EFT (Ewing sarcoma) gene expression sonification sound prints to those of different standard cell lineages, researchers were able to accurately identify the genetic lineage of the cancer (Staege, 2016). Meanwhile, deep learning algorithms, visualizations, and novel spectroscopy/microscopy techniques have elucidated new discoveries about how proteins fold, work, and interact, allowing for identification of novel drug targets as well as novel protein synthesis (Ferreira, 2023; Goloubinoff, 2014). Sonification has the potential to act as a tool for both improved visualization (Rau et al., 2015) and feature generation—Yu et al. have added to the field's arsenal of de novo protein design techniques by sonifying proteins to create musical scores which are then fed into music creation machine learning tools to design new proteins, thus using sonification to inform the design of completely new materials (Yu et al., 2019).

Sonification has also been leveraged for the tools and methodologies researchers use to generate and interpret data. Sonification can be used to add an extra source of information for users during process monitoring tasks (Hildebrandt et al., 2016). For example, at Brookhaven National Laboratory, researchers sonified X-ray diffraction beams using Fast Fourier Transforms (FFT) allowing them to multitask sample preparation and listen for beam misalignments in real-time, increasing their work efficiency (Horowitz, 2014; Schedel & Yager, 2012). It can also provide a complementary source of features for existing research tools, especially those using machine learning models. For example, a skin cancer diagnostic tool created by Dascalu and David incorporated sonification as a feature fed into a deep learning model which allowed the tool to achieve the same accuracy as more sophisticated scopes despite using lower-resolution input (Dascalu & David, 2019). Beyond the researchers' sphere, sonification has garnered attention for science accessibility. Science accessibility includes making accurate scientific information more accessible and interesting to the public (Hopf et al., 2019; Larson, 2018) as well as ensuring that data availability is inclusive and accessible to anyone (Tuosto et al., 2020). Sonification has helped address these challenges by offering new and potentially more appealing media through which to engage the public with science (Plaisier et al., 2021; Zanella et al., 2022), as well as being more accessible than visual data for those who are blind or visually impaired (BVI) (The Space for Persons with Disabilities Project, & United Nations, 2023).

This review aims to introduce the science and art of sonification to the greater biology and biotechnology community to expand its use and inspire researchers to adopt it as a tool for scientific discovery and communication. We first introduce the history of how sonification developed as a tool, exploring how the field has evolved over time and how researchers in other fields have used it. We then discuss several classic and recent developments in the application of sonification for studying and communicating biological datasets in the context of genome-level data, protein sequence data, data collection and analysis, and science accessibility. Applications of sonification specific to the field of clinical medicine (such as biofeedback, EEG sonification, and surgical process monitoring), which are vast in number, will be briefly highlighted. Selected sound files from various research works are available in the supplementary information and serve as instructive examples. Through this review, we hope to introduce sonification to biology researchers more broadly to inspire new and creative sonifications to improve our fundamental understanding of the biological world.

1.1 | A brief history of sonification

Detecting useful information from sound patterns is a research tool that has been exploited for centuries (Worrall, 2019). In ancient Egypt, the pharaoh's aides analyzed the verbal commodity trading accounts of granary masters by listening for differences in voice speed and intonation to identify fraud (Boyd, 1905). Developed in the 1920s, the Geiger counter registers the flux of radioactive particles across a detector through a series of clicking sounds to let scientists and safety personnel readily detect unsafe levels (Knoll, 2000). With the advent of computers and related audio technology, humans gained a new form of agency over the creation of sound. As designers began to create the first personal computers and interactive operating systems in the 1980s, auditory display, or the use of sound to communicate information (e.g., car alarms, notification bleeps, or video game sounds) quickly became essential to our interactions with computers and other devices. Researchers then began to use these technologies to transform their data into sound, creating sonification (Hermann et al., 2011b).

Over the past few decades, sonification has established a particularly rich history of use in geology and astrophysics (e.g., Harrison et al., 2021; Misdariis et al., 2022; Zanella et al., 2022). Sonification came naturally to these fields in part due to their collected data often being in the form of difficult-to-visualize signals or waves that had similar features to sound waves. Waves from one modality (such as seismic waves or electromagnetic waves) can be interpreted directly as sound waves and then manipulated to put them in the audible range, in a sonification process known as audification (Kramer, 1994). Astrophysicists at the laser interferometer gravitational-wave observatory (LIGO) regularly take advantage of audification to detect events within noisy data, because changes in the waveform (such as a “chirp” from the collision of gravitational waves) can be distinctly heard but can be hard to recognize on visual waveform graphs (George et al., 2018; Hughes, 2003). Astronomers use audification to identify planet transits in front of stars (Brown et al., 2022) and analyze galaxy spectra (Trayford et al., 2023). Seismologists similarly “pitch up” signals from seismological data to analyze different types of earthquakes quickly and accurately by identifying magnitude and depth (Fowler, 2014; Holtzman et al., 2014; Kilb et al., 2012; Simpson et al., 2009). By transforming data from one waveform-type into sound, researchers in these fields can use the human ear's sensitivity to changes in sound to probe for patterns and features

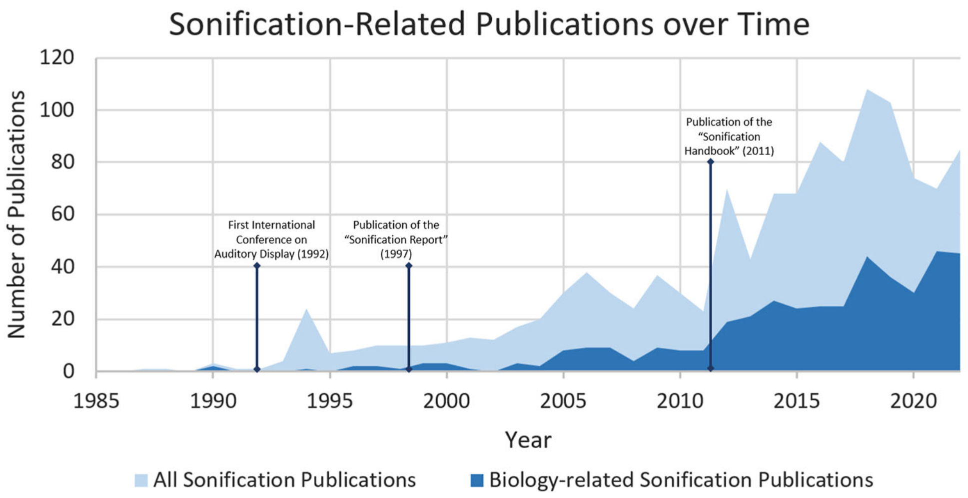

FIGURE 1 References to "sonification" as a keyword in a Web of Science search of published works, with the proportion of biology-related works highlighted in the dark blue. Notable sonification publication events are indicated with vertical navy lines. "Sonication" results were omitted, and the data was hand-pruned to remove any results that mislabeled sonication as sonification.

they might have otherwise missed in visually represented data. They also use the resulting sounds in educational materials to communicate research findings to the public in novel and interesting ways. Demonstrations of such outreach projects include media publications of the LIGO gravitational wave collision (Garisto et al., 2023) and NASA's interactive web demos of Milky Way sonifications from the Chandra X-ray observatory (Mohon, 2020), among many others (e.g., Harrison et al., 2021).

As sonification gained popularity, its works began to emerge in the field of biology as well. Figure 1 shows the usage of "sonification" as a keyword in publications archived by Web of Science by year, with the subset of biology-related applications denoted. Beginning in the 2000s, the increase in biology-related publications contributed to the overall growth of the sonification field. As part of this trend, we highlighted notable publications dedicated to summarizing the state of the field, specifically a key conference paper that summarized the early field entitled "The Sonification Report," the seminal introductory and instructive text the "Sonification Handbook," and the first International Conference on Auditory Display; their subsequent impact on expansion of the field can be seen in the graph (Hermann et al., 2011a; Kramer et al., 1999), and they all offer useful insight and instruction for the field. As the number of publications of biology-related sonification works has increased, so has the diversity of applications, which are showcased in our review of the literature that follows.

2 | SONIFICATION IN BIOLOGY-RELATED LITERATURE

As in the earlier examples of gravitational waves and seismological waves, audification, or the transformation of wavelike data into sound waves, can and has been used to sonify wavelike biological data such as IR spectra (Delatour, 2000) and brain waves (Hermann & Baier, 2013). However, in sequence-type data, such as genomes and proteins, the information of interest is quantized. For these datatypes, a different sonification approach called parameter mapping is used (Grond & Berger, 2011). In parameter mapping, acoustic event features such as notes are mapped to individual data points by relating aspects of the acoustic event such as pitch or loudness to variables associated with the data point (e.g., by mapping the pitch of a note to a certain DNA base pair). This is the most readily used method to sonify DNA and protein sequences, and many projects highlighted in this review have explored how to best extract new variables or features from the existing data. These works also highlight how both audification and parameter mapping have been skillfully leveraged to appropriately sonify various forms of biological data, and how the techniques have been applied to improve research tools and increase science accessibility as well.

2.1 | Sonification for studying the organization and regulation of genetic data

Throughout the past few decades, genomic sequencing techniques have evolved and flourished, generating plentiful datasets to explore how genetic information is organized and regulated. Many genomic sonifications aimed to discover or interpret patterns, identify single genes, and compare different genes from these datasets. Early implementations of DNA sonification occurred in the 1980s, where a motivating factor was the creation of new music that could allow for increased appreciation of the recently published troves of DNA sequences and an enhanced understanding and memory of the patterns in them. In arguably the most seminal example, Hayashi and Munakata (1984) ascribed musical notes to DNA base pairs and upon playing a genetic sequence back as music, discovered that certain musical patterns were related to thermal stability (GC richness) and were able to identify transcription codons that indicated the start of genes. Ohno and Ohno (1986) used similar codon-to-note sonifications, but also inverted the process to translate classic pieces of music back into DNA sequences. They found that classical music sometimes generated patterns that were similar to existing protein genes, which they suggested implied a natural tendency for repetition in DNA. To create an effective sonification platform for DNA analysis, Temple (2017) developed a tool that provided different DNA sonification methods, exploring sonifying single nucleotides, nucleotide pairs, codons, and the option of using multiple reading frames. He found that concurrently listening to all three codon reading frames at once while using auditory cues to signal stop and start codons facilitated easy identification of open reading frames and repetitive DNA sequences, making an argument for the inclusion of sonification analysis in the DNA sequence browser toolkit.

Building on productive applications to DNA sequences, sonifications relating to gene expression and regulation within cell phenotypes emerged as well. Staege (2015, 2016) created the Gene Expression Music Algorithm (GEMusicA), which sonified gene expression data from sources such as microarrays and used it to create a new method for discrimination between different gene expression data sets, specifically applying it to successfully characterize cancer cell lines and probe for similarities as an alternative approach to conventional gene expression data analysis methods. Cittaro et al. (2016) created a method to sonify ChIP-seq data (which identify the binding sites at which transcription-factor proteins bind to DNA in the genome and influence phenotypes) and used the sonification to successfully identify the extent of gene expression in a sample. Brocks (2015) created a method to sonify the methylation states of CpG dinucleotides (a specific DNA pattern that can undergo methylation to regulate transcription) in the genome, known as the methylome, to shed light on epigenetics patterns in genomes and generate more public interest. As RNA folding drew attention, Grond et al. (2010) presented a tool allowing for the audio-visual display of RNA, sonifying the overall secondary structures using the sound synthesis platform SuperCollider as an integrative display option to identify RNA folds, loops, and stems that may correspond to a biological function (Wilson et al., 2011). Paul et al. (2021) used Harr wavelet transforms to sonify the spike protein gene of the 2019 coronavirus and other viruses such as Influenza and Ebola to identify structural differences, as well as classifying different virus genes into their respective viral families. As genomic data becomes more available and new parameters and features are generated, we anticipate that sonification will continue to offer an alternative to traditional visualizations and analyses for researchers to explore their own data or communicate to others.

2.2 | Sonification for the study of the structure and function of proteins

As availability of proteomic data and crystal structures increased, researchers sought to relate amino acid sequence-level information to protein folding, function, and interactions (Dill et al., 2007; Kuhlman & Bradley, 2019). Some early protein sonifications aimed to identify protein secondary structures through repeating amino-acid motifs within the sequences. For example, Riego et al. (1995) assigned each known amino acid codon a musical note, which they then used to translate human and mouse interferon genes from which they identified long, repeating patterns of notes distinct from randomness. These would likely now be recognized as amino-acid repeats—strings of repeating amino acid patterns that play critical roles in biological function (Luo & Nijveen, 2014). Bywater and Middleton (2016) introduced amino acid hydrophobicity and surface proximity within protein sequences as features to create and compare different sonification approaches that then allowed them to recognize structural patterns such as alpha helices and beta sheets and validated their findings using a perceptual survey with 38 participants. To address issues with early visual expression of protein sequences that used colored bands at the time, King and Angus (1996) invented PM—Protein Music, an algorithm that incorporated amino acid properties such as hydrophobicity into the overall musical composition. They posited that sonification added an advantage over visualization of proteins and genes due to each amino acid being represented distinctively by a unique note, which could avoid possible issues with visual “color blending” between bands in the color displays. More recently, Martin et al. (2022) used sonification to explore proteins more effectively and designed a tool like that of King and Angus to identify amino-acid repeats within protein sequences and conserved domains between different proteins. They explored five different sonification algorithms and found that it was important to design the sonification in task-specific ways for the tool to be beneficial to users. Sound samples for these five sonification algorithms applied to various proteins including human insulin and transmembrane protein 14C can be found in Supporting Information S2: File S1.

To better understand how proteins related to each other, a combined audio-visual approach to protein structural analysis was taken by Hansen et al. (1999), who created PROMUSE, a tool that incorporated amino acid and protein features such as polarity and secondary structure to sonify the structural alignments (a measure of similarity) between two proteins in conjunction with visual representations. They found that for certain tasks, when compared to visual information alone, the addition of sonification led to a large increase in accuracy and efficiency of protein data interpretation by a test group. Other sonifications aimed to deduce structural or functional information through sonification. Picinali et al. (2012) transformed influenza proteins into a signal-based sonification by taking the electron-ion interaction potential of their amino acids and applying a Fast Fourier transform to shift the signals into the audible range, allowing the amino acid qualities to be present in the resulting sounds without encoding individual features such as hydrophobicity. These amino acid sonifications were then used to translate the proteins into more information-dense music that could communicate properties of the protein beyond its sequence. Also, in the work of Monajjemi (2019a, 2019b), amino acid NMR data underwent direct audification to inform parameter mapping of amino acids as well as the overall rhythm of the final sonification piece, which was used to study the ribosome and human insulin proteins with the goal of creating a more melodious sonification that was easier to listen to.

More recently, understanding and communicating protein folding and interactions led to new sonifications that aimed to enhance visual models. Rau et al. (2015) added sonification of molecular dynamics simulations of water interacting with a protein to a CAVE virtual environment molecular visualization of the protein shape, allowing the visualization to communicate the formation and disruption of hydrogen bonds without visibly overwhelming the user. Scaletti et al. (2022) created protein folding animations that used sonification to highlight the free-energy state of the protein as it folded to more effectively communicate protein folding concepts to undergraduate students. Moving away from visualization entirely, Bouchara and Montes created a sonification of a 3D protein in a virtual environment to create a sound-based platform for the communication of 3D shapes for protein studies (Bouchara & Montes, 2020).

Beyond understanding protein function, newer techniques in synthetic biology aim to design novel proteins or improve existing proteins. Sonification was leveraged as a feature generation method by Franjou et al. (2019, 2021), Yu and Buehler (2020), and Yu et al. (2019), who audified the vibrational spectra of individual amino acids to inform how they would be represented as notes in the sonification, using protein secondary structure to communicate rhythm. The resulting musical scores were then used to train a neural network designed for score generation, and the neural network created new scores that were then translated back into de novo proteins. These novel approaches that take advantage of sonification as a feature generation tool in deep learning show that sonification still has many unexplored applications and potential benefits.

2.3 | Integration of sonification for data collection and interpretation

While the previous works have exemplified how sonification has been used to explore and analyze existing datasets, the following works show how sonification can be used in creative ways as a tool for data collection and interpretation. For example, researchers have developed sonifications to assist microscope users with identifying relevant data features. Peruzzi et al. (2015) and Braun et al. (2020, 2023) directly translated video feed from microscopes into sound by interpreting the image as a "sonogram" to capture bacterial movement and probe for changes in swimming patterns in response to chemical stimuli, with the goal of creating a real-time chemotaxis assay using sound. Lee et al. (2022) sonified the spectral patterns of fluorescent images of tumors to help users detect and discriminate small tumorous conditions in living animals. Ngo et al. (2022) sonified the *x-y* movement of cells under a microscope to identify and relate phenomena such as mitosis and cell migration to study cancer by mapping different locations on each axis to pitch or left-right panning.

Sonification has also been used to create or identify helpful features in existing data that were not previously apparent. When Boevé and Giot (2023) sonified chemical characteristics of various volatile compounds, they found that the resulting peak sound pressure was correlated to the substance's human olfactory threshold, providing an easier-to-calculate alternative to replace human tests. Stables et al. (2017) sonified the Raman Spectra of brain tissue for cancer diagnosis, increasing the diagnostic accuracy by 25% after extracting features using machine learning methods compared to purely visual methods, allowing doctors to spend more time with patients rather than wait for visual test feedback. These works showcase the potential for sonification to become part of the scientist's standard toolbox for discovery. They also showcase how very unique problems can be addressed through creative sonification.

2.4 | Sonification as a tool in clinical practices

The sonifications implemented in the medical field provide excellent examples of the technique's potential to be used as a daily tool. While this review has focused on research applications, we will provide several sample references for those interested in researching these clinical applications further. Sonification is frequently used as a process monitoring tool for surgeons to monitor their actions during operations (Black et al., 2017, 2018; Maintz et al., 2019; Vajsbaher et al., 2020, and patient conditions such as heart rate (Aldana Blanco et al., 2020; Bahameish, 2019; Ballora et al., 2004; Janata & Edwards, 2013; Riveros Perez et al., 2019; Stahl & Thoshkahna, 2016) and oxygen monitoring (Collett et al., 2020; Deschamps et al., 2016; Hinckfuss et al., 2016; Paterson et al., 2016, 2017) along with several other medical applications (e.g., Burdick et al., 2020). Audification has frequently been used to translate various signals in the body, such as electroencephalography (EEG) brainwave signals (Baier et al., 2007; Elgendi et al., 2013; Hermann et al., 2006; Väljamäe et al., 2013). EEG audifications have been used to study various phenomena, including sleep and sleep disorders (Fernandes et al., 2021; Moradi et al., 2020), depth of anesthesia (Glen, 2010), epilepsy and seizures (Lu et al., 2018; McCredie, 2020), and even using sonified EEG as biofeedback to alter mood and brain response (Sanyal et al., 2019). Biofeedback itself is a popular category of sonification in medicine in which patient data is sonified in real time and played back to the patient (Kosunen et al., 2018). For example, to help with injury rehabilitation and sports training, sonified movement signals of a person are played back to them in real-time to help them monitor their own behavior (Guerra et al., 2020; Kantan et al., 2022; Kantan, Dahl, et al., 2023; Kantan, Dahl, Serafin, et al., 2023; Schaffert et al., 2019). Similarly, neurofeedback, or the sonification of brain waves played back to the patient, is a well-explored clinical practice for the therapy of neurological disorders (Marzbani et al., 2016). These sonifications have been very well established, have led to many clinical improvements, and are active areas of research.

2.5 | Making scientific data more accessible

To make science more accessible to the public and to systemically excluded groups such as BVI individuals, many researchers sought to combine sonification with visual representation to communicate more information synchronously or communicate the same information more efficiently. In recent years, several such sonifications were developed in response to the COVID-19 pandemic, during which communicating scientific information to the public about the virus was important. With this aim, Buehler used a machine learning method for translating amino acid sequences to create a popular sonification of the 2019 coronavirus genome (Venugopal, 2020) (Supporting Information S1: File S1). Similarly, Temple (2020) sonified the 2019 coronavirus RNA genome and its metadata to showcase the virus' life cycle and inspire interest in the general public to learn more about genetics and the virus's physiology. Several sonifications were also developed to help communicate case rates and the spread of the virus in an accessible way. For example, Holloway et al. (2020, 2022) created a method to sonify data about the spread of COVID-19 in Australia to ensure that people who are blind or have low vision would be able to access the same information as those who use visual graphs. Similarly, Biggs et al. (2022) developed a web-based audio map to show the spread of COVID-19 data by State in the United States and evaluated it with a BVI test group, finding a strong general desire for sonification-enabled accessible maps.

While science and data analysis have historically leaned heavily on visual representations to communicate findings, researchers have shown that the addition of sound can make such representations much more effective and engaging, which can be leveraged for both discovery and outreach. Garcia-Ruiz et al. (2004), Garcia-Ruiz (2001, 2002) found that the addition of sonification to visualized proteins and DNA sequences enhanced middle school students' understanding of molecular properties and helped them identify structures, and this was further enhanced when students were involved in the sonification design. Shi et al. (2007) used Morse code to assign amino acids to short melodic sequences and rhythms and explored a range of scales to affect genre and mood of the resulting music to motivate students to learn biology. Takahashi and Miller (2007) used the chemical similarity of amino acids to assign them to various chords to make the resulting sonification more melodic and assigned rhythm based on the frequency of the residue in a protein, aiming to increase accessibility to nonsighted scientists and young people. Plaisier et al. (2021) used DNA sonifications to communicate bioinformatics basics to the general public and found that sonification-related activities worked well to engage their audience in thinking about biological concepts.

Sonification tools for education are of course not just limited to biology datasets. While the list is numerous and is beyond the scope of this review, a couple examples of these are a "talking multimeter" by Lunney and Morrison (1981), which was created to allow nonsighted students to take measurements in lab, and Yeung (1980) developed a sonification method to display multivariate data and allow for pattern recognition and even accurate value estimation. In chemistry, Mahjour et al. (2023) sonified chemical footprints, incorporating information such as molecular weight and hydrogen bond centers, to provide a more information-dense representation of a molecule than a diagram or webpage. Several researchers have also been working to create auditory graphs to improve math education (Ahmetovic et al., 2019; Barbieri et al., 2008; Tomlinson et al., 2016).

On a larger scale, Larsen and Gilbert (2013) and Larsen (2016) created a tool, "Microbial Bebop" that assigns multidimensional data to a variety of auditory dimensions such as notes, chords, and rhythm to create a jazz-inspired sonification. The tool is used to analyze variables of interest from microbial datasets, with the input parameters ranging from gene expression levels to location temperature to produced metabolites and is intended as a science communication tool for the general audience (Supporting Information S1: File S3). Wheless et al. (1996) used sonification to improve their understanding of and the communication of results from their Chesapeake Bay Virtual Environment simulation, a modeling framework that integrated hydrodynamic circulation models and various biological multidimensional data with computer visualization variables to investigate the interplay between physics and biology in the Chesapeake Bay ecosystem. Gibson (2006) sonified plant data for a botanical garden and paired it with time-lapse videos to give visitors an appreciation for the growth of plant life, which occurs too slowly for the eye to appreciate. Kim et al. (2021) sonified microbiome data as an educational science project and art piece called "Biota Beats" to establish a connection between individuals and their bodies and make the science of the human microbiome more connected to the human experience. Similarly, Rudin and Demirjian (2022) sonified infant microbiomes to showcase how the populations varied over time and between individual infants, mapping traits such as Gram stain and bacterial family to different musical notes, with the aim of teaching users about microbiome variability. These works show how datasets from diverse fields can undergo sonification to create unique approaches for communication and learning.

2.6 | Sonification design considerations and limitations

Taking an informed and design-forward approach to developing a sonification is essential for its success, and the omission of this may lead to ineffective sonifications. For example, simply mapping each unique amino acid to a note on the piano and then playing them back along the sequence might sonify a protein, but without an understanding of what each amino acid might contribute to the structure or function of the protein, the sonification may just sound like a random tune. For this reason, feature generation is an important aspect of sonification design. The features that are important will depend on the problem that needs to be solved or the question of interest, and for a sonification to be effective, these features need to be recognized distinctly (Neuhoff, 2019). Good design is difficult, and incorporating too many features of a data point (e.g., attempting to capture several features of an amino acid in the same note) may make a complex sonification that is difficult to interpret or lead to "ear fatigue" (Lawrence & Yantis, 1957; Worrall, 2019). However, if the features are too trivial, the sonification may not be useful. Ultimately, if a data set is unable to provide sufficiently distinct features or the features are difficult to translate into sound parameters, the problem may not be ideal for sonification, just as not all data can be represented visually.

Similarly, the intention of the sonification can come with limitations. Studies have shown that certain auditory parameters can have subjective relations from person to person (Neuhoff, 2019), or interfere with one another such as in the case of equal-loudness curves (Fletcher & Munson, 1933), making consistent or quantitative interpretations of sonifications difficult. Often, in such cases, users will also need extensive training to learn how to use a sonification, so it may not be a beneficial approach in all scenarios. The way users interact with data is also uniquely different from visuals. Listeners may need to listen to a sonification over a length time to properly interpret it, and if the sonification is long, it would not be ideal for scenarios where immediate interpretation is required. On a more practical end, sonification research can be difficult to publish in traditional media, because unlike graphs and figures for visualization, sound cannot be printed. Just as visualizations and graphs have best practices (such as using intelligible colors and scales) and limitations, sonifications have best practices and limitations as well, and will be most effective when designed intentionally.

3 | CONCLUSION

Sonification methods reported in biological literature have increased substantially over the past two decades. Its core uses have been in recontextualizing biological data as an expression for common sequences such as DNA and amino acids as well as acting as a tool to extend research in new directions such as de novo protein synthesis. It has also been extended to data collection platforms to add more information to existing microscopy and spectroscopy tools and data collection processes. Others have leveraged the technique to improve scientific outreach, finding that it can help overcome barriers associated with data literacy. Sonification approaches also served the BVI community by making data more accessible (Sawe et al., 2020).

While the number of works that have led to discoveries integral to biology is modest, sonification is gaining momentum, especially in the medical field where the impacts of its use are evident. If leveraged correctly and creatively, sonification has the potential to similarly impact fundamental biology research. The current body of biological sonifications illustrates the diversity of problems to which the technique can be applied, ranging from nucleotide sequences to EEG signals to microscope feeds. Sequences and spectra are notably nontrivial to visualize (van der Linden et al., 2023; Sawe et al., 2020), which may have motivated researchers to explore sonification as an alternative. As difficult-to-visualize multivariate omics-style data is increasingly produced (Cambiaghi et al., 2017; Gehlenborg et al., 2010), sonification provides a complementary approach. Similarly, the more novel works that have been recently developed using sonification (e.g., Braun et al., 2023; Franjou et al., 2019) are evidence that sonification as a research tool still has plenty of unexplored potential. Despite the limitations of the technique, sonification finds itself within a thriving community of scientific researchers who often reach across disciplines and collaborate with talented artists and educators to develop new approaches to understanding complex phenomena. With its capacity to provide unique auditory insights, the adoption of sonification remains a compelling consideration when confronted with complex datasets in biology and beyond.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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