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Innovative communication of molecular evolution through sound: a biological sonification concert

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Abstract

Background A major challenge of evolutionary biology is making underlying concepts accessible to wide audiences. One method for doing so is to utilise multi-media formats that have potential to engage and inform through entertainment. This pilot study outlines and discusses a sonification concert that integrated musical performance with a range of evolutionary concepts and ideas fundamental to an understanding of evolution, such as protein sequences. We aimed to showcase sound-art objects and live-coding performances created using sonification as a mechanism for presenting complex biological processes to both researcher and non-researchers. We sought to evaluate the effectiveness of this art-adjacent practice for public engagement with evolutionary biology research, and also to gather feedback to guide future events. Toward this end, we held a live concert showcasing biologically-based algorithmic music exploring links between evolutionary biology research, sound art, and musical performance. The event had three main acts: a generative audio-visual piece giving an artistic representation of SARS coronavirus based on a parameter-mapping sonification of protein sequence of the replicase polyprotein; a pre-recorded string ensemble demonstrating the effects of codon selection on translation speed using parameter-mapping sonification; and a live-coded music piece interactively sonifying protein structures.

Results Our event attracted 90 attendees. We evaluated success using direct observation and written feedback forms with a 58% response rate: 95% of respondents stated they had enjoyed the event and 63% indicated they were inspired by it.

Conclusions Presenting the sonic outputs of sonification research in a concert format showed good potential for the pursuit of public engagement with evolutionary biology research, demonstrating the ability to engage curiosity and inspire an audience while also conveying scientific content alongside the nuanced and complex world of modern evolutionary biology.

Keywords Sonification, Public engagement, Generative music, Coronavirus, Molecular biology, Algorithmic music, Live coding, Protein structure, Qualitative research, Molecular evolution

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Background

An ongoing challenge of evolutionary biology is engagement of students, scientists, and other sectors of the public with underlying concepts. When perceived at a natural history level, adaptation to environmental conditions is readily accessible, but the underlying molecular processes that are now prominent scientific tools for understanding of evolution are more abstract and do not lend themselves to readily accessible intuitive graphical representation. For example, the data-rich nature of bioinformatics tends to render the underlying data less transparent. As genomics and other bioinformatics tools grow increasingly prevalent in evolutionary research, it is critical that pedagogical tools keep pace to enable understanding of this methodology and its scientific contribution and importance.

The challenge of conveying the complexity of modern evolutionary research warrants experimentation with novel methods of conveying those concepts. Music has a long history of engaging people with abstraction and complexity while at the same time evoking strong impressions on an intuitive level. One example of such experimentation is the expression of evolutionary concepts through the medium of rap music (Brinkman 2015), which, while perhaps unexpected as a format for engagement with evolution, certainly evokes a response and has potential for conveying content through an entertaining format. We explore here an additional type of sensory engagement, music derived from sonification of biological data. This is specifically designed to make the data-intense richness of bioinformatics content underlying modern evolutionary research more intuitive and accessible, both to evolutionary biologists and others. As David Worrall put it, sonification gives vibrant voices to unseeable things (Worrall 2019).

Sonification, a group of methods of data representation using sound, engages with both empirical scientific research and contemporary sound art (Kramer et al. 2010). Bioinformatics sonifications engage with a variety of data sets for a range of purposes: de novo protein design (Yu and Buehler 2020), characterisation of differentially expressed genes (Staege 2016), human olfactory threshold investigation (Boevé and Giot 2023), predictive modelling (Fox et al. 2017), public engagement (Plaisier et al. 2021), and protein sequence analysis (Martin et al. 2021). They employ diverse techniques, including interactive sonification (Choi 2018), real-time event based sonification (Baier et al. 2007), and web-based auditory/visual display (Temple 2017, 2020). And while much scientific sonification research focuses on the development of cutting-edge tools to aid researchers in the empirical interpretation of scientific data, sonification researchers also create tools for the communication of scientific concepts. This occurs in a range of contexts: between researchers in the same, adjacent, or diverse fields; to educate students with varying levels of expertise and aims in learning about science; with research-adjacent professionals such as funders, administrators, and officials; and with broader publics less connected to research. Sonification research is pursued for a range of artistic and scientific goals, often aiming for a blend of both (Neuhoff 2019).

The processes of sonification necessarily create sound objects that can be considered and presented as art objects regardless of their intended uses. Presenting sonification sound objects as art speaks to an idea articulated by Mark Ballora, that "sonification's potential value, like much of the scientific visualisation content, probably lies less in hard facts and more in how it may serve as a stimulant for curiosity" (Ballora 2014). In a meta-discussion of the field, John G. Neuhoff has recommended that a more rigorous distinction between—and devoted adherence to—the purposes of sonification design would improve research in the field, whether for aesthetic or empirical purposes (Neuhoff 2019). While remaining neutral on Neuhoff's conjecture, presenting sonification sound objects in an art context, and thus considering these outputs as art, may be a fascinating and valuable method of public engagement. Much like awe-inspiring clinical, microscopy, or astronomical images produced for research purposes but presented in artistic settings (Draycott and Dakin 2017; Kukula 2018; Tyurina 2020), we may be able to produce art-adjacent engagement works of great power by presenting research outputs in new contexts.

Ballora mentions the *wow-factor* as an important part of public engagement which sonification is able to achieve, and states that its benefits are largely intangible (Ballora 2014). Inspiration, a seemingly integral part of the *wow-factor* Ballora discusses, is a key concept in the subjective experiences of both consuming art and in public engagement with scientific research, where it functions to share scientific research in a way which inspires curiosity and learning, making research more accessible (Reed et al. 2018). It is not our aim to give an account of the subjective experience or design principles of *wow-factor*, however we wish to highlight that experiencing an artwork is a complex phenomenon, and multiple impressions are made on individuals and between different audience members. While sonification sound objects may stimulate curiosity and inspire a *wow-factor* style response in audiences, they also have potential to simultaneously convey content as well as nuance of scientific results to a broader public audience (Sawe et al. 2020). In addition to this, sonification-derived sound objects have potential for the portrayal of scientific complexity. Also, due to the diversity and depth of emotional responses to

music, these sonifications can be designed to cause audiences a diverse range of emotional responses, following data visceralization traditions to represent data in a way not only seen but felt (D'Ignazio and Klein 2020). The effects of the sonification sound objects can thus be seen as multi-faceted, not simply impressive through stimulating curiosity, or educational by conveying content, but also emotional, nuanced, and complex.

Presenting research outputs in artistic contexts mirrors much work in the arts, where the communication of a single meaning is not the aim of the work. Instead, audiences engage with the work drawing their own deeper understandings of the world informed by the art presented to them. Within the field of public engagement with scientific research, it is valuable to portray the complexity, uncertainty, and nuance of research, just as it is important to engage with emotionality. By using art-based approaches, we can increase engagement with research content through making it appeal to more of our senses and tapping into socio-emotional aspects of the human condition (Kukkonen and Cooper 2019). Also, by creating the spaces in which arts-based engagement occurs, we are also creating spaces for debate and dialogue.

Students, scientists, and other sectors of the public each bring different considerations to the approaches and content for engagement with evolutionary biology. We can consider these groups in terms of depth of investment with the field, which is perhaps correlated with knowledge of the field. Under this assumption, scientists have the deepest investment, followed by students, and then broader publics. If we consider effectiveness of an engagement project only to be teaching previously unknown factual information about evolutionary biology, those with the deepest investment will then be the hardest to engage with effectively. If we consider effectiveness to be encouraging audiences to think deeply about evolutionary biology, those with the deepest investment can be considered as having the richest relevant experience to bring to interpretation of the work. Creating engagement projects that appeal across these broadly defined groups speaks to identifying content of general relevance, but also creating work which is not prescriptive in interpretation. This allows those with different levels of investment in the field to bring their own understandings of the world to interpret the work in a way which is rewarding. Although the factual content contextualising the work may not be new to the scientists or students, the subjective experience of engaging with the work as art allows for understanding to blossom. Thus, we use the tenets of the creative arts to create engagement projects that engage effectively across our audience groups, an approach which speaks to traditions of art-based research in the social sciences (Chilton and Leavy 2020).

Here, we present a pilot study based on a concert exhibiting the sonic outputs of different researchers engaged in a variety of sonification research projects. We do this in order to initially investigate how the presentation of sonification sound objects as art objects in a contemporary art context (i.e. a concert) impacts an audience for the aim of public engagement with evolutionary biology research, specifically investigating whether the audience felt *inspiration* and also whether the concert was successful as an art-event. The event will also raise awareness about bioinformatics and sonification research among our audience. The insights gained from hosting and evaluating the event will inform future research process and directions, as will the skills cultivated in the pursuit of this type of public engagement. These insights and skills will have future applications by leveraging the emotional impact of sonification for arts-based public engagement for other aims, such as mobilising change in behaviour of stakeholder groups or affecting changes at policy level through advocacy (Kukkonen and Cooper 2019; Ball et al. 2021). In these future directions we foresee avenues for this approach to work towards the propositions that public engagement with scientific research projects should focus on "ensuring that science contributes to the common good" (Wilsdon and Willis 2004), and restoring public trust in science (Wynne 2006).

The event, titled *Harmonic Function*, was held in a lecture theatre in the University of Edinburgh central campus on 5th March 2020, with four performers comprising three acts presenting a total of six sonification pieces to an audience of 90 people. Though principally representing biological research, one piece was algorithmically generated from non-biological data. The concert participated within three musical performance traditions which together establish the cultural context for the event. The first tradition, in which all the pieces participated, is the showcasing of sound objects derived from sonification research (Barrass 2012a), whereby sonification research is presented in a publicly-accessible concert (Barrass 2012b). The second tradition, in which three pieces participated, is live-coding and algorave, whereby a performer creates music algorithmically by the spontaneous manipulation of computer code as a mode of improvisational performance (Collins et al. 2003; Collins and McLean 2014). In presenting all the works as sound art objects, sonification processes developed for varying research aims thereby become methods of algorithmic composition, participating in our third, centuries-long tradition of creating music programmatically (Edwards 2011).

Methods

The concert consisted of three acts, presented in the order of performance in this section. A large projection screen was available to all performers to present accompanying visualisations. The evening was hosted by Edward J. Martin (EJM), who also performed, alongside showcases by Shelly Knotts (SK), Nicholas Weise (NW), and Michelle Phillips (MP). Each performance, and its related sonification work, was developed independently prior to the conception of the concert. The audience were seated for the duration. Publicity for the event occurred through both university and non-university channels, through posters, email, and event-aggregating websites. The event was free and open to all who came.

Protein sequence sonification of ESX1, HTT, and SARS coronavirus

EJM performed three pieces, each based on the protein sequence sonification algorithm presented as *algorithm I* in previous research (Martin et al. 2021). The algorithm maps the amino acids of a protein sequence to pitch based on their hydrophobicity.

Sonification design

The first piece *played* the ESX1 protein on a synthesizer to illustrate the mapping without adornment, which can be listened to in the referenced link (Martin 2023a). The tempo range was chosen to balance discernment of individual amino acids with the brevity of the piece. The tempo was subtly altered algorithmically throughout to give a feeling of *rubato* or rhythmic variation as if a human performer were performing emotively. The synthesizer sound design aimed to create a dramatic and compelling piece of music, forefronting musicality with a retrofuturist aesthetic engaging with popular traditions of science-fiction associated music.

The second piece used the same algorithmic mapping as the first to present the effects of Huntington's disease on the amino acid sequence of a human HTT protein, available for listening in the referenced link (Martin 2023b). Representations of the HTT protein with different repeated glutamine chain lengths were played successively. The repeated glutamine chain, which is the section of the protein relevant to the development of the disease, sounds as a single note repeated multiple times. This creates a moment of reflection, where the melody sounds interrupted. A marimba-style synthesizer was used here to give a respectful and more neutral sound in light of the emotive nature of degenerative conditions.

The third piece, more ambitious in scale, was an audio-visual presentation combining live-mixed generative music with animated visuals. The music was generated algorithmically from the amino acid sequence of the replicase polyprotein of SARS coronavirus (Uniprot accession P0C6X7) and produced and synthesized live on stage by EJM. Given the pre-lockdown context of this concert, this piece was particularly topical.

The percussion, bassline, synthesizers, and distorted lead melody were simultaneous sonifications of the same replicase polyprotein amino acid sequence data, triggered and synthesised live using MaxMSP software and a MIDI protocol (Loy 1985). MaxMSP was used to index through the replicase polyprotein sequence data, sending the residues to each *instrument's* subprocess simultaneously. Each track utilised the data differently: the percussion used each amino acid residue to trigger a small sample of a recorded drum loop, the distorted lead synthesizer used the *algorithm I* mapping used in the first two pieces to sonify each amino acid residue into a melody, and the bassline and other synthesizers used randomly selected intermittent residues to determine their pitches. During the live performance, having initialised the MaxMSP process, EJM activated, silenced, and controlled the relative levels of the tracks using Ableton Live software to create the musical piece. EJM also used Ableton Live to trigger speech-based audio samples of historic news reports about viral outbreaks accessed via the British Universities Film & Video Council archives (Researcher's Guide to Screen Heritage 2023). The performance aspect of the piece was improvisational. Aesthetically, the sound design of the work aimed to sincerely engage with feelings of contagion and threat, creating work that elicits an uneasy response in the audience. The visual element of the performance derived from an educational video on retroviruses reproduced with permission from the Howard Hughes Medical Institute. A recorded version of the performance is available online (Martin 2023c). More discussion of the piece can be found in Martin (2021).

Concert design

EJM introduced the concert, the other performers, and sonification as a method of understanding data through sound. EJM introduced how proteins are constructed from a sequence of amino acids and explained how the sonification algorithm, *algorithm I*, assigns pitch values to the amino acids based on experimental measurements of their hydrophobicity. EJM explained how the *ESX1* protein was selected for its musicality and used to demonstrate *algorithm I* in a transparent way without the sophistications of the following two pieces. EJM played the piece for the audience, which can be heard in the referenced link (Martin 2023a).

EJM introduced the second piece by talking about huntingtin, a protein is widely expressed throughout the brain, and Huntington's disease, where mutation causing extra tandem repeats of the CAG codon (coding for

glutamine) causes severe issues due to altered shape of the protein. EJM explained that this makes use of the same sonification process *algorithm I*, which is used to sonify successive examples of the huntingtin protein with the use of a low chime to represent when a new protein starts. EJM played the second piece, available for listening in the referenced link (Martin 2023b).

EJM introduced the third piece by introducing the SARS coronavirus with its growing notoriety at the time. EJM explained how the polyprotein being sonified comprises the SARS coronavirus replicase and is used by the virus to hijack the ribosome of the host to reproduce. EJM emphasised that the although the same algorithm has been used as the first two, *algorithm* I, this piece has not been designed such that the audience can follow the amino acid sequence, which is over 7000 residues long. EJM emphasized that instead the polyprotein sequence has been used as the basis of distinct generative processes to create the sound of each musical element of the piece using MIDI processes in a different way. EJM also explained how the piece had improvisational elements using live mixing to manipulate the relative sound levels of the *tracks* created by these various algorithmic processes, and by manually triggering samples to create the musical piece. EJM also acknowledged the sources of the visualisation and the sound excerpts. EJM then performed the work, of which another recorded version is available online (Martin 2023c).

Music and mutation

MP and NW presented a video recording of a performance by acoustic musicians put on in 2018 as part of the Manchester Science Festival, available at the referenced link (Weise and Phillips 2023). Excerpts were played of a single movement out of the three which were composed to demonstrate the biomolecular concepts: codon optimisation and heterologous gene expression.

Sonification design

Codons that are rare for the organism in question tend to be slow to translate. Due to the time-linear nature of music, sonification presents an excellent opportunity to illustrate this concept, which is fundamental to an understanding of synonymous codon bias and evolution (Sharp and Li 1987; Wright 1990). For the composed pieces each part of the genetic code was assigned a unique chord. As the full genetic code comprises all 64 possible combinations of the four nucleobases (A, C, G, and T) in groups of 3, so a full complement of 64 chords were devised to represent this.

For the first position of each group of three (or codon) each of the four nucleobases was assigned to one of the first four semitones of a C to C scale. This process was repeated for the four nucleobases at the second codon position with the next four semitones, and again for the last position, with each nucleobase being assigned one of the final four semitones of the scale. This was done to keep all variations within one octave ensuring that 64 harmonically distinct chords would result, minimising audience misidentification of chord inversions as representing the same codon. For the specific sequence presented, each chord was also assigned a duration correlating with the codon usage bias of the organism within which the gene was expressed. The resultant chord and note length matrix constitutes a generic formula by which any genetic sequence can be sonified, illustrated in Fig. 1.

Any resulting compositions allow for the differences between mutated (or codon optimised) sequences to be identified by chord differences alone, whereas jarring, stalling, or glitching effects of longer chords can be used to signify the presence of rarer used codons. This becomes particularly important when listening to wild-type sequences in either their host or a laboratory strain organism, where differences in pace and length become evident and highlight to the audience the importance of introducing mutations to increase translational efficiency. This latter point can be further demonstrated by the sonification of a codon-optimised version using the laboratory strain organism's usage bias to direct chord duration.

Concert design MP introduced the questions motivating the work. *Does communicating mutation through music aid the understating of that data for those who don't normally engage with science? Is the mutation music enjoyable?* NW introduced the class of enzyme phenylalanine ammonia-lyase with an example from a slime mould, mentioning its relevance in treatment in cancer and for sustainable chemistry. NW explained how DNA is used to in protein creation via transcription and translation, emphasising the relevance of codons and highlighting codon redundancy. NW explained about the different of speed of translation of different codons, and how this idea of efficiency is a difficult concept to communicate to undergraduate biologists. NW explained the mapping used in their sonification in detail using the visualisation in Fig. 1. He emphasised how in the sonification, the length of the note represents the duration of the codon being *read* during the translation process. NW then spoke of the difficulty of using a slime mould in the lab and suggested that we would want to look at the same protein using *Escherichia coli* bacteria, as it is much easier to use for research. He highlighted that using the identical DNA sequence in *E. coli* would lead to inefficiency in the trans-

Building Block	Code(s)	Building Block	Code(s)
Ala / A	gct gcc gca gcg	Leu / L	tta ttg ctt ctc cta ctg
Arg / R	cgt cgc cga cgg aga agg	Lys / K	aaa aag
Asn / N	aat aac	Met / M	atg
Asp / D	gat gac	Phe / F	ttt ttc
Cys / C	tgt tgc	Pro / P	cct ccc cca ccg
Gln / Q	caa cag	Ser / S	tct tcc tca tcg agt agc
Glu / E	gaa gag	Thr / T	act acc aca acg
Gly / G	ggt ggc gga ggg	Trp / W	tgg
His / H	cat cac	Tyr / Y	tat tac
Ile / I	att atc ata	Val / V	gtt gtc gta gtg
START	atg	STOP	taa tga tag

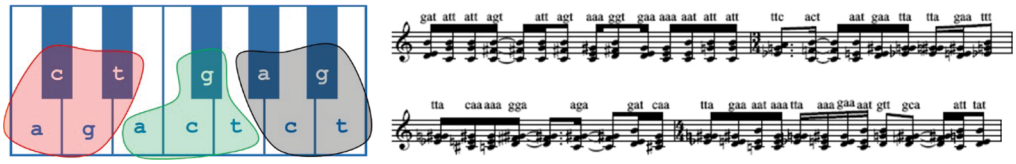

Fig. 1 A panel diagram showing the full genetic code (top) with each nucleobase component of the triplicate codons colour mapped onto the 12 tones in keyboard representation (bottom left) along with an excerpt of the resulting musical score (bottom right)

lation process. The audience were then played excerpts from a concert preforming the piece, emphasising the different translations speeds of codons in different species.

MP introduced the context of sonification as a composition practice for artistic purposes. Following the performance, MP explained they aimed to keep the piece as close to the data as possible during composition and avoided the impulse to compose the work in a traditional way. MP also highlighted the technical difficulty for instrumentalists of performing the resultant piece. MP expanded on the performance context of the excerpt, at a *coffee and a concert* series in Didsbury, which typically attracts a musically conservative crowd. MP discussed feedback taken at the concert recording, noting that the audience considered the piece much more effective than enjoyable. MP finished by noting how the work caused reflection in both performers and audiences on how art can be scientific, in addition to how scientific research is creative.

Molecular soundscapes and AlgoRIOTmic Grrrl!

SK performed two pieces. The first piece used sonification processes developed during the Leverhulme Trust funded project Molecular Soundscapes which aimed to generate strategies for converting molecular biology into sound. A recording of another performance of the piece with additional live instrumentation can be viewed at the referenced link (Knotts 2023).

Sonification design

Developing sound-art works which provide an accurate and robust data representation at the molecular level has the potential to provide a new complementary representation of the dynamic behaviour of proteins that are a challenge to represent using current visualization platforms. The richness of sound enhances the visual information, making computational chemistry concepts accessible to a broader audience while also offering the scientific community an alternative method to approach information on the structure and dynamics of proteins.

SK worked with molecular dynamics simulation data generated by Dr. Agnieszka Bronowska and her research group at Newcastle University. The data related to the process of designing drugs to treat neurodegenerative diseases such as Parkinson's and Alzheimer's. IPAS131 is a protein that is a potential target for drug design for these diseases. The data provided by Bronowska was a simulation of the protein over 1000 ns.

The main focus of the sonification was to represent the relative flexibility of constituent parts of the protein. Aspects of the dynamics such as flexibility of the protein, position of molecules and molecular sequence are mapped to musical parameters such as pitch, resonance, timbre, spatialisation, and melodic patterns. An interactive interface allows the selection of specific regions of the protein and of time spans of the simulation as well as the selection of sonification layers.

The second piece, *AlgoRIOTmic Grrrl!*, involved the algorithmic remixing of a corpus of riot grrrl music, using machine listening techniques via a JavaScript web-based interface and live coding in Supercollider. This piece can be heard in Knotts, (2023), and is discussed in depth in Knotts and Collins (2021).

Concert design SK introduced the original context of *Molecular soundscapes* as an artist residency in a chem-

istry department, working alongside researchers designing drugs for neurodegenerative diseases to create an original hour-long interactive installation. SK explained how the researchers' work focuses on protein flexibility: how proteins in the body change shape over time, how these different shapes create spaces that allow interaction with drugs, and how drugs administered to patients cause these changes. The changes were demonstrated with two 3D printed physical models of the proteins and a screen-based visualisation.

SK explained that the complexity of dynamic 3D visualisation motivated the chemists to look for different modalities for representing their work. They were interested in how sonification may help identify the most flexible part of the protein. The chemists also wanted a way of speaking to people who aren't specialists about what they do. The audience had the sonification mapping explained to them. Protein flexibility is represented by the sonic resonance: *springy* resonance shows flexibility, and *plate-like* resonance shows less-flexible parts. SK explained that the work plays through the protein multiple times, sonifying different shapes of the protein on each repetition. SK then performed a live-coded performance of the piece with accompanying visualisation for six minutes.

SK introduced the second piece *AlgoRIOTmic Grrrl* explaining that it is created by algorithmically remixing a large corpus of riot grrrl music. By writing search algorithms in Supercollider, SK says how she looks for parts of the corpus that have a certain kind of data, and then uses those data to create musical rhythms and patterns.

Evaluation methods

Reed et al. (2018) suggest three ways to evaluate public engagement: evaluate the design of public engagement activities for a given purpose and context, evaluate the delivery/outputs of public engagement, and evaluate the impacts of public engagement. In this pilot study, we focussed our feedback methods to collect data on the delivery/outputs of the event, centring the immediate effects on our audience. The immediate outputs we wished to measure were the effect of *inspiration* on our publics, and the success of the concert as an arts event, using *enjoyment* as a proxy measure. We also gathered some information on the nature of our audience. Measuring the impacts of the event is beyond the scope of this pilot study. We attempted modest evaluation of the design of the event by self-reflection, detailed in the Discussion section.

To evaluate the delivery/outputs of the event, we distributed hard-copy forms. We made the forms anonymous. We wanted them to be quick to complete for higher response rates, so we limited the number of questions and opted for Agree/Neither/Disagree responses over Likert scales where relevant. We aimed to target our complete population of event attendees by distributing questionnaires to all of them. We used three tick box questions followed by four free-text responses:

Q1. I am a University of Edinburgh member of staff/I am a University of Edinburgh student/I am not associated with the University of Edinburgh (Select One)
Q2. I enjoyed the event (Agree/Neither/Disagree)
Q3. I feel inspired by the event (Agree/Neither/Disagree)
Q4. What was the best thing about the event? (Free-text)
Q5. What was the worst thing about the event? (Free-text)
Q6. Where did you hear about the event? (Free-text)
Q7. Any other comments (Free-text)

Question 1 aimed to understand the publics which we were reaching. Question 2 aimed to simply capture the success of the delivery of the event, assuming that one *enjoys* an art event when one has appropriately accessed it. Question 3 measured a key output of our event, as we aimed to *inspire* our public. Question 4, 5, and 7 aimed to capture more diverse qualitative responses to the delivery and outputs of the event, with an eye to improving the design and process of future research. Question 6 aimed to guide publicity channels for future events.

The responses to the free-text questions (Q4, Q5, and Q7) went through a process of inductive thematic content analysis using word processing software (Patton 2015). The responses were categorised into common themes and counted to allow for quantitative summaries of the data. The analysis was entered into without preconceived analytical categories, and common themes were identified through comparing responses. EJM conducted the analysis and Daniel Barker (DB) moderated EJM's analysis, with discrepancies resolved by discussion.

Results

Of the 43 responses to Q2, 41 (95%) indicated that they enjoyed the event, with none disagreeing and 2 (5%) responding neutrally. Of the 41 responses to Q3, 26 (63%) reported that they felt inspired by the event, with 1 (2%) disagreeing, and 14 (34%) responding neutrally, as seen in Fig. 2 plot A. Of 62 responses to Q1, 52 (84%) were associated with the University of Edinburgh, with 41 (66%) students and 11 (18%) staff. 10 (16%) were not associated with the university, as seen in Fig. 2 plot B. The attendance level was higher than anticipated leading to a

shortage of feedback forms, which may be the main cause of moderate return rates for feedback.

Aggregated responses to questions 4, 5, and 7 of feedback form

Responses to the three free-text questions (Q4, Q5, and Q7) averaged 11.4 words per answer, and ranged from single-word answers to a 50 word paragraph. The quantitative summaries of the inductive thematic qualitative analysis is shown in Table 1. The word clouds in Fig. 3 give an impression of the lexicon used by respondents. Example responses have been given in the supplementary materials.

The most common response to the best thing about the event was specific compliments about the individual works presented: pleasingly each piece presented by each performer was singled out as the best thing about the event by at least one respondent. Seven people cited learning about sonification as the best thing about the event, with six enjoying the novelty of the approach to data representation, five enjoying the variety of performances in the event, and four enjoying the event for the blending of music and science. Two people gave nonspecific compliments on the event as a whole, while two people spoke about the effect of experiencing the music as the high point. One person mentioned the effect of the event in motivating them to work on their own projects, and another saw the combination of sound and visuals as the best thing. One person expressed joy in watching the reactions of the audience to the pieces.

Operational issues made up a large proportion of the *worst thing about the event* responses (68%), including software technical issues, venue choice, and stage management during the event. Insufficient explanation may also be seen as an operational concern, reflecting on planning and time allocation. Five people gave negative aesthetic opinions on some or all of the sound used in the event. Four kind people refused to give negative feedback, stating "nothing was bad" or something similar. Two people gave specific feedback on methodology employed in the creation of some of the sonifications, and one person bemoaned a lack of visualisation to accompany some of the pieces.

Most (68%) of the any other comments responses gave straightforward positive feedback: complimenting the event, thanking the hosts, or encouraging the

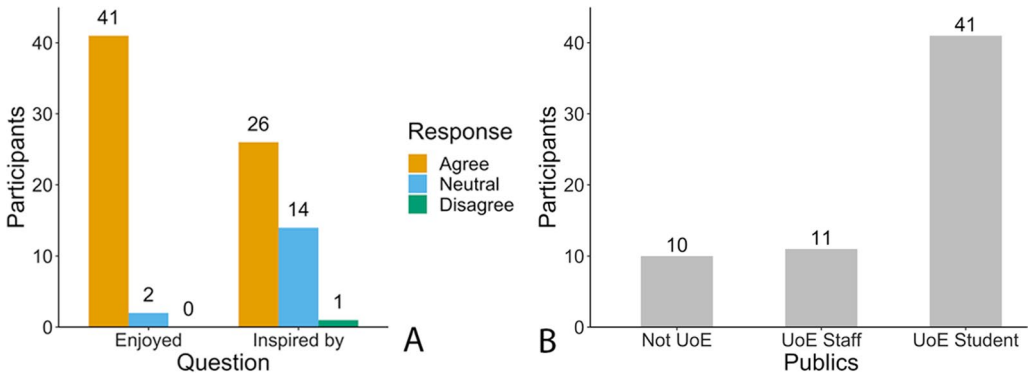

Fig. 2 Tick-box questionnaire data collected by physical forms in the immediate aftermath of the concert. **A** Details responses to the statements "I enjoyed the event" (n = 43) and "I felt inspired by the event" (n = 41), with respondents able to indicate Agree/Neutral/Disagree. **B** Reports responses to "I am a University of Edinburgh member of staff/I am a University of Edinburgh student/I am not associated with the University of Edinburgh" with a single ticked box (n = 62)

Fig. 3 Word clouds showing responses to free-text feedback questions. Word clouds feature the 30 most commonly used words with size scale proportional to the square root of the frequency of the words. Made using (Davies 2023). One piece of personal data has been redacted

Table 1 Feedback form questions with free-text responses categorised by theme

	Count	Percentage (%)
Q4—What was the best thing about the event? (n = 44)		
Specific works/performances	20	45
Learning about sonification	7	16
Novelty of approach	6	14
Variety of performances	5	11
Music/science combination	4	9
Compliments	2	5
Experiencing the music	2	5
Effect on motivation	1	2
Combination of sound and visuals	1	2
Audience	1	2
Q5—What was the worst thing about the event? (n = 40)		
Software technical issues	16	40
Insufficient explanation	8	20
Stage management during the event	7	15
Aesthetic opinions	5	13
Venue choice	4	10
"Nothing was bad"	4	10
Specific feedback on methodology	2	5
Lack of visualisations	1	3
Q7—Any other comments (n = 22)		
Compliments	10	45
Thanks	3	14
Aesthetic opinions	2	9
Sound	2	9
"Do more"	2	9
Recommendations on content	2	9
Lack of visualisations	1	5
Publicity approach	1	5
Musical artist suggestion	1	5

Percentages are calculated as proportion of n respondents for each question, ignoring blank responses, and are rounded to nearest integer value. Themes are not mutually exclusive, some respondent's comments contained two themes. Example responses can be found in the supplementary materials

organisers to host additional similar events. Two participants chose to add their aesthetic opinions on their impression of the overall sound of the event, another two made recommendations about content to include in future events, one person said they had preferred the presentations with visual accompaniment, one gave feedback on the publicity approach, and someone named some musical artists, perhaps for the hosts to listen to.

Discussion

Through its three acts, our concert highlighted a number of basic evolutionary principles: including variation, mutation, and biological function. In addition to the musical entertainment value, we also used this concert as a pedagogical experiment. By engaging with the audience, we were able to elicit reactions to the presentation at the time of the performance itself.

Painting in broad brushes, the responses to Q2 & Q3 give us confidence that the event was a success. With 95% of respondents stating they had enjoyed the event and 63% indicated they were inspired by it, the event seems successful in both the aims of inspiring our audience and in functioning as a successful art event which our audience enjoyed.

Attendees were mostly associated with the University of Edinburgh, as shown in Fig. 2 plot B. This contextualises our findings, as those who study and work at a university likely have different responses to events aiming at public engagement with research than a broader general public. Most of our participants discovered the event via the university, through departmental email or colleagues, and we found promotion of the event easier on campus. Efforts were made to distribute posters off-campus and to make contact with event-aggregating websites and magazines. Q6 gave us evidence that it was rewarding to publicise the event via a range of channels, and also informed us that secondary publicity had occurred via email lists and social media posts which were not sent by the organisers.

Evaluation by self-reflection

Events, such as our concert, have a broader impact on the field of sonification: one that remains unmeasured but need not remain unmentioned. In hosting a sonification event, we facilitate a bevy of positive community effects which benefit the research field: those with shared interests in sonification technologies were able to network and collaborate on future projects; skills in performance, securing funding, and event administration were developed by performers and hosts; and relationships were cultivated between researchers and audience members. Our event also met many of the goals shared by diverse public engagement processes: achieving increased awareness of the topic, creating a space for dialogue and debate, increasing the accessibility of the research, increasing the engagement of the audience with research content, and raising the profile of the field, researchers, and the institution.

One of the most fundamental concerns which came from our feedback process relates to the feeling of a lack of information by the audience at various points in the concert. Performers will gain experience through events such as these and improve their skills and practice as communicators thus improving future events. Also, we feel there are organisational steps which could mitigate this impact in future events. Principally, we recommend that future similar events create a physical or digital program for attendees to keep and refer to during performances. This complementary means of communication will remove some of the onus of information sharing from the performers.

Much of the constructive feedback provided to us concerned the stage management of the event and the choice of venue. Many of the ways to improve this is to take lessons from concerts and theatre performances. We include here a short list of recommendations for ourselves for future concert-style public engagement events: delegate responsibility for hosting to a non-performer to give performers more capacity to focus on their part; allow generous time for rehearsals to mitigate software/technical issues; use technicians with events experience to support the running of the event; and ticket the event, even if it is free, to allow better anticipation of attendance. Venue choice will make a huge difference to the event: use a venue designed for hosting your kind of event (in our case, a gig-venue). This will give you access to their built-in audio system and the expertise of their technicians. The space will be better designed for movement and socialising. Avoiding university venues will remove gatekeeping impacts associated with these spaces.

Our event had unanticipated benefits: new projects and collaborative opportunities arose for stakeholders, the potential to leverage further funding for other events increased, and new connections were created. The most consequential but unintended influence on our own research has been the new topics and avenues of research derived from audience feedback and appetite. This publication is a key part of creating wider impact beyond the performers, stakeholders, and attendees of the event itself, and we hope that communities of researchers, engagement practitioners, and educators are influenced by our approach.

Future development

How *inspiration* was experienced by our attendees remains obscure to us via our feedback approach. Future events would benefit from follow-up interviews or focus groups to reveal a greater depth of insight into the experience of our audiences. Also, questions seeking insight into the understanding of concepts being communicated may improve future evaluation approaches. Data such as our attendees' relationships to research, formal scientific training, and relationship with *avant-garde* or experimental music would be interesting questions to ask, allowing more depth in analysis of the context of feedback of future events.

While any future performance of these sonification works would provide an opportunity for the discussion of evolutionary ideas, the expansion of these sonification approaches provide interesting future directions to develop their connections to evolutionary concepts. The way in which these methods could be developed is highly linked to the modes of presentation in which they would be presented. Radio shows, installations in museums and galleries, videos, podcasts, and further concerts all provide different emphases and diverse potential audiences, each requiring a different focus for successful communication.

The sonification approach presented in the first performance by EJM could be expanded into a range of similar works each demonstrating a separate molecular process by which evolution occurs, providing a suite of music illuminating the basis of the practically unseeable molecular forces of evolution. The sonification of the huntingtin protein could be framed in a wider discussion of hereditary diseases in the context of evolution and modern medicine. The sonification of the SARS coronavirus replicase polyprotein could be expanded to explore the relationships between different viruses and their hosts. The work presented by MP and NW could be expanded to compare different conceptions of synonymous codon bias, or to explore the commonality between different species using the music/musician as a metaphor for the ribosomal processes. SK's work demonstrating the flexibility of proteins could be used to explore ideas around evolvability related to protein dynamism, and to challenge the assumptions that proteins possess absolute specificity of function (Tokuriki and Tawfik 1979; Marsh and Teichmann 2014; Pohorille et al. 2017). Each of these developments would cultivate more specific connections to evolutionary ideas, and developed with an appropriate context in mind could create interesting and innovative works communicating biological ideas.

Conclusion

Presenting the sonic outputs of sonification research in a concert format showed good potential for the pursuit of public engagement with evolutionary concepts and scientific research more broadly, demonstrating the ability to engage the curiosity and inspire an audience while also conveying scientific content alongside the nuanced, and complex world of evolutionary biology research.

Abbreviations

ESX1	Homeobox protein ESX1
HTT	Huntingtin protein
MIDI	Musical instrument digital interface
SARS	Severe Acute Respiratory Syndrome

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12052-024-00200-5.

Supplementary Material 1. Example qualitative response for each theme in our thematic content analysis of our questionnaire feedback data.

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Author contributions
EJM organised the event, collected and analysed the data, and was the major contributor in writing the manuscript. EJM, MP, NW, and SK all performed at the event and wrote manuscript sections pertaining to their own performances. DB contributed supervisory support throughout. DB and TRM contributed substantive revisions to the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
Partial data generated or analysed during this study are included in this published article. Example responses to the questionnaire are available as supplementary materials.

Declarations

Ethics approval and consent to participate
This work is approved by the Ethics Committee at the School of Biological Sciences, University of Edinburgh (Reference number dbarker-0002). The legal basis of processing data in this paper is the public task of the University of Edinburgh (GDPR Article (6)(1)(e), https://www.legislation.gov.uk/eur/2016/679/article/6). All methods were carried out in accordance with relevant guidelines and regulations.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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