Dinosaur Choir: Designing for Scientific Exploration, Outreach, and Experimental Music

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ABSTRACT
Lambeosaurine hadrosaurs are a group of duck-billed herbivorous dinosaurs that possess variably shaped hollow cranial crests that are among the most extreme cranial structures ever to evolve. These crests developed as expansions of the nasal passages during sexual maturity and acted as resonators for vocal communication and visual display. This paper discusses the work-in-process, *Dinosaur Choir*, which recreates lambeosaurine skulls as musical skull instruments. The skull and nasal passages were created using Computed Tomography (CT) scans of hadrosaur skulls and the larynx is constructed based on paleontological research. Musicians and participants use the instruments by blowing into a mouthpiece or microphone, and the larynx creates the sound that is then resonated through the nasal passages. The instruments are intended for scientific experimentation, interactive exhibition, and musical performances. *Dinosaur Choir* aims to give an embodied experience with extinct animals long lost to the past. This paper considers how scientific research as well as musical and practical concerns impact the design process, exploring how to balance rigorous exploration of dinosaur communication with informed speculation and experimental music.

Author Keywords
NIME, dinosaur, hadrosaur, sound installation, digital fabrication

CCS Concepts
• **Applied computing → Sound and music computing**; Performing arts; • Applied computing → Life and medical sciences;

1. INTRODUCTION
Dinosaur Choir consists of a series of instruments exploring dinosaur vocalization, where each instrument allows musicians and gallery visitors to blow into mouthpiece to create sound via an artificial larynx. That sound is then resonated through hollow nasal passages in the skull replicas. This project is an extension of the first author's previous work, *Rawr! A Study in Skulls* (see Figure 1) [1]. The aim of this project is to allow an embodied interaction with extinct non-avian dinosaurs and highlight their complex social behaviours that are often overlooked by popular media. Musical works using the instruments will use extinction and evolutionary change as subject matter, drawing attention to ecosystem instabilities and climate change. Musicians and museum participants will interact with the reconstructed skulls using their own breath, making the experience of the irretrievable loss of dinosaurs a visceral one. In this paper, we present 1) the artistic and musical concerns of dinosaur skull instruments, 2) new motivations and approaches for continuing the work begun by *Rawr!*, 3) the scientific context of dinosaur vocalization impacting skull instrument design, 4) the detailed implementation and planning of the first instrument in the *Dinosaur Choir* series, an adult *Corythosaurus*, and 5) future work and directions. *Dinosaur Choir* is a way of continuing the visual tradition of paleoart into the medium of embodied sound.

Paleoart (the artistic depiction of prehistoric life) is an important way for the wider public to learn about past life on Earth, and is often used as a scientific aid [2]. *Dinosaur Choir* aims to be as anatomically rigorous as possible within the practical and artistic constraints of new musical instrument design. We use an iterative design process to facilitate increasing scientific rigor, incorporating more research as it becomes available, and as the necessary technology advances become cheaper and more available. We expect this accounting of our process and approach to be valuable to those in the NIME community pursuing work engaging with paleontological research and more generally collaboration with on-going biological and scientific research.

Figure 1. Exhibition of Previous Work, *Rawr! A Study in Sonic Skulls*

Popular depictions of dinosaur sound, such as in the *Jurassic Park/Jurassic World* franchise [3][4], have also dealt with the competing goals of scientific accuracy and artistic needs. However, rather than being concerned with narrative tension as in such films, a goal of the *Dinosaur Choir* series is to be able to create the maximum variety of sounds to promote scientific exploration, musical experimentation, creativity, and long-term engagement. *Rawr!* has been involved in the creation of several musical works, collaborations, and improvisations throughout the decade since its first conception [1] [5], and similar plans exist for the instruments of *Dinosaur Choir*. Further, the work must be transportable, durable for use in professional exhibition, and easy to operate and understand for the novice gallery visitor, while allowing for extended possibilities and nuanced control of sound parameters for the advanced musician.

Many new instruments have been created for vocal musical expression [7]. Most such work engages with extant animals and include those that engage with the human voice such as SPASM [6], the ArtiSynth [8] and DiVa systems [9], and a recreation of an Egyptian mummy's vocal cords [10]. Musical instruments inspired by animal vocalization include those dealing with bird vocalization [11], whale vocal box instruments intended for interspecies communication [12], *RhumbLine*, a networked interactive frog vocalization [13], and *On Board Call* [14] a digital musical instrument recreating various wildlife sounds in order to facilitate deep listening practices. Humeau's *Opera of Prehistoric Creatures* imaging the sounds of extinct mammals such as the mammoth [15][16] is of particular note, as her work engages with 3D replication of larynges of extinct creatures and paleontological research similar to the work described here. The sculptures are intended to look futuristic and raise questions about cloning and resurrection [15]. However, the *Dinosaur Choir* skull instruments each present as a skull fossil, which emphasizes the connection the instrument has to the prehistoric past. Humeau's work also used a pneumatic system to activate the sounds [16], but *Dinosaur Choir* builds on this to create a material, physical, intimate interaction between human and dinosaur via breath and sound.

2. NEW APPROACHES AND OPPORTUNITIES OF DINOSAUR SKULL MUSICAL INSTRUMENTS

The motivations to continue the work of *Rawr!* are multifold, with a major reason being the public demand for dinosaur outreach, education, and media. Such content inspires children and others to pursue scientific fields, and, in the case of *Rawr!* it has introduced new audiences to new and experimental music. Another main motivation is the opportunity to iterate upon *Rawr*! to incorporate an updated and more scientifically informed model of dinosaur vocalization. In the intervening years since the creation of the original instrument, both science and technology has progressed. More is known about dinosaurian vocal abilities and less trade-offs must made due to practical 3D printing concerns.

To this end, *Dinosaur Choir* will employ a computational larynx running on a minicomputer instead of a fully physical larynx mechanism as in *Rawr!* [1], as computational models can more easily be updated. Musicians and gallery visitors will blow into a microphone instead of a fully physical system, and the computational model will adjust in real-time, allowing for gallery visitors to listen to different versions of the larynx based on different biological assumptions. This educational feature will allow audiences to understand the speculative aspects of the work and the nature of competing scientific hypotheses. Further, the use of a microphone as an input allows safer and more sanitary interactions with what is essentially a wind instrument in an exhibition context. This aspect had previously caused some interaction hesitation that was only exacerbated by the COVID-19 pandemic, and it became a serious obstacle to exhibiting the work in a gallery or museum. Solutions such as bellows or pneumatic tubes to create airflow interfere with the goal of intimate embodied interactive sound, but we have circumvented this issue using a contactless microphone activated by breath. During exhibition, we also will incorporate the use of an optional throat microphone to accommodate those wearing masks.

Crest size and shape not only varies between species, but also through ontogeny (development and aging) within a single species (Figure 2). For instance, *Rawr!* is the reconstruction of a subadult *Corythosaurus* (CMN 34825) with only a partially developed crest that differs substantially from the large crests of adults [17][18][19]. Recreating the skulls of different individuals at different ages therefore allows exploration of their changing voice throughout maturity, and provides a glimpse of the prehistoric soundscape. Additionally, crests are highly species specific because the vocal calls (as well as the visual display of the crests) were likely a major component of sociosexual display and competition [17][18]. Thus, the future incorporation of skulls from multiple species will bring to life these vocal differences, as well as give opportunities for orchestrating new musical works using dinosaurs as instruments.

Figure 2. Juvenile (left; ROM 759), subadult (center; CMN 34825), and adult (right; ROM 1933) skulls of *Corythosaurus* in right lateral view.

3. PALEONTOLOGICAL CONTEXT AND DESIGN SPECIFICATIONS

Research on non-avian dinosaur vocalization has been relatively sparse, and soft-tissue vocalizing organs such as the larynx rarely preserve [20]. Thus, scientists use more indirect forms of evidence to investigate the topic. One common technique is phylogenetic bracketing, that uses the closest and second-closest living relatives to make interferences about extinct species [21][22]. For instance, while the lack of direct evidence for vocal organs in non-avian dinosaurs has led to speculation that the common ancestor of dinosaurs was mute [23], more recent research suggests that vocalization is an ancestral trait of all choanate vertebrates (e.g., birds, reptiles, mammals, amphibians) [24]. In the case of non-avian dinosaurs such as hadrosaurs, the closest and second-closest living relatives are birds and crocodilians, respectively, and thus form the basis for our comparison. Birds have a unique vocal mechanism called a syrinx that differs markedly from the mammal-like larynx in crocodilians [25]. Previous evidence suggested that the syrinx is a more recent adaptation appearing after the last common ancestor of hadrosaurs and birds [20]. However, a rare dinosaur larynx fossil from an Ankylosaur, a relatively close hadrosaur relative, was discovered to be bird-like, suggesting a sound source such as the syrinx [26].

Two-mass vocal model computational simulations have been shown to adequately model both human [27], bird [28][29], alligator [25] vocal fold sound excitation. This result suggests that use of the two-mass computational model for the vocal apparatus of hadrosaurs would be an informed speculation appropriate for this project. Additionally, vocalization across terrestrial vertebrates relies on a source-filter paradigm, in which vocal folds, cords, or syrinx membranes create sound excitation in response to air pressure from the lungs, which is then filtered by the shapes of the various tubes of the anatomy, including trachea, nasal passages, mouth, and others [30]. As various real-time physically-based models have been developed based on this paradigm for bird [31][32][33] and human vocalization [7][8], we are using a physically-based modeling synthesis approach and are currently in the process of building a hadrosaur larynx model with parameters that approximate hadrosaur anatomy. One additional aspect of dinosaur vocal sound is suggested by a comparative analysis of archosaur vocalization, concluding that larger masses correlated with closed mouth vocalization styles such as the low-pitched calls of a cassowary, a large Asian bird species [34]. Therefore, we aim to reproduce the closed mouth vocal sound in our larynx model.

Along with phylogenetic bracketing, paleontologists examine the fossil record of other sound related organs to infer dinosaur vocalization. Lambeosaurine hadrosaurs, for instance, have long been hypothesized to use their crests for vocal resonation [17][18][19][36][37][38]. The first author's encounter with the digitally simulated call of the hadrosaur *Parasaurolophus* [37] was the impetus for creating the interactive replicas in *Rawr!* and *Dinosaur Choir*. The hypothesis that hadrosaurs used their crests for vocal communication led some researchers to study the inner ear of these animals, which were tuned roughly to the resonant frequencies of their crests [36], supporting the acoustic resonance hypothesis since animals tend to be tuned to their own vocal range [36]. Additionally, hadrosaur brains are distinctly large, and are consistent with the cognitive requirements of vocal communication and sociality [36]. One of the specimens examined in this inner ear research was also the specimen replicated in *Rawr!* (CMN 34825), and vocal frequency range estimates for that specimen were able to be obtained (267 Hz center frequency and 1534 Hz high frequency drop-off) [36]. However, such analyses have not been done for adult *Corythosaurus* specimens and reproducing the vocal capabilities of mature individuals will therefore provide a significant scientific contribution, in addition to engaging the public.

Our design goal is to allow a frequency range that is as inclusive as possible of all predicted frequencies and sounds rather than exclusive. We intend to preserve, within reason, the possibility of creating frequencies that may be outside the predicated vocal and hearing range for hadrosaurs. The ability to exploit an instrument for new or unpredicted sounds in unexpected ways opens up new possibilities for musical exploration and creativity, and thus, is a critical feature in a musical instrument [38][39][40], even if it allows for biologically implausible sounds. Due to the adjustable nature of the computational larynx solution, we will be able to modify the vocal capabilities to be more biologically plausible in appropriate settings, such as a more science-focused exhibition.

4. HADROSAUR SKULL MUSICAL INSTRUMENT IMPLEMENTATION WORK-IN-PROCESS

We are in the process of building the first prototype of the musical skull instrument of the *Dinosaur Choir* series. The instrument is based on CT scans of an adult *Corythosaurus* skull (ROM 1993), allowing insight into vocal calls through ontogeny. The musical instrument consists of two main parts: the 3D printed skull and nasal passages, and the computational unit, including minicomputer, sensors, and full-range driver speaker. We use a microphone to capture the breath data, and will use face-tracking to control additional vocal model parameters, inspired by De Silva, et. al.'s work with face-tracking controllers [11]. We are also designing a column support, which supports the skull and provides housing for the computational elements of the instrument (see Figure 3). We use an iterative process for each aspect of the project, with the prototypes of *Rawr!* [1] as the initial iterations. This section addresses our work to date, addressing current and future plans.

Figure 3. Depiction of the Dinosaur Choir skull instrument in exhibition.

4.1 Skull Design and Implementation

In this section, we describe the process of designing and fabricating a resonating skull from the CT scan data. We replicate the full skull with integrated nasal passages so the external skull can function as a presentational aid. We considered replicating the nasal passages only, as it was more cost-effective and the relative simplicity of the model allowed for more fabrication possibilities, such as using wood or other materials chosen for resonation properties. However, constructing the model in this way builds upon previous experience from *Rawr!* as when that musical instrument was displayed as the full skull, it generated significantly more excitement and engagement than when it consisted of only nasal passages. We have chosen to realize the model using 3D printing technology rather than CNC machining to implement the undercuts, i.e., recesses that cannot be molded or machined, but which are common in biological structures.

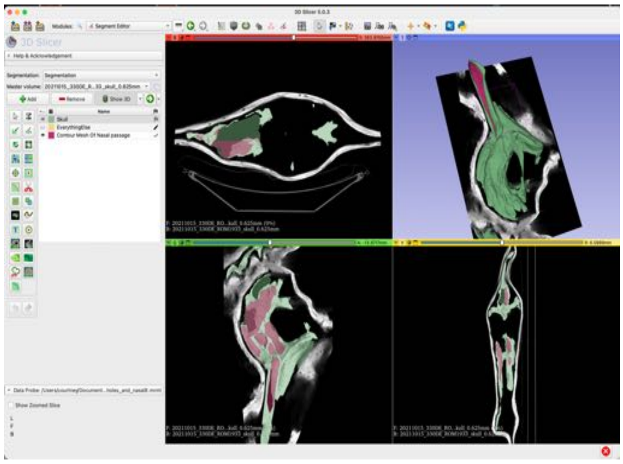

Figure 4. The process of data segmentation from CT Scans of ROM 1933 skull specimen using 3D Slicer

While *Rawr!* was based on the models published by [34], the current work is based on original CT data. The first step of our procedure was data segmentation, where we digitally separated 3D models of the skull and internal nasal cavities [41]. Segmentation and the production of these two 3D meshes was completed using 3D Slicer[1] (See Figure 4). The 3D models were then subjected to retrodeformation, where we patched holes, cracks, and missing sections of the skull, and corrected for deformation in areas that were damaged and twisted during fossilization (see Figure 5) [42][43]. Retrodeformation was completed using the open-source 3D modeling software Blender[2] as it was both cost-effective and has a history of use in paleontology [42][43][44][45]. Diagrams [18] [35] [36] and the skull and nasal passage models of the subadult *Corythosaurus* (CMN 34825) were used as aids in reconstruction. Small, less than 5 cm prototypes of both skull and nasal passages were 3D printed as intermediate prototypes to guide our design decision-making, and we are currently in the process of refining the models to be more scientifically accurate.

[1] https://www.slicer.org/

[2] https://www.blender.org/

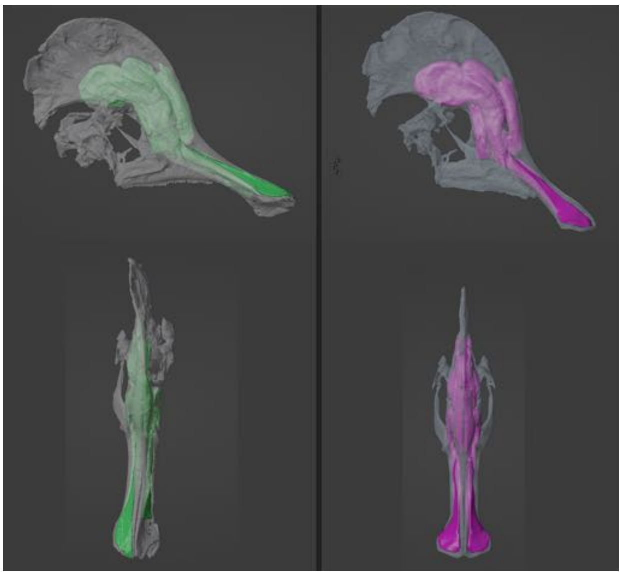

Figure 5. Skull and Nasal passages (ROM 1933) before (left) and after (right) retrodeformation. Note that this is still work-in-process.

4.2 Computational Unit Design and Vocal Model Implementation

This system describes our computational system, including inputs, software, and hardware. When a user blows into the microphone, the audio signal inputs into the vocal modeling software running on the minicomputer enclosed in the support column (See Figure 6). A video camera captures the face for face-tracking control, also sending its data to the vocal model as well. The vocal modeling software generates the sound, outputting through a speaker attached to an enclosure leading to the nasal passages. See Figure 7 for an illustration of where the sound should enter the nasal passages.

We use Raspberry PI 4 Model B[3] minicomputer, using a IQaudio DigiAMP+[4] board for audio feeding into a full-range driver speaker. Raspberry PI was chosen because it is a common platform, which tends allows for more support, user uptake, and instrument longevity [44]. The size of the speaker is constrained, as it must fit into the column support and skull, and so the speaker[5] was chosen considering both size and the low end of its frequency response, given the predicted dinosaurian vocal range. The system will use a small shotgun microphone[6] for breath input from users, but we will also include an optional throat microphone[7] for mask wearers during exhibition context. We incorporate a Raspberry PI Camera Module 2[8] for face-tracking.

We are developing the vocal model using the ChucK[9] programming platform to rapidly prototype. We have implemented a syrinx model based on [32], and are also working towards a more biologically accurate model [28][29] for exhibition. Parameters such as trachea length will be adjusted from bird-like values to dinosaurian proportions. Both models accept air pressure and muscle or membrane tension as real-time inputs into the model. An upcoming challenge in this work will be designing sound interactions [47].

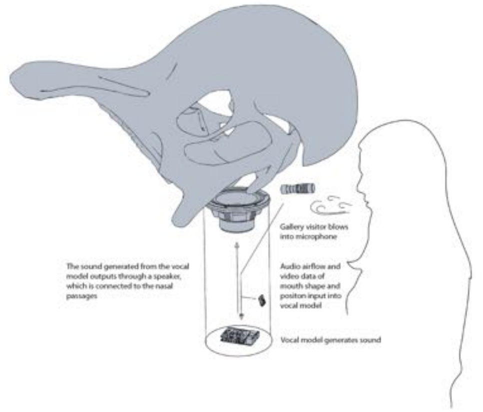

Figure 6. Diagram of signal flow between physical parts of the musical instrument

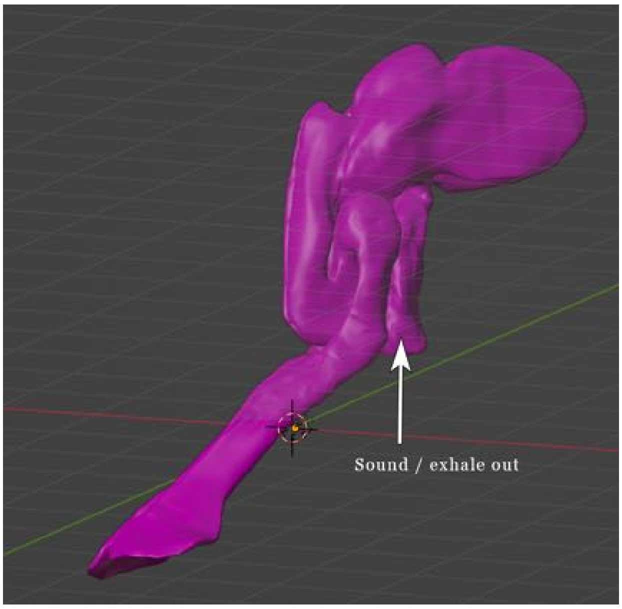

Figure 7. Nasal passages of ROM 1933 showing where the sound and exhaled breath enters.

5. FUTURE WORK

Future plans include deploying the vocal model on interactive online contexts as well as for use in the dinosaur skull instrument. We plan to make some models of *Dinosaur Choir* open-source, so that musicians who would like to create their own instruments would have the means to do so. However, there are some barriers to this plan, as many museums will not allow CT scans to be made public as loading and providing replicas of desirable fossils is a significant part of how they fund their activities, although this is changing. Further, researchers require access to data to be controlled before publication, although they are more open to making data publicly available. Morphosource[10] and Sketchfab[11] are platforms that host such publicly available

[3] https://www.raspberrypi.com/products/raspberry-pi-4-model-b
[4] https://www.raspberrypi.com/products/digiamp-plus
[5] https://www.madisoundspeakerstore.com/approx-6-fullrange/markaudio-alpair-10-grey-6-full-range-gen-2/
[6] https://www.movophoto.com/products/vxr10-universal-cardioid-condenser-mic?_pos=1&_sid=cd97c6e19&_ss=r&variant=7906850668588
[7] https://www.superaudioworld.com/product-page/av-jefe-tr-15-throat-transdermal-microphone-for-speech-difficulties
[8] https://www.raspberrypi.com/products/camera-module-v2/
[9] https://chuck.stanford.edu/
[10] https://www.morphosource.org/
[11] https://sketchfab.com/

biological data. Therefore, any plan to make these instruments open-source must be carried out with full participation of all stakeholders.

We have considered both exhibition and more traditional musical performance as outcomes of this project, and we have described design considerations for both applications. Accordingly, we also plan to develop musical works using the instruments and begin developing a performance practice, exploring the musical potentials.

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7. ETHICAL STANDARDS

Rawr!: A Study in Sonic Skulls has been made accessible to the public as an interactive installation displayed at museums and galleries open to the public at several locations and used in several public performances. No empirical user studies have been performed with the instrument, so issues of inclusion in that context are not relevant to this work.

For *Rawr!,* balloons must be replaced on the instrument during normal practice and every week during public use during installation. Mouthpieces are replaced with every user for sanitation during exhibition. However, the computational larynx of *Dinosaur Choir* does not require replaceable parts and thus is more sustainable. Our intentions towards open-source deployment are also stated in the Future Work (Section 5).

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