Visualizing Life in the Deep: A Creative Pipeline for Data-Driven Animations to Facilitate Marine Mammal Research, Outreach, and Conservation

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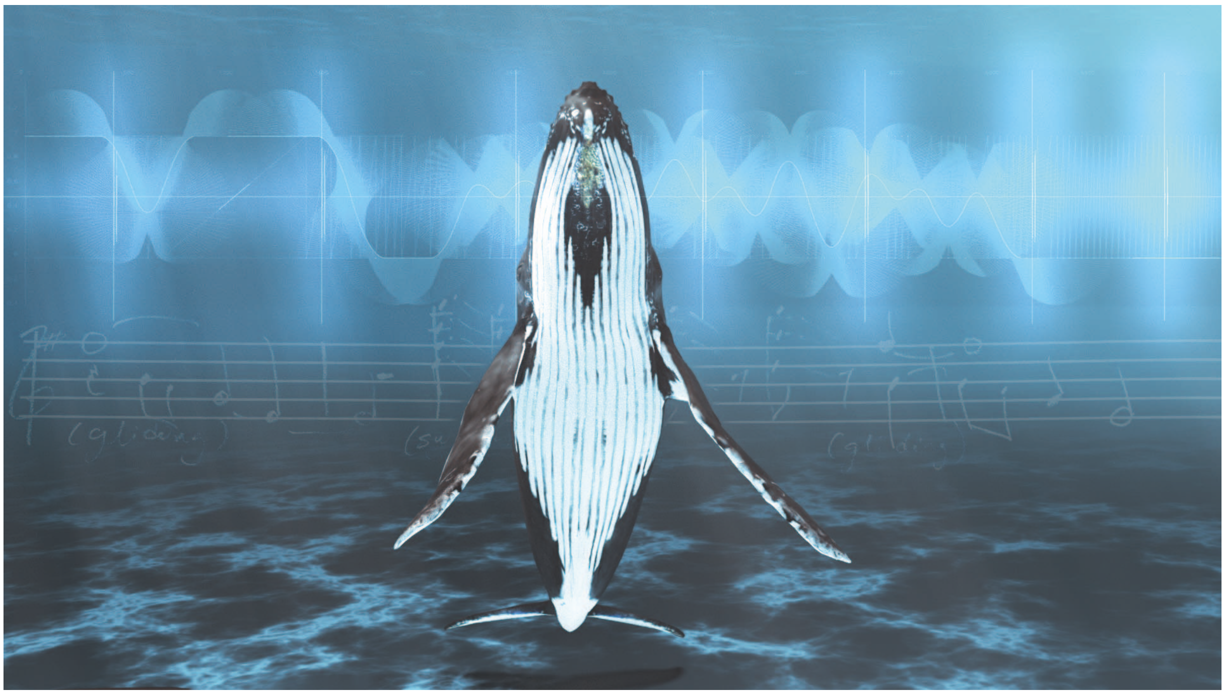

Figure 1: Illustration of an animated 3D humpback whale combined with a representation of several data streams used in our data-driven animation pipeline. The ribbons of data shown include: swimming and gliding data from an elephant seal, the waveform of a soundtrack generated from the beating heart of a narwhal, and notes of a custom musical score for one of our animations.

Abstract

In this paper, we introduce a creative pipeline to incorporate physiological and behavioral data from contemporary marine mammal research into data-driven animations, leveraging functionality from industry tools and custom scripts to promote scientific insights, public awareness, and conservation outcomes. Our framework can flexibly transform data describing animals' orientation, position, heart rate, and swimming stroke rate to control the position, rotation, and behavior of 3D models, to render animations, and to drive data sonification. Additionally, we explore the challenges of unifying disparate datasets gathered by an interdisciplinary team of researchers, and outline our design process for creating meaningful data visualization tools and animations. As part of our pipeline, we clean and process raw acceleration and electrophysiological signals to expedite complex multi-stream data analysis and the identification of critical foraging and escape behaviors. We provide details about four animation projects illustrating marine mammal datasets. These animations, commissioned by scientists to achieve outreach and conservation outcomes, have successfully increased the reach and engagement of the scientific projects they describe. These impactful visualizations help scientists identify behavioral responses to disturbance, increase public awareness of human-caused disturbance, and help build momentum for targeted conservation efforts backed by scientific evidence.

Keywords: Data-driven animation, marine mammals, art-science research, science communication, ocean sciences.

1 Introduction

To mitigate disturbance and conserve marine mammal populations, it is critical to understand marine mammals' responses to disturbance [50]. Human-caused disturbances such as entanglement in fishing gear and exposure to underwater noise can negatively impact individuals with population-level consequences [39]. These responses lie at the confluence of physiology, kinematics, foraging behavior, and animal movement ecology. Tagging technology has

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allowed scientists to describe and quantify the three-dimensional responses of marine mammals below the surface, by simultaneously recording positional data such as accelerometry, magnetometry, gyroscope, depth, geolocation, video cameras, and additional sensors that provide physiological measurements such as electrocardiograms [4, 32, 55, 58].

Behavioral and kinematic tagging data can also provide insight on physiological processes. Time depth recordings can provide information on the rate at which animals drift up or down in the water column, which is directly related to their buoyancy and thus their internal fat stores, a measure of body condition and health [4, 9, 18, 45]. Video footage of foraging can reveal total feeding attempts and prey availability, which has implications for animal health [2, 17]. Accelerometry informs 3D position, orientation, and the stroke rate of the fluke or flippers, which is related to the metabolic cost of transport [22, 30, 57].

In this paper, we explore the challenges of unifying disparate datasets with an interdisciplinary team and outline the design process for creating meaningful data visualization tools and animations (Fig. 2). Our work involved close collaboration between animators, computer scientists, and biologists to visualize and sonify the behavior and physiology of deep-diving marine mammals in extreme environments. Our framework directly incorporates behavioral and physiological data streams to depict stark shifts in swimming behavior (stroking and gliding), body condition (negatively buoyant to positively buoyant), and heart rate (extreme bradycardia and tachycardia). Our tools visualize changes across several orders of magnitude in space and time, from fine-scale body maneuvers to broad-scale trans-Pacific migratory patterns. We built custom tools including (1) scripts to visualize 3D position and orientation, (2) stroke and glide controllers to control organic swimming animations based on raw accelerometer data, and (3) a heartbeat sonifier to hear pronounced shifts in heart rate. In addition to developing new animation tools for data visualization and science communication, it is critical to provide accessible training to encourage broad use of these tools. Through a series of workshops titled "Animation for Science Communication" and several online tutorials and recordings, we taught a wide range of animation skills to over a hundred students, researchers, and faculty at the University of California, Santa Cruz throughout the 2020-21 academic year.

By reviewing existing approaches to animating ocean science data and meeting regularly with our interdisciplinary team of scientists and artists over the course of two years, we solidified the core goals for the development of our data-driven animations:

- **Research:** Collaborate with biologists to address the research tasks above and elucidate how marine mammals respond behaviorally and physiologically to different types of disturbance.
- **Clarity:** Ensure that each of those insights is communicated clearly via the visualization by combining 3D animation, narration, annotations, line animations, and visual effects.
- **Reach:** Increase the readership and comprehension of scientific papers by creating accessible and engaging animations.
- **Impact:** Work with scientists to develop a clear and succinct take-away that summarizes the consequences of disturbance and provides conservation recommendations.

1.1 Related Work

Researchers in the visualization and data art communities advocate for the incorporation of creative methodologies from interactive design and visual arts practice, particularly when working on collaborative projects that bridge multiple disciplines [14, 15, 48, 51] and when translating scientific results to the public [20, 42, 43, 52]. While data visualization research often focuses on the development of effective techniques and tools to facilitate exploration and analysis of data, data storytelling approaches emphasize how visualization techniques can persuasively communicate scientific results through a compelling narrative and interpretation of a dataset [29, 40, 46]. To support scientific engagement and communication, researchers have recently promoted the use of "cinematic" data visualization, leveraging 3D modeling, motion graphics, and visual effects software tools used most often for animations and games [5, 6, 47]. Our data-driven animation pipeline draws from this work by creating cinematic depictions of contemporary marine mammal research that integrate physiological and behavioral datasets from a suite of animal-borne sensors (Fig. 2).

1.1.1 Visualization tools for tag data

Visualization tools are critical for data exploration and interpretation for animal-borne tags. *TrackPlot*, a 3D visualization software created by biologists and data visualization experts, facilitated the first detailed description of benthic side-roll feeding by humpback whales and greatly advanced our understanding of complex biomechanics and kinematics [44, 54–56]. Existing marine mammal tag visualization tools, such as *TrackPlot*, Sea Mammal Research Unit's *MAMVIS*, and Wildlife Computers' *Data Portal*, are primarily focused on geolocation or kinematic representations of dive behavior and rarely incorporate physiological measurements such as heart rate, which are often recorded using separate dataloggers [13, 35, 54]. Physiological instruments such as animal heart rate loggers by UFI Instruments and Star-Oddi currently do not support adjacent 3D track visualization. Our animations present behavior alongside physiological data to unify and expedite data exploration and interpretation. In addition, our animations visualize fine-scale behaviors such as mouth openings, fluke and flipper swimming strokes, and fine-scale flipper maneuvers to improve realism and create an engaging experience.

1.1.2 3D Modeling tools

3D modeling of marine mammals is useful for assessing animal health, locomotion costs, and functional anatomy [1, 21, 53]. Beyond addressing scientific questions related to body mass and shape, certain anatomically accurate 3D models have been textured and rigged for use in animations [21]. However, high-quality rigged models with sophisticated animation controls often lack scientific rigor and accuracy. Although access to 3D photogrammetry and LIDAR 3D scanning has facilitated the creation of 3D models and even 3D reconstruction of an animal's environment, these tools are still challenging to implement in the field [21, 31]. Behaviors of interest may not fit within the repertoire of a rigged model and custom controls and rigging may be required. By modifying existing rigged models and creating custom 3D models, we hope to increase the availability of realistic models for both scientists and animators.

1.1.3 Marine Mammal Animations

Marine mammals are commonplace in animations targeting younger students and children, including feature films, computer games, and educational videos [12, 28, 34]. Educational 3D animations accurately depict marine mammal anatomy and even simulations of dive physiology, but these animations do not usually incorporate tagging data [11, 36]. Our animations directly incorporate tagging data from current research projects to make it accessible to the scientific community, policymakers, and the general public.

2 Key Tasks and Data Types

Supporting our high-level goals, we worked closely with our collaborators to identify the key visualization tasks to facilitate effective scientific communication:

T1 Present and align behavioral and physiological data streams collected from animal-borne tag sensors.

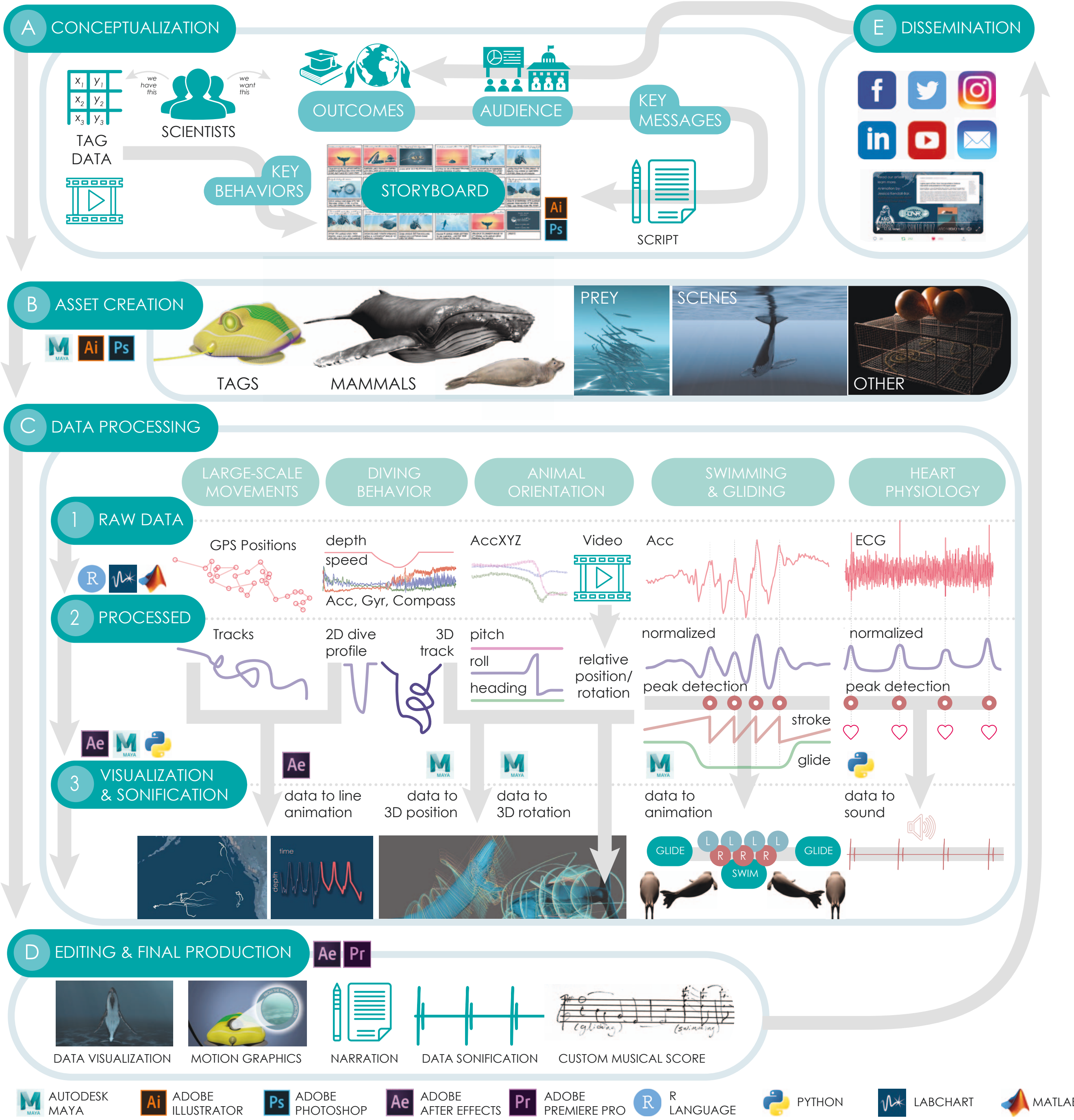

Figure 2: **Conceptual diagram of the animation process** from (A) conceptualization to (B) asset creation, (C) data processing, (D) editing and final production, and (E) dissemination. **(A) Conceptualization.** We demonstrate how we created a storyboard and script based on key features of the data as well as taking into account our desired outcomes (education and conservation) and audiences (government, NGOs, and academics). **(B) Asset Creation.** We demonstrate the range of customized assets we created in Autodesk Maya (3D models), Adobe Photoshop (digital paintings and 3D model textures), and Adobe Illustrator (vector graphics). **(C) Data Processing Pipeline.** We show the process of data mapping from raw data to processed data to abstraction (data visualization or data sonification) for five major data types, including (1) large-scale movements (from GPS positions to line animations), (2) diving behavior (from inertial motion sensors to two- and three-dimensional dive tracks), (3) animal orientation (from inertial motion sensors to three-dimensional rotation), (4) swimming and gliding (from raw accelerometer data to animated swimming), and (5) heart physiology (from ECG data to sound). **(D) Editing and Final Production.** We combine data visualization, custom 2D illustrations and 3D assets, motion graphics, narration, data sonification, and custom musical scores in the final compositions to prepare them for **(E) dissemination** to reach our key audiences and achieve desired outcomes.

T2 Correlate data streams to generate hypotheses about the responses of marine mammals to disturbance.

T3 Compare behaviors across time, ecosystems, and species to generate overarching theories about the impact of disturbance across animal systems.

T4 Use this data to inform policy related to marine mammal and ecosystem conservation.

We refer to these tasks below when describing details of the visualization pipeline (Sect. 3). Achieving each of these tasks requires the use of a wide range of data types, including the following:

Position and rotation: We calculated pitch, roll, heading, and three-dimensional position from inertial sensors on tags from Customized Animal Tracking Solutions (Queensland, Australia; cats.is), UFI tags (Morro Bay, California; ufiservingscience.com), Wildlife Computers' Daily Diaries, and Mk10 tags (Redmond, WA; wildlifecomputers.com). Then, we visualized the position and rotation of 3D models of elephant seals, narwhals, and humpback whales to demonstrate underwater behaviors such as cooperative feeding and predator evasion.

Reconstructing social behaviors from video tags: We analyzed video footage from animal-borne CATS tags to reconstruct the 3D position, rotation, and swimming behavior of other humpback whales relative to the tagged whale. In addition, we used timepoints from the video data to link the onset and duration of animated mouth openings and demonstrate feeding synchronicity.

Large scale animal movements: We linked the GPS position of a dozen elephant seals on their annual foraging trips from Beltran et al. [4] to line animations using Adobe After Effects.

Swimming speed (stroke rate): We analyzed accelerometer data for fluke and flipper strokes using normalized peak detection algorithms and paired the stroke rate (in fluke or flipper beats per minute) of the tagged animal to the rigged 3D model. Stroking and gliding have physiological implications for the animal's energy expenditure and oxygen utilization, which we visualize and sonify with the sound of a tail moving through water.

Heart rate: We analyzed electrocardiogram recordings of narwhals and elephant seals to extract heart rate data using cyclical peak detection algorithms [58]. We present this data visually as well as auditorily by linking instantaneous heart rate to the sound of a beating heart.

Body condition: From examining diving behavior and specific segments of dives where animals drift passively through the water column, we can identify shifts in the animal's buoyancy due to its changing fat stores throughout its migration [9, 18]. We linked these shifts to line animations.

We established an interdisciplinary team with experts in illustration, animation, data visualization, visual effects, computer science, science communication, and marine mammal biology. We united experts in different animal systems to develop the 4 animations described below. These animations were designed to accompany the publication of scientific articles, some of which are in preparation and others published. Each animation was created following a four-stage approach: conceptualization (storyboarding and scriptwriting), asset creation (creating custom models and illustrations), animation of behavior and physiology (pairing data to 3D and 2D assets), and final production (annotations, narration, and music) (Fig. 2). Excerpts from these animations are included in the supplementary video that accompanies this article.

Our four animations incorporate the data described above to address our key tasks:

Animation 1: Humpback Alliance. Our 3D humpback whale animation visualizes the position and orientation of a group of whales foraging on the ocean floor to determine whether there is coordination or competition between individuals of the group. Our animation emphasizes the importance of minimizing the use of bottom-set fishing gear that could disturb and entangle bottom-feeding humpbacks.

Animation 2: Lightscapes of Fear. Our 2D elephant seal animation demonstrates state-dependent risk aversion by showing the shifting decision-making by a seal as it travels across the North Pacific [3, 4]. The animation visualizes the geographic location, body condition, and rest timing of elephant seals on their 7-month-long foraging trip. This animation shows that as an animal shifts from inferior to superior body condition (negative buoyancy to positive buoyancy), the seals begin to prioritize resting during the safer, darker, and earlier hours of the day.

Animation 3: Sounds of Fear. Our 3D elephant seal animation visualizes the position, orientation, swimming behavior, and heart rate of a seal as it dives under two conditions: with and without disturbance caused by the vocalization of a killer whale predator produced from an animal-borne acoustic tag. We pair the animal's heart rate and stroke rate data to sound. This animation demonstrates the fear response of an elephant seal in the wild and helps us understand how these animals respond to stress in their natural environment.

Animation 4: Paradox of Fear. Our 3D narwhal animation visualizes the position, orientation, swimming behavior, and heart rate of a narwhal after release from net entanglement in East Greenland. We pair heart rate and stroke rate data to sound. The animation demonstrates the paradoxical fear response of a narwhal, where a very low heart rate co-occurs with rapid stroking [58]. This animation demonstrates the impact of an acute disturbance on a wild narwhal and elucidates potential paradoxical physiological responses which could contribute to marine mammal strandings.

3 Visualization Pipeline

3.1 Conceptualization

A critical first step of each collaboration included an iterative process of storyboarding, data sharing, and scriptwriting. For each animation, we distilled the primary research findings, identified the target audience and the desired conservation or outreach outcome. For example, the storyboard shown in Fig. 3 presents our vision for the *Humpback Alliance* animation. This storyboard helped us determine how to visualize social behaviors between humpbacks, especially the spatial orientation of the animals as they approach each other at the bottom of the ocean. In addition, this visual storyboard allowed us to identify critical data streams to integrate into the animation, such as the position and rotation of focal animals during feeding events, the timing and duration of mouth openings, and the precise pectoral flipper movements used to regulate small adjustments in position. The conceptualization process also clarified our key message: the ocean floor presents an important foraging habitat for humpback whales and therefore, we must work to minimize the danger of whale entanglement from bottom-set fishing gear.

3.2 Asset Creation

3.2.1 References and existing assets

When available, we assembled and incorporated existing assets either directly or as references for creating original assets, always ensuring explicit permission, proper attribution, and that we displayed relevant permit numbers. Helpful assets for this suite of animations included drone videos, reference photos, underwater videos,

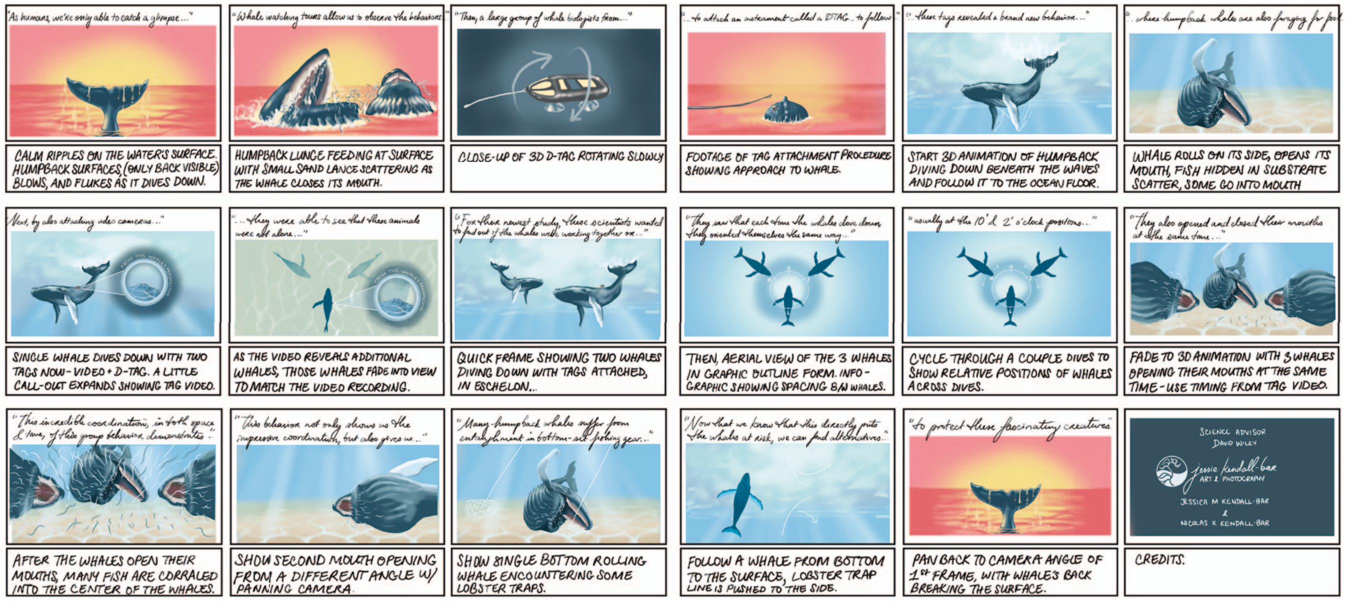

Figure 3: This figure shows an original illustrated storyboard for the *Humpback Alliance* animation. Shown here are 18 illustrations of the animation sequence, highlighting the action and camera angles for each shot. These storyboards were a valuable component of the creative pipeline, allowing us to begin discussing the necessary elements of the animations before devoting time to creating custom assets or data analysis tools.

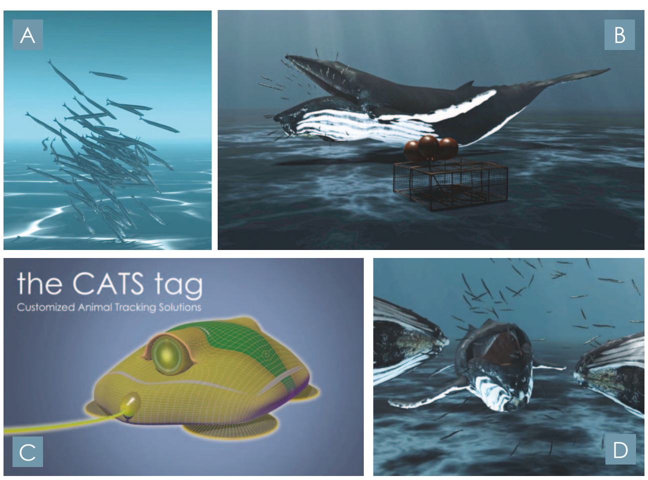

Figure 4: **Custom assets for Humpback Alliance animation.** We created (A, B & D) schooling Atlantic sand lance, (B) a buoyless lobster trap, (C) a 3D model of a CATS tag (used to collect the data analyzed), and (B & D) customized a rigged humpback whale to allow ventral groove expansion and flexible fin mobility.

technical illustrations, biological illustrations, and photogrammetry models (including textures). For example, a detailed technical illustration by Alex Boersma of the CATS tag served as the basis of our 3D tag reconstruction [16]. Our 2D elephant seal animation incorporates illustrations by UC Santa Cruz undergraduate Danielle Dube who partnered with elephant seal biologists through the Art-Science residency at the Norris Center for Natural History.

3.2.2 Creating customized 3D models

We customized all of our rigged 3D models to ensure that we could map behaviors of interest to these assets (Fig. 4). We purchased and modified an existing rigged model for our humpback whale animation [33]. We added additional flipper joints and controls to enable fine-scale flipper maneuvers that allow the whales to navigate close quarters at the bottom of the ocean during cooperative feeding. We also created controls for opening the model's mouth to emulate realistic foraging behavior (up to 60-80 degrees). Finally, we created four separate controls to depict the expansion of ventral grooves during engulfment, which allowed flexible alteration of the forward, side, and back of the whale's buccal cavity. Our elephant seal model was similarly customized based on existing assets to augment anatomical accuracy [8]. We modified the mesh and dimensions of another rigged seal model to match those of juvenile elephant seals measured and photographed in the field. We painted a custom 3D texture using Substance Painter. Our 3D narwhal animation modifies an existing anatomical model to depict and emphasize physiological processes [10].

In addition to creating 3D models of focal animals, we created unique or custom supplementary models that were critical to the narrative of our humpback whale animation. We created a 3D model based on technical drawings of CATS tags to describe the biologging technology and integrated sensors. We modified the buoy configuration of an existing lobster trap model and added a custom modeled rope to demonstrate the functionality of novel, buoyless fishing technology.

We created a school of 200 prey items, Atlantic sand lance, for the whales to feed on. We created a 3D mesh, custom texture, and rigged skeleton with 8 joints and 5 controllers to create a swim cycle for a single fish. Then, we rigged the single fish to a MASH flight network in Autodesk Maya, which creates a simulation of schooling or flocking patterns for dozens of individual nodes in three dimensions around an attractor. In our case, we generated an initial search path emanating from a central point below the sand's surface (where these bottom-dwelling fish reside) and customized their motion around an attractor path before disappearing into the sand again. We added the whales as collision nodes for scenes with humpback predators to create avoidance behaviors by schooling fish.

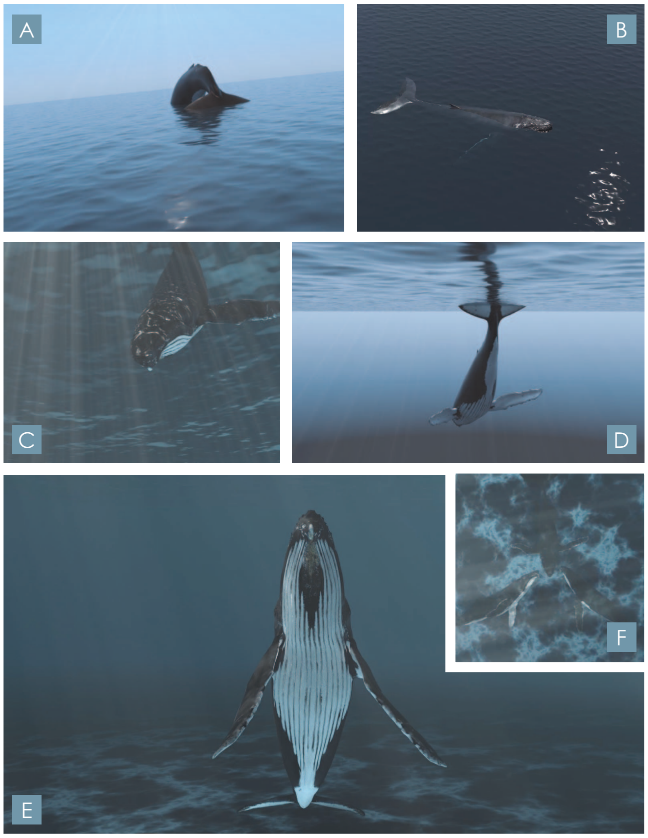

Figure 5: **Underwater environment.** Rendered results of our four-source lighting scheme (A & B) above water, (C & D) just below the surface, and (E & F) on the ocean floor (40m).

3.2.3 Creating the ocean's surface and underwater lighting

We created a photorealistic underwater environment for each of our 3D animations to depict the animal's natural environment and its turbidity, darkness, and depth (Fig. 5). We generated surface waves with the Boss Spectral Wave Solver, a fluid simulation engine in Maya, with wind speed, wind fetch, water depth, and wave height parameters matching those in the open ocean. We rendered a single high-resolution ocean tile using these parameters and cached these results into a 120-frame animated sequence of wave motion. We then replicated this pattern for a larger ocean surface plane extending to the horizon. We imported the cached image sequence into the displacement node of an Arnold surface shader with high specularity and transmission.

We placed our scene within an Arnold atmosphere volume with scattering and absorption coefficients matching those of water, where peak absorption fell within low wavelength red-orange hues. We used three-point lighting with a high-intensity key spotlight focused on the animal from the perspective of the camera, a low-intensity wide-angle overhead sunlight, and a spotlight for the dappled underwater caustics. To create dynamic underwater lighting ("caustics"), we generated an animated loop of fractal noise in Adobe After Effects that we used as a gobo filter over an Arnold spotlight.

3.3 Linking behavior to animation

3.3.1 Animating dive behavior

We processed raw accelerometer data from inertial sensors on CATS tags, Wildlife Computers' Daily Diaries, and Mk10 tags to obtain the position (x, y, and depth) and rotation (pitch, roll, heading) of tagged animals. We used the following equations to estimate pitch ($\hat{p}$) and roll ($\hat{r}$) from accelerometer data $A = [a_x\ a_y\ a_z]$ and then applied these and the magnetometer data to derive an estimate of heading ($\hat{h}$) based on a gimbaled magnetometer in the horizontal reference frame of the animal $M^h = [m_x\ m_y\ m_z]$ [23]:

$$\hat{p} = -asin(a_x/A)$$

$$\hat{r} = atan(ay/az)$$

$$\hat{h} = atan(-m_y^h/m_x^h)$$

When possible given the collected data, we aligned tag axes with animal axes and made other corrections to improve estimation accuracy. In order to precisely calculate and incorporate three-dimensional position in the water column, it is necessary to estimate the animal's speed. For high-speed behaviors (>1ms^{-1}), estimates of speed can be performed based on the vibration of the tag, but these methods lose accuracy at lower speeds [7]. Therefore, our *Humpback Alliance* animation included three-dimensional rotation and position until the onset of low speed benthic foraging events where we excluded shifts in horizontal position (Fig. 6).

Our elephant seal and narwhal animations (Animations 2, 3, and 4) visualize dive behavior on a single plane to simplify visualization of deep dives. We included measures of pitch and roll to demonstrate body position, translated the animal's vertical position with respect to depth, and approximated a speed of 1ms^{-1} for visualization. Data collected at high frequencies occasionally included artifacts that were smoothed using the "simplify curves" tool in Maya. Animation keyframes for position and rotation were set using a custom Python script and the .setKey() function in Maya's PyMEL core. Note that the default axis configuration in Maya is different from the default conventions for accelerometer data, with the z- and y- axes switched. Code, tutorials, and sample data are available on our GitHub code repository [27] and project webpage [24].

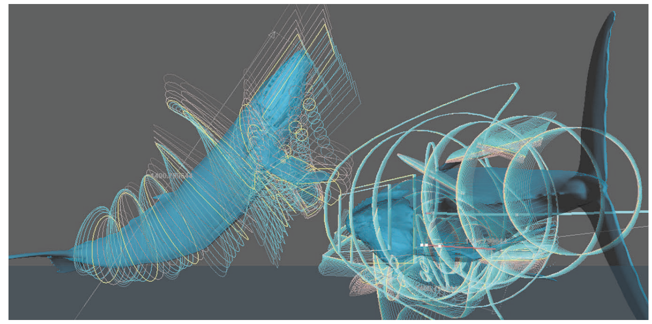

Figure 6: **Integrating position and rotation data for 3D behavior of humpback whales.** This image demonstrates the analytical advantages of loading and displaying data in Maya, where it is possible to enable motion paths for individual animals and enable ghosting to visualize and compare the speed and movement of animals over time.

3.3.2 Animating migratory behavior

To reconstruct the migratory tracks of elephant seals for our *Lightscapes of Fear* elephant seal animation, we visualized animal position in two dimensions using time-referenced latitude and longitude positions from Wildlife Computers Spot and Mk10 tags [4]. We selected a subset of 12 seals that represented the vast geographic distance covered by these deep-diving marine mammals across the Northeast Pacific ocean [4]. We used a custom program in MATLAB to create Google Earth .kml files from matrices of time, latitude, and longitude [41]. We then assembled these .kml files and ingested them into the interactive Google "My Maps" app to display metadata, including animal age, total dives, number of drift dives, and

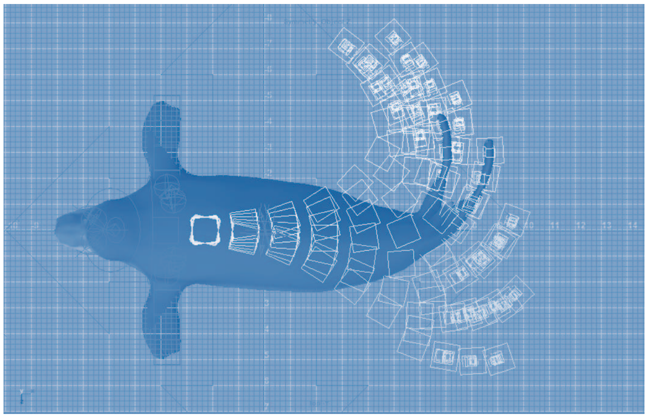

Figure 7: **Elephant seal swim cycle.** Snapshot of a frame from the offset swim cycle of a northern elephant seal with ghosting enabled to demonstrate future tail positions in pink and past tail positions in blue. This snapshot shows a central tail location to demonstrate that, with an organic swimming animation, the central tail position includes posterior tail rotation which must be eliminated to bring the animal into a straight gliding position.

trip duration [3]. We then converted this data into a scalable vector graphic (SVG) and animated the tracks using Adobe After Effects.

3.3.3 Animating swimming behavior

For our narwhal and elephant seal 3D animations, we created a method in which raw accelerometer data can be used to drive the animation of organic swim cycles, alternating between periods of swimming and gliding. We analyzed raw accelerometer data to obtain instantaneous flipper/fluke stroke rate. Beat detection for flipper and fluke strokes was performed in LabChart (ADInstruments^{TM}) with a sine-wave cyclic measurement using custom parameters for narwhals and elephant seals. For elephant seals, we analyzed the y-axis accelerometer data that captures the majority of back and forth swimming with the hind flippers. We chose 500-millisecond smoothing with a median window of 3 samples, high pass filtering at 0.3Hz, a detection threshold of maxima above 0.5G, and excluded stroke cycles faster than 900ms (61bpm). For narwhals, we analyzed z-axis accelerometry to reflect up-and-down fluke stroking. This allowed us to calculate instantaneous stroke rate as well as identify the onset of each stroke cycle.

We produced additional data streams to be used as inputs for the glide and stroke controllers. The glide controller was based on instantaneous stroke rate that maps stroke rates below 15 bpm to 1 (gliding) and above 15 bpm to 0 (stroking), with a triangular smoothing window of 15 seconds.

We animated a single swim cycle with each animal model (Figure 7). We offset the keyframes of successive joints to produce organic swimming movements from head to tail. Since this offset causes the tail to be curved when placed between right and left positions, we created two separate controllers: a swim controller and a glide controller. The swim controller controlled the back-and-forth movement of the tail, while the glide controller pulled the tail into a central gliding position.

We wrote a custom Python function in Maya that links the rotation of all joints in the skeleton to a set of expressions. The expressions set the animal's pose to a blended and interpolated output of both swim and glide controllers. A value of 0 for the swim controller sets the tail position to the first frame of the swim cycle (tail right) and 1 to the last frame of the swim cycle (return to tail right). A value of 0 for the glide controller does not inhibit the motion of the tail, while a value of 1 suppresses all tail rotation, bringing the tail to a

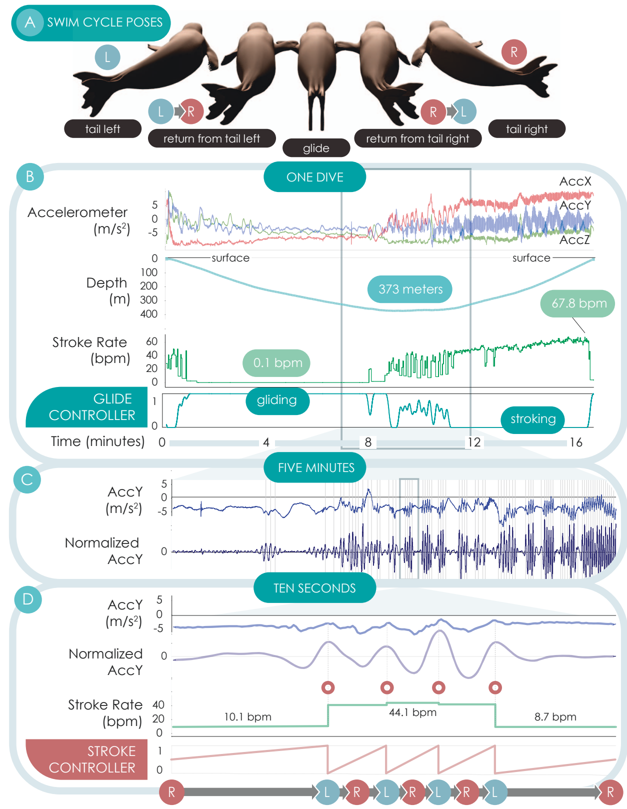

Figure 8: **Stroke rate data processing pipeline.** Raw and processed swimming data for (A) one dive, (B) five minutes, and (C) ten seconds showing raw depth (m) and accelerometer data (g), smoothed and normalized y-axis accelerometer data (g; arbitrary scale), the results of our cyclic measurement peak detection (stroke rate [bpm]), and two generated metrics - the glide and stroke controllers (values 0 to 1) - that drive our animation.

central gliding position. After linking the rig's controls to the swim and glide controllers via these expressions, we set keyframes for the controllers based on the data (Fig. 8).

3.4 Linking physiology to animation

3.4.1 Sonifying the marine mammal heart

The electrocardiogram (ECG) was recorded at 100 Hz using custom physiological loggers (UFI Instruments) for both elephant seals and narwhals. Exported data was processed for heartbeat detection in LabChart (narwhal data) and using custom MATLAB processing scripts (elephant seal data). QRS-detections were validated and confirmed using visual inspection and then converted to instantaneous heart rate for visualization. QRS-detection events were exported as a series of timestamps to be used for sonification. From these events, we calculated the interbeat interval to be used as a millisecond-precision delay between heartbeat sounds. Extreme bradycardia of 2.9106 beats per minute was identified for narwhals after escaping from entanglement [58] (see Fig. 9).

When sonifying large shifts from bradycardia below 3 beats per minute to surfacing heart rates over 60 beats per minute, it is insufficient to warp the playback speed of a sound file with multiple heartbeats at a set heart rate. Instead, we linked the onset of each heartbeat to the onset of a sound file with millisecond precision to present accurate and extreme shifts in heart rate. We took advantage of the high-temporal-precision neurophysiology toolbox PsychoPy to present these sounds [37]. Our script plays a sound file and then waits for the exact duration of the interbeat interval before playing the subsequent heartbeat. We recorded these generated heartbeat sounds and then linked them to the animations of swimming and diving behavior (Fig. 9).

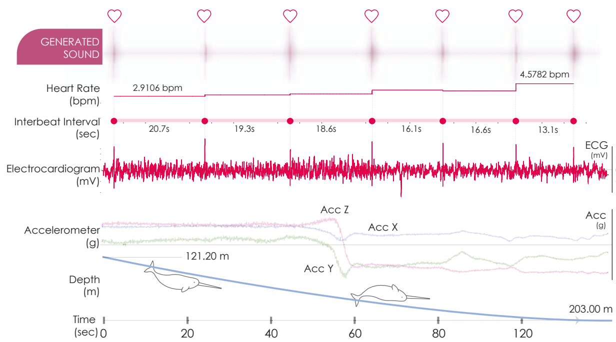

Figure 9: **Linking physiology to sound.** Raw tagging data (3-axis accelerometer [G-forces (g)], depth [meters (m)], and electrocardiogram [millivolts (mV)]) with peak detection analysis (heart rate [beats per minute (bpm)] and interbeat interval [seconds (s)]), and resulting generated heartbeat waveform (arbitrary units). The animal demonstrates a very low bradycardia after release from net entanglement. Given the long duration between beats, this example demonstrates the utility of triggering heartbeat sounds at specific time points as opposed to warping the speed of existing human heart rate soundtracks.

3.5 Editing and final production

3.5.1 Animating datastreams and visualizing signals in 2D with line animations

We visualized physiological data streams such as body condition and instantaneous heart rate as well as behavioral data streams such as GPS position, pitch, roll, heading, and depth using 2D line animations. Depending on the density of data points and the desired flexibility of the animation, we either linked CSV data directly to the paths via a custom expression in Adobe After Effects (see GitHub and tutorials) or used a static vector graphic of a line chart [24, 27]. In both cases, we generated trim paths along the path created by the data and tapered the stroke width to display the changes in data over time (Fig. 10).

3.5.2 Annotations, narration, and music

We provided the context of each animation in the form of chart labels, narration, annotations, and captions. These narrations ensured that each graph is interpreted rapidly and properly. We believe that these verbal descriptions and context clues are essential to understand the science as well as the intended message of each animation. In addition to verbal descriptions, we worked with the musical composer Connor Vance to create musical scores to accompany and underscore the narrative arc of each animation. Musical instruments were selected to match the relative size of animals and frequency of motion. For example, lower register cellos were selected to portray slow movements of large whales and the vast ocean environment, while an ensemble of violins and swelling string glissandos accompanied the turbulence of a smaller elephant seal's tail moving through water. The musical accompaniment focused attention on certain movements, created a narrative arc, enhanced production quality, and fostered empathy between the audience and the animal protagonists.

4 Discussion and Outcomes

Our animations addressed the four tasks outlined in Sect. 2 by establishing a creative pipeline for high-impact animations that reach

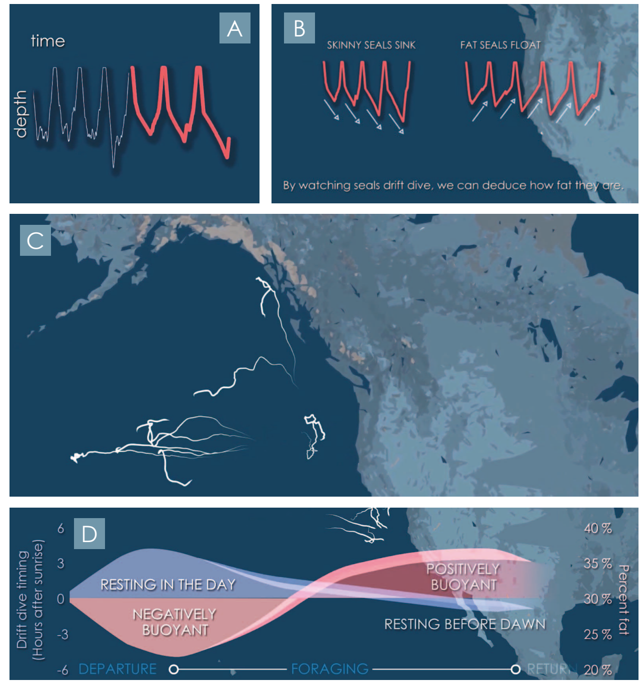

Figure 10: **Three techniques for line animation with data in Adobe After Effects.** (A & B) Flexible line animations of diving behavior generated using a custom expression in Adobe After Effects. This script links the control points of paths on the canvas to values from a CSV containing downsampled diving data. (C) Line animations demonstrating the migratory paths of female northern elephant seals across the Pacific generated using KML data from geolocation tags. (D) Tapered line animations with shaded areas based on a figure generated in R and assembled in Adobe Illustrator, showing a shift in predator avoidance behavior associated with internal body condition [3, 4, 26].

a target audience to promote desired outcomes in education and conservation (Fig. 2). By visualizing the invisible underwater behavior of marine mammals, we aim to create evocative animations which foster connection, empathy, and compassion between humans and the natural world. Our 3D humpback animation illustrates the risk-reduction benefit of ropeless fishing gear to humpback whales cooperatively foraging on the ocean floor. Our 2D elephant seal animation follows a cohort of seals halfway across the Pacific as they weigh risk and reward based on their rapidly changing internal and external environments [4]. Our 3D elephant seal animation shows diving behavior and physiology to better understand their fear response to natural killer whale predators. Our 3D narwhal animation tells the story of its human-caused paradoxical fear response, which involves a pronounced decrease in heart rate during escape, to help us recognize our role and impact on marine mammals.

Our goals with this framework were to incorporate raw tagging data to control animations that facilitate research as well as clearly communicate scientific results to maximize their reach and impact. As a tool for research and data exploration, our team worked closely with biologists to generate hypotheses about the synergistic effects of disturbance on physiology and behavior. Our tool serves to unite disparate data streams across space and time, from shifts in heart rate and orientation which occur within seconds and across individual dives to large scale movements during seven-month foraging trips. Our animations consolidate data across space, time, physiology, and behavior to facilitate the identification and characterization of responses critical to survival. While we explore marine mammal animal-borne sensors in the present study, our pipeline can be broadly applied for other animal systems in studies of functional anatomy, ecophysiology, and movement ecology.

In our capacity as communicators, these animations targeted three key audiences: scientists in the fields of biologging, ecology, biology, and physics, the general public, and policymakers who can translate this research into legislative protections. Our *Lightscapes of Fear* animation, which accompanied the publication of a scientific article, reached these three key audiences and increased the paper's accessibility, reach, and visibility. Our tweet sharing the animation alongside the paper received over 100,000 views, with more than half of the comments specifically citing the animation. The article received a high attention score, scoring in the top 5% of all research outputs scored by Altmetric, with 311 tweet mentions and over 490,000 followers. In our process posts of other animations, we have had engagement from veterinarians as well as activists and policymakers. These metrics demonstrate that short, cinematic, and informative animations can increase the accessibility of scientific results and promote the conservation of marine mammals.

Beyond creating tools for data visualization, it is important to facilitate the implementation of new tools. We taught a wide range of animation skills to over a hundred scientists through a series of "Animation for Science Communication" workshops and created an online learning center with workshop recordings [24]. These workshops included specialized and advanced topics such as 3D-track visualization and custom scripting in Maya and Adobe After Effects, and covered powerful built-in animation tools in PowerPoint. We continued this educational outreach through a data visualization collective in Winter 2021 that united students from various academic departments, including Astronomy & Astrophysics, Art: Games & Playable Media, Ecology & Evolutionary Biology, and Computational Media to create animations and data visualizations for science communication [25]. We have facilitated several animations inspired by our workshops by providing technical, design, and narrative advice [19, 38, 49]. Our GitHub repository and webpage offer in-depth tutorials for working with our custom scripts [24, 27]. Through educational outreach, we are creating forums for scientists to seek guidance on designing and sharing compelling stories with their data. We argue that by equipping biologists to leverage industry animation tools, we can expedite complex data analysis, promote science communication outcomes, foster empathy and compassion for the natural world, and better serve the ecosystems we aim to protect.

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