MULTI-CHANNEL SPATIAL SONIFICATION OF CHINOOK SALMON MIGRATION PATTERNS IN THE SNAKE RIVER WATERSHED

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ABSTRACT

Spatialisation, pitch assignment, and timbral variation are three methods that can improve the perception of complex data in both an artistic and analytical context. This multi-modal approach to sonification has been applied to fish movement data with the dual goals of providing an aural representation for an artistic sound installation, as well as a qualitative data analysis tool useful to scientists studying salmon migration. Using field data collected from three wild Chinook Salmon (*Oncorhynchus tshawytscha)* living in the Snake River Watershed, this paper will demonstrate how sonification offers new perspectives for interpreting migration patterns, including the potential to display the impact of environmental factors on the lifecycle associated with this species. Within this model, audio synthesis parameters guiding spatialisation, microtonal pitch organization, and temporal structure are assigned to streams of data through software applications developed for the project. Collection and interpretation of field data was performed in partnership with the University of Idaho – Water Resources Program.

INTRODUCTION

Clearly and meaningfully presenting complex datasets within auditory displays is a problem shared by those creating musical compositions from data and those endeavoring to use sonification as an analytical tool. The sonification of multiple data streams is complicated by the difficulty in conveying the complexity of the data in sound space [1]. Spatialisation and timbral variation are two methods that can improve the perception of complex data in an artistic and analytical context; both of which are active areas of study within the sonification field [2]. Working within a cross-disciplinary team, we have utilized both scientific and musical perspectives to create meaningful sonifications of complex, temporal data of salmon movement. As such, consultation with the Water Resources Program has directly informed the choices and tuning of key sonification parameters.

The sonification of Chinook salmon migration data from the Snake River watershed to the Pacific Ocean is a multi-year project that is currently in the proof-of-concept stage of development. The project's primary goal is to track the life history of juvenile salmon (fry to smolt) via sonified out-migrations. The timing and duration of these movements are influenced by environmental factors experienced by individual fish, such as water temperature and food resources. Recent large changes in this migration timing may indicate adaptation to changes in the habitat of this species from human impacts such as dams and land use change. Subtle differences in movement timing can be difficult to easily discern graphically or statistically. Working in a multidisciplinary team we seek to use data-to-sound auditory display in the dual role of artistic auditory installation and as an analytical aid for fish and wildlife scientists.

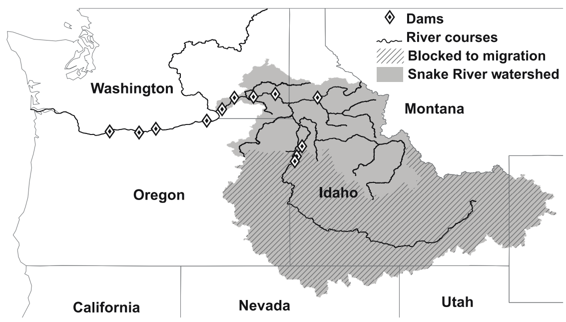

Figure 1. Snake River Watershed

1. OTOLITH STRUCTURE AND FUNCTION

Analysis of otoliths collected from wild salmon has played a fundamental role in tracing the geographic movements of these fish. Otoliths are balance and hearing organs in bony fishes (cartilaginous fish, such as sharks and rays do not possess them) [3]. These organs are roughly analogous in function to the human inner ear and are used for hearing, as well as orientation. The otolith is located below the brain in fluid-filled sacs and includes a pointed structure, called the rostrum, attached to nerves that sense the motion of the organ within this fluid. As the fish moves through the water, the otolith moves within the surrounding fluid relative to the fish's orientation to gravity. In structure, the otolith is not truly a bone; instead it is a calcium carbonate deposit that accretes a new layer of calcium carbonate each day. These layers accumulate much like tree rings, wider during periods of fast growth and narrower when growth is low. This mineral is deposited as amorphous, crystalline aragonite. Aragonite is one of three forms of calcium carbonate, including calcite and vaterite. Also, like the rings of a tree, chemical signatures found in otoliths can reveal important details about the lives of these fish [3].

Because calcium and strontium are close on the periodic table, strontium (and other elements such as barium, manganese and magnesium) occasionally substitutes for calcium in a crystal structure. Since these isotopes and elements are unique for many rivers, it is possible to determine where a fish has traveled in fresh water by recovering the chemical and isotopic signatures of these substituted elements from within the otolith. This data is combined from measurements made on two different mass spectrometer devices; one that measures elemental ratios (weight of individual atoms of an element as a ratio with calcium) and another that measures isotopes ratios (the difference in the number of neutrons between atoms of the same element) [4].

2. SONIFICATION PARAMETERS

2.1 Temporal Framework for Otolith Measurement

Measurement and incremental assessment of the otolith of each fish in the study yields important details of its lifecycle. Not unlike reading the growth rings within a tree, measuring the distance from the center of the otolith indicates the age of the fish [4]. By statistically relating the distance from the otolith core (measured in microns, 1/1000 of one millimeter) with known chemical signatures from rivers in the study area, it is possible to determine the location and timing of life events; such as birth, maturation, migration patterns, and death. A significant finding of our project includes the practical translation of measurements associated with physical mediums, such as the otolith, into a temporal function inherent to sound generation.

For the purposes of auditory display, micron data is transformed into temporal parameters, establishing a rate at which aural events unfold. After multiple trials, the current sonification model utilizes a time rate of 50 milliseconds (ms.) per micron measured within each otolith. Three salmon were tracked in this study: one female (#5133) and two males (#2693 and #3206). These fish were chosen, in consultation with the University of Idaho – Water Resources Program, as representative data samples from the environment and as preliminary models for future sonification applications that could include a wider sampling of wild salmon. The choice of time scaling works to simultaneously display the entire lifecycles for each of the three fish within a manageable time period for observation. As the otolith of the fish with the greatest longevity (#3206) was measured at 2337 microns, the entire duration of playback for the display is 116,850 milliseconds, or ~117 seconds. Initially a playback rate of 100 milliseconds per micron was chosen. However, early tests conducted at the University of Idaho concluded this slower rate of playback to be less effective in tracking meaningful transitions in location and chemical signature. Further trials are certainly needed to optimize playback rates for meaningful auditory display.

Sonification linking the physical structure of otoliths to the inherently temporal nature of both the medium and the subjects' lifecycle is further accomplished by correlating the maturation period and overall longevity of each fish to changes in overall amplitude. Accordingly, these changes in amplitude signify the most significant life events for the subjects. In turn, each of the fish displayed is assigned a unique amplitude envelope. Important temporal markers, including birth, completion of the maturation period, and death**,** act as breakpoints within these overlapping envelopes (see Figure 2).

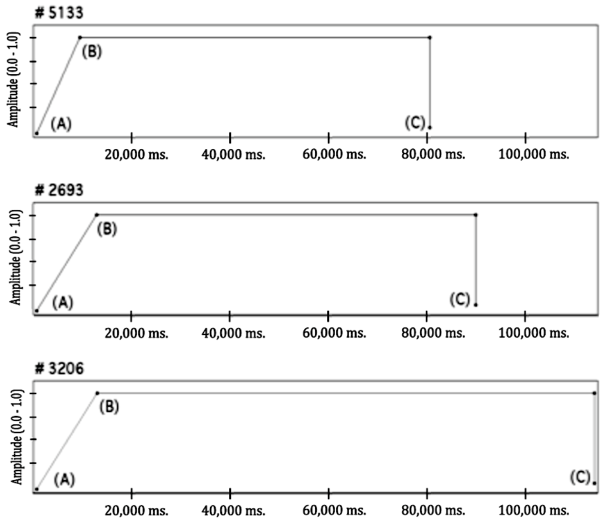

Figure 2. Simultaneous Amplitude Envelopes
[A = Birth] [B = End of Maturation] [C = Death]

Birth and death stages are represented by an overall amplitude value of 0.0. The maturation period is heard as a linear crescendo beginning with an amplitude value of 0.0 and ending with a sustained amplitude value of 1.0. For example, in both males (#2693 and #3206), a maturation period of just over 250 microns encompasses the center of the otolith, while the female matures within 181 microns. In turn, these measurements are represented by crescendos with durations of 125,500 and 9,050 milliseconds, respectively. Thereafter, death is punctuated by a sudden decrescendo into silence.

During simultaneous playback, changes in cumulative amplitude generated by these envelopes function as a coarse, auditory indication to the listener of how many fish are currently active within a watershed or marine system at a given time. Furthermore, the rate of crescendo (amplitude gain versus time in milliseconds) informs the listener of the rate of maturation for individuals or groups of fish.

2.2 Spatialisation and Strontium Isotopes ($^{87}Sr/^{86}Sr$)

Just as time may be measured as a function of physical growth, past locations for each salmon can be indicated by the presence of a specific range of strontium isotopic ratio ($^{87}Sr/^{86}Sr$) values sampled from the otolith. The ability to approximate location from this data is owed to the fact that isotopes of strontium are not recognized by the organism's cells. Therefore, the chemical signature of the water through which the fish migrates is the same as the value recorded in the otolith. This signature originates from the decay of rocks in the watershed and is unique to each environment. Thus, the strontium isotopic ratio can be used to link a fish's location to a specific watershed [5].

Application of strontium data is used to define spatialisation within the listening environment. Since this sonification model may be presented as a public installation, the program is written so that sound sources representing data from groups or individual fish can be distributed across a four-speaker (quadraphonic) sound system. Within this model, strontium isotope values indicative of the presence of fish in the Lower Snake River (LSK) are represented by the assignment of corresponding aural materials to the left-front (LF) loudspeaker (in relation to observers), sound materials indicative of data from the Clearwater River System (CWS) are assigned to the right-front (RF) loudspeaker, indications of fish in the Upper Snake River (USK) to the right-rear loudspeaker (RR), and data suggesting the arrival of fish in the Pacific Ocean signified by sound in the left-rear (LR) speaker. For stereo playback (i.e. headphones) applications, LSK and Ocean data will sound in the Left Channel, while CWS and USK data will sound in the Right Channel.

It should be noted that quadraphonic diffusion is far from optimal in terms of modeling continuous motion between loudspeakers. However, in the project's current proof-of-concept stage, spatial modeling of data is being treated as primarily, discrete sound sources. The majority of strontium isotope data associated with the LSK, USK, and CWS is displayed according to a range in which an average of these values collected from a given watershed is assigned to a specific speaker (LF, RF, LR, RR) and aural materials associated with an individual or group of fish are assigned accordingly. This component of the auditory display is key to identifying migration behaviors within separate water systems. Meanwhile, transitional values between these averages are expressed as motion between speaker channels. As such, the panning algorithm is entirely linear, whereas the mean value within a given crossover range of strontium data is assigned a 50/50 division of amplitude between two respective loudspeaker channels.

Sonifying results connected to migration patterns into the Pacific Ocean requires further insight into characteristics of strontium isotope distribution, universally present in otolith samples associated with a marine environment. For example, samples connected with time spent in the Pacific Ocean represent the stabilization of the strontium isotope ratio at 0.70918, a marine signature consistent throughout the world's oceans [6]. The presence of this data necessitates a less linear approach to sonification. Accordingly, the audio software is written so that hard panning to the LR speaker (associated with migration to the Pacific Ocean) only occurs when the strontium isotope values consistently match a mean value of 0.70918 over the course of eight, consecutive micron samples. To efficiently process the large quantities of data collected, samples are taken every three microns. Because the mass spectrometer used in collecting chemical data measures a small quantity of atoms at a given time, a great deal of variation in the strontium isotope signature is present. Consequently, this data is averaged using a 20-point rolling average over time in order to display meaningful results [4].

Referencing only strontium isotope signatures, it is also worth noting that a great deal of crossover between chemical signatures is present in fish migrating through multiple locales. For example, certain strontium isotope signatures associated with the CWS were also measured in fish inhabiting the LSK. Likewise, similar values collected from fish migrating through the LSK were also present within otolith measurements from fish known to be present in the USK (see Table 1 and Figure 3).

Location:	Strontium Isotope ($^{87}Sr/^{86}Sr$):	Loudspeaker:
LSK	0.709080 < 0.711560	LF
CWS	0.710927 < 0.713022	RF
Pacific	0.708684 < 0.710072	LR
USK	0.708983 < 0.709584	RR

Table 1. Strontium Isotopic Ratio ($^{87}Sr/^{86}Sr$) Range

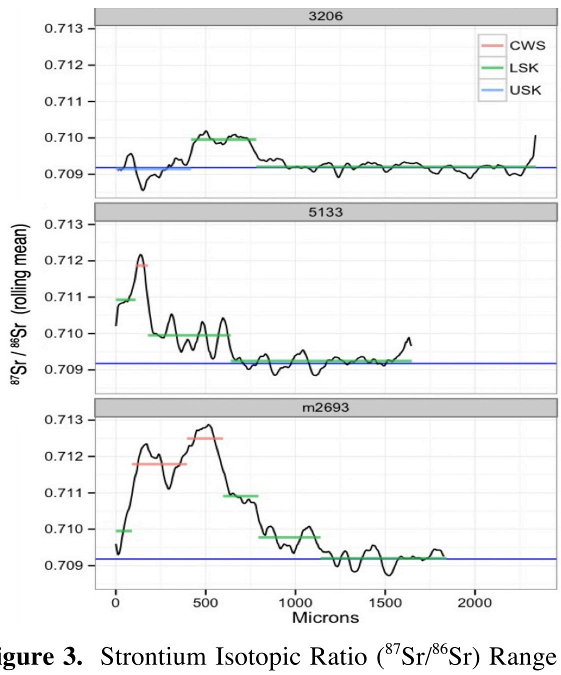

Figure 3. Strontium Isotopic Ratio ($^{87}Sr/^{86}Sr$) Range in Three Otolith Samples

Insight into this variability can be gained by understanding that chemical signatures present in the otolith at early ages are informed by the signature inherited from the mother. This signature is heavily influenced by the marine environment. As the egg grows within the mother while she is still in the ocean, the chemistry reflects this trait. Young fish are nourished by a yolk sac derived from the egg until they grow large enough to emerge from the gravel and feed on their own. Consequently, the first ~250 microns of $^{87}Sr/^{86}Sr$ data are not exact representations of the small fish's location [4].

Consequently, while strontium isotope signatures indicate general patterns of migration, this data alone does not necessarily pinpoint the exact location of a fish within its lifecycle. Creating an accurate auditory display that addresses both chemicals signatures and known location requires a multi-modal approach encompassing the inclusion of other discrete forms of data assignment performed in concert with spatialisation.

2.3 Pitch Change and Geographic Location

To address disparities between data from known locations and locations suggested by strontium isotope data, a multi-modal sonification technique employing both spatialisation and momentary pitch change is utilized. While spatialisation via four-channel diffusion intimates the motion in migration patterns, early tests at the University of Idaho indicate that panning alone does not adequately identify the exact moment of entry into a given water system. Consequently, instantaneous pitch change has been employed to give a clear and unmistakable indication of entrance into specific water systems. As such, a specific pitch is assigned to each system. Using conditional data algorithms programmed in Max/MSP (i.e. "if, then, else" expressions), changes in pitch occur when incoming micron values match the first measurement taken at a specific site, as confirmed by field data. For example, fish #2693 enters the CWS at 252 microns. Thus, at 12,600 milliseconds into playback (252 microns at a playback rate of 50 milliseconds per micron unit), the pitch for this stream of data changes from 275 Hertz to 385 Hertz (See Table 2).

	Maternal	CWS	USK	LSK	Ocean
Pitch	110 Hz	275 Hz	330 Hz	385 Hz	605 Hz
	f * (1/1)	f * (5/2)	f * (6/2)	f * (7/2)	f * (11/2)
f = 110 Hz	A1 + 0 cents	C#3 - 14 cents	E3 + 2 cents	G3 - 31 cents	D4 + 51 cents
5133	0 - 9050 ms			9050 - 32,000 ms	32,001 - 82,500 ms
	0 - 181 Microns			181 - 641 Microns	641 - 1645 Microns
2693	0 - 12,600 ms	12,600 - 32,000 ms		32,000 - 57,100 ms	57,100 - 91,950 ms.
	0 - 252 Microns	252 - 600 Microns		600 - 1142 Microns	1142 - 1839 Microns
3206	0 - 12,700 ms		12,700 - 21,100 ms	21,100 - 39,050 ms	39,050 - 116,850 ms
	0 - 254 Microns		254 - 422 Microns	422 - 781 Microns	782 - 2337 Microns

Table 2. Pitch Assignment By Location

Pitch assignment for each location is intended to aid the listener in making clear distinctions between environments encountered during migration. The central frequency range spans just under four and one-half octaves; with the "Maternal" and "Ocean" signatures occupying the lower and upper bounds at 110 Hertz and 605 Hertz, respectively. All three fish sampled pass through these two systems, as well as the LSK. Consequently, an easily distinguishable application of range was a conscious choice in programming this component of the auditory display.

Likewise, the decision to include non-tempered, or *just*, intervals to represent both discreet stages in migration and concurrent geographic relationships between groups of fish is informed by this necessity. Utilizing the Maternal Signature assignment of 110 Hertz as the fundamental frequency (*f*), octave transpositions of the 5th, 6th, 7th, and 11th partials in the overtone series yield the just intervals, 5/2, 6/2, 7/2, and 11/2. These just intervals correspond with entry into the CWS, USK, LSK, and Ocean, respectively. While concurrent pitch relationships between the Maternal Signature, CWS, and USK reference, familiar – albeit, justly tuned – triadic harmonies, inclusion of pitch assignments for the LSK and Ocean introduce less-familiar, microtonal intervals. As these two regions are encountered by all three fish throughout the study, the ability to aurally identify change and convergence is vital for data interpretation. In turn, distinctive intervallic choices, such as the *septimal* minor third sounding between data streams from fish #5133 and #3206 at 254 microns, are aimed at making these momentary distinctions unmistakable, as well as lending unique harmonic colouration. (See Figure 4 to view these changes in the form of a musical score).

Figure 4. Musical Score for Pitch Assignments

An emergent property of assigning pitch values to location data includes cumulative changes in amplitude. As such, crescendos and decrescendos result from greater or fewer fish occupying a given location. Through analysis of the entire spectra produced in playback, three fish assigned to 605 Hertz create a greater spectral peak at 605 Hertz than a single fish would; thus indicating a larger number of fish present in the corresponding location, the Pacific Ocean.

Another component of the lifecycle suggested – yet only coarsely touched upon through spatialisation – is the maturation period, or "maternal signature". Within this range, chemical signatures, such as strontium isotope ($^{87}Sr/^{86}Sr$) and Strontium/Calcium ratios (Sr/Ca), exhibit chemical traits reflecting the chemistry of the mother [4]. Higher chemical signatures from this time in each young salmon's life are consistently presented within the first 250 microns of otolith samples. These high signatures, retained from the mother, can likely be attributed to her travels through the Columbia River, a habitat with similarly high signatures [3]. Prior to evidence of entry into the CWS, USK, or LSK systems, sounding of a slow crescendo with a central pitch of 110 Hertz indicates the presence of this maternal signature during playback. Again, punctuation of this component of the lifecycle is displayed using discrete changes in pitch working in concert with other aural dynamics.

2.4 Variations in Timbre and Strontium/Calcium (Sr/Ca) Ratio Intensity

In addition to strontium isotope signatures, the intensity of strontium/calcium (Sr/Ca) ratios collected from otoliths offer another useful chemical indicator of location. Sharp increases in Sr/Ca intensity are particularly evident upon entry into a marine environment [3]. In fact, the Water Resources Program's choice to include Sr/Ca data as a key sonification parameter – as opposed to barium or magnesium signatures, also present in otolith samples – reflects the particular importance of calcium as a primary indicator of marine migration. As indicated by initial tests at the University of Idaho, sonifying transitions to the Pacific Ocean requires a multi-modal approach to sound generation that extends beyond simple, spatial diffusion. Just as changes in pitch are used in concert with panning to punctuate changes in location, variation in timbre is also linked to spatialisation. In terms of chemical indicators (on-site field observations aside), concurrent stabilization of $^{87}Sr/^{86}Sr$ signatures to a mean value of 0.70918 and sharp peaks in Sr/Ca intensity are evident when migration into the marine environment is likely. These peaks are generally observed when the Sr/Ca intensity exceeds a value of 1.0. An average $^{87}Sr/^{86}Sr$ range of $0.7085 < 0.7098$ retains a mean value of approximately 0.70918, the stabilized $^{87}Sr/^{86}Sr$ intensity indicative of entry into a marine environment. Though the entire continuum of strontium data measured from all otolith sections affected by the Pacific Ocean encompasses a wider range of $0.708684 < 0.710072$, measurements from the periphery of this data are applied as transitional breakpoints during spatialisation. From this data, a conditional algorithm determines when audio signals representing migration patterns of an individual are to be assigned to the Left-Rear (LR) speaker channel; thus indicating entry into the Pacific Ocean. This conditional expression reads as follows:

If [0.7085 < $^{87}Sr/^{86}Sr$ < 0.7098] & [Sr/Ca > 1.0], then hard-pan signal to Left-Rear (LR) speaker channel.

(1)

In contrast, the evolution of timbre and associated parameters are derived solely from Sr/Ca intensity values. Initially, the team explored the use of additive resynthesis techniques to address each chemical signature as a separate, spectral component. However, the lack of perceptual traceability – particularly by those observing from a biological discipline – led the group to simply its approach. Ultimately, a modified form of amplitude modulation (AM) synthesis using a unipolar, random-amplitude carrier waveform ("rand~" object in Max/MSP) and a sine waveform modulator was chosen. The frequency of the modulating waveform (f_{mod}) is controlled by pitch assignments from each location signature (Maternal = 110 Hz; CWS = 275 Hz; USK = 330 Hz; LSK = 385 Hz; Ocean = 605 Hz). This value determines the center frequency of the resulting AM waveform. As discussed, these pitch values vary discretely, according to entry into each water system. The carrier waveform generates random amplitude values (between -1.0 and 1.0) at a specified rate (f_{rand}). This rate is derived from scaling Sr/Ca intensity data. According to data collected, the range of Sr/Ca intensity values for the marine environment vary between 0.947882 (Sr/Ca_{min}) and 2.55 (Sr/Ca_{max}). These values are scaled in a linear fashion, to an output range between 50 Hz ($f_{randmin}$) and 800 Hz ($f_{randmax}$).

$$f(x) = c\,[1 - (x - a) / (b - a)] + d\,[(x - a) / (b - c)]$$

Whereas:

$f(x)$ = Carrier Frequency (f_{rand}) — x = Sr/Ca Intensity

$a = 0.947882$ (Sr/Ca_{min}) — $c = 50$ Hz ($f_{randmin}$)

$b = 2.55$ (Sr/Ca_{max}) — $d = 800$ Hz ($f_{randmax}$)

(2)

As this modified AM synthesis model utilizes a unipolar, random-amplitude carrier waveform, amplitude output is divided in half and then increased by a value of 0.5 to constrain signal values to a range of 0.0 to 1.0. The use of a unipolar carrier distinguishes this algorithm from most traditional forms of AM synthesis, which generally utilize a unipolar, modulating waveform [7].

$$[rand\,(2\pi f_{rand}) * 0.5 + 0.5] * [\cos(2\pi f_{mod} + \phi)]$$

Whereas:

rand = Random amplitude values (0.0 < 1.0)

f_{rand} = Carrier Frequency (noise bandwidth)

f_{mod} = 110 Hz, 275 Hz, 385 Hz, or 605 Hz

(3)

In preliminary tests, identification of changes aural characteristics were readily noted by the team from the University of Idaho – Water Resources Program, suggesting the saliency of this technique and the range of synthesis parameters chosen. As the carrier frequency is increased, the noise bandwidth surrounding the center frequency (f_{mod}) is broadened and recognition of a perceived pitch is obscured. In contrast, Sr/Ca intensities below 0.947882 reflect migration through freshwater environments and generate timbres that retain a more sinusoidal, or *pure*, tone. On a figurative level, the increased noise bandwidth resulting from higher Sr/Ca intensity (indicative of entrance into the ocean) has been described by scientific team members as eliciting aural sensations associated with the wind and surf (i.e. "noisy" or "washy" timbre) of a marine environment. From a sound design perspective, the associative qualities and simplicity of the modified AM synthesis algorithm speak to its potential in conveying the character of environments encountered during out-migration.

CONCLUSIONS

Utilizing continuous timbral variation, microtonal pitch organization, site-specific spatialisation, and the translation of physical measurement into temporal structure, this project has sought to create clear and useful auditory displays of salmon movements gleaned from the unique chemistry of otoliths. This data, being inherently temporal, is an ideal data source for sonification. However, its complexity makes statistical and graphical analysis of subtle movements difficult. Therefore, our goal is to eventually create a comprehensive sonification tool that allows scientists to explore these complex datasets more easily. Further validation of observations made in the development process could certainly aid in honing the auditory display. Likewise, we await additional input from other members of the scientific community as to the total scope and potential applications for auditory display in the evaluation of environmental impacts on salmon migration. As such, a future stage in the project could include the administration of perceptual testing with other fish and wildlife scientists from beyond the University of Idaho to address the effectiveness of sonification techniques, specifically the efficacy of spatialisation and timbral variation in conveying complex data.

From the perspective of the composers and sound artists working on the project, the role of salmon migrations in the Pacific Northwest and the richness of the available data are compelling in their musical merit. Looking forward, our immediate plans for presentation of this auditory display include a public installation in Spokane, Washington. At the moment, and in consideration of the current scale of sites addressed in the study (CWS, USK, LSK, & Pacific Ocean), real-time diffusion via four loudspeakers has been employed. However, additional locations added to the study and inclusion of a more comprehensive diffusion system of eight or more channels could certainly benefit presentation of such data. The accumulation of otolith signatures from more subjects, in addition to data from the first three fish already displayed, could also add a dimension of richness and density; both in terms of aesthetic and scientific potential. One could feasibly envision microtonal clusters derived from data of twenty or more fish enveloping listeners.

In regard to process and creative development, working in a multi-disciplinary team has yielded important insights that could be otherwise overlooked operating in a single field. The dual concerns of artistic engagement and maintaining scientific cogency seem best addressed via a multi-modal approach. Exploring a means of sharing the unique lifecycle and potential human impacts on the Chinook salmon, an emblematic species of the greater Pacific Northwest, certainly warrants the careful attention, innovation, and cooperation from both scientific and artistic disciplines.

Acknowledgements

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