Digital Naturalist Design Guidelines: Theory, Investigation, Development, and Evaluation of a Computational Media Framework to Support Ethological Exploration

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ABSTRACT
This research aims to develop and evaluate a design framework for creating digital devices that support the exploration of animal behaviors in the wild. This paper quickly shares the main concepts and theories from the fields forming Digital Naturalism's foundation while presenting the key challenges emerging from these critical intersections between field biology and computational media. It then reviews the development of this research's hybrid methodology designed specifically for its multi-year series of "Qualitative Action Research" fieldwork carried out at a rainforest field station.

This paper analyzes the resulting on-site ethnographies, workshops, design projects, and interactive performances, whose take-aways are synthesized into design guidelines for digital-natural media. This framework, itself, is then evaluated via an extra iteration of fieldwork and the results discussed. Finally, the paper identifies targets for continued research development. Further areas of interest are presented which will promote Digital Naturalism's progression into its own topic of study.

Author Keywords
Biomedia; biological media; behavioral media; cybiotic.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

INTRODUCTION
This research studies the role that digital media can play for biological field work. The collaborations growing between biologists, designers, engineers, and artists spawn new challenges and design spaces inherent to these parent fields. Specifically, this research focuses on new combinations of ethological practice (the naturalistic study of animal behavior[46]) and computation as a unique[25], behavioral[3] media form. It looks to uphold the naturalistic values developed by these wilderness explorers, while investigating the new abilities offered by digital technology.

Carrying out this work requires a study of ethology's foundational ideas (via historical literature) along with ethology's contemporary principles (via fieldwork at a rainforest field station, the *Smithsonian Tropical Research Institute (STRI)*[53]). These theoretical and pragmatic investigations include on-site ethnographies, workshops, design projects, and interactive performances. The work is qualitatively analyzed and then synthesized into a framework to support digital-ethological practice. Finally, this framework is practically evaluated through the design and implementation of additional ethological expeditions.

The resulting framework encourages digital technology that supports four key concepts. *Technological Agency* pushes for devices that promote understanding of their own internal functions. The tenet of *Contextual Crafting* leads designers and ethologists to create devices in close proximity to their intended use. *Behavioral Immersion* promotes visceral interactions between the digital and organismal agents involved. Finally, *Open-Endedness* challenges researchers to create adaptable tools which strive to generate questions rather than answering them.

Figure 1 – The four concepts of Digital Naturalist Design

This paper consolidates the findings of several years of this work originally described but unpublished in the much larger volume [31]. It intends to share the process of this framework's development, explain the resulting tenets, and provide concrete illustrations for utilizing these guidelines. The intention is that the intention both biologists and digital designers may benefit from this research process and examples. Overall, this research, referred to as Digital Naturalism, explores a developing design space for computers in the wild.

HISTORICAL AND THEORETICAL BACKGROUND

Two key disciplines feeding into this research: Ethology and Digital Media.

Ethology

Ethologists, a name given to scientists studying the behaviors of animals in their natural environments, are primary stakeholders targeted by this research. Understanding the best ways to support these scientists first requires a deep analysis of ethology itself. A cultural and technological history provides the context for the specific set of principles guiding this research in digital studies of animal behavior in the wild.

Studying animal actions dovetails into the development of many fields of science. As former STRI Director Bill Wcislo explains:

> Animal behavior is central to biology. Behavior is the interface between mechanistic and ecological studies – what Marston Bates called 'skin-in' and 'skin-out' biology. It is the means by which animals shape their environments, and determines the flow of energy and information among organisms [54].

This field, however, has traditionally held an enigmatic position among the other scientific fields. Whereas laboratory research typically venerates efficiency, control, and reduplication, the infinite unpredictability of fieldwork pushed ethology to develop supplementary values. Biologists studying animal behavior in the field have long defended the values of open-ended exploration[11] in natural settings. Scholars like Niko Tinbergen and E.O. Wilson have endorsed such "seemingly aimless wanderings in the fields" as indispensable to later "experimental analysis" [44:306]. Present-day ethologists continue to press for such open-ended exploration, for instance, Martin concurs: "The value of broad description arising from sheer curiosity should not be under-estimated." [19]

These principles of open-exploration derive from ethology's roots in Romantic naturalism. Joining such romanticism with techniques within scientific empiricism gives ethology a unique hybrid nature. Operating as a chimera between humanistic and scientific academic institutions, this field often suffered challenges in its acceptance. [46] Its special intersection of positivism and naturalism, rigid experimentation in conjunction with visceral, undirected natural engagement[44] gives ethology "an inclusive approach that provides a way out of the fruitless nature/nurture dichotomy" [51].

Ethological Technology

The unique difficulties which challenge wildlife researchers inspire a need for personalized tool-making. Few mass-produced instruments meet the specific requirements of a researcher's desired interaction with a wild animal living in a unique situation. Therefore, many field biologists find themselves crafting their own tools. Tinbergen's gull-head puppets [45] and Frisch's rotatable bee hives [7] are examples of key scientific tools built from scratch and formed by the research questions being asked.

Additional simple appendages are often improvised from the environment to extend the abilities of the ethologists. Sticks, rocks, and piles of dirt can lengthen our reach, prod at different physical scales, or modify the landscape. For instance, Hölldobler and Wilson discussed insights found when adapting parts of their own bodies to interact with animals. Hölldobler describes,

> …while waiting on the edge of a road for a car ride, Wilson succeeded in "milking" giant scale insects surrounded by ants, simply by touching them with hairs from his head … (Such are the informative pleasures that fill the idle hours of naturalists in the field.)[11].

Some of the most exalted experiments amongst these researchers are those that gathered enough background intuition to manage multiple environmental and animal factors in elegant ways. For instance, in one famous recent study of ant navigation over bleak shifting dunes in the Sahara, Wittlinger, Wehner, and Wolf proved how ants counted their steps by gluing tiny stilts onto the ants' legs[52]. This simple manipulation directly targeted the research question without greatly detracting from other environmental influences. Such experimental elegance is created by meshing a deep understanding of both theoretical literature as well as practical engagement with the creatures, environment, and materials.

Digital technologies, with their abilities to create interactive behaviors, stand to grant even more powerful, dynamic faculties to such open-ended exploration. However, one must always be wary of blindly introducing technology into any practice.

Digital and Behavioral Media

Digital technology offers unprecedented new abilities to extend human analytical and interactive abilities. As the ethologist Chauvin points out, "The behavior of computers constitutes the only possible analogy with animal behavior" [52]. The singular behavioral properties of digital technology allow ethologists to generate sophisticated virtual models like those of Couzin[4], Pratt[27], and Hrolenok [12]. Additionally, though, computers also allow ethologists to create behavioral interactions with living

creatures in the real world. Ryan's "Robo-frog," [14] for instance, can be programmed to move in realistic ways, letting scientists ask dynamic questions in their experimental setup. Due to their unparalleled advantages, computers "have become increasingly popular for collecting data in enclosure and laboratory settings" [17:256]. Lehner, however, warns scientists should "remember data loggers are only a faster and more efficient way of collecting and storing data… [They] will not substitute for a poorly designed study" [17:256].

This sentiment points to the dual-edged sword of computers' present role within ethology. As Agre notes, "computing has been constituted as a kind of imperialism; it aims to reinvent virtually every other site of practice in its own image" [1:1]. The extraordinary new abilities of digital technology can augment the biologist's abilities. At the same time, there is the danger that the computer's affordances and limitations also might force ethologists into unproductive patterns as they do not relate to their field.

The wildness and discovery of ethology, however, have generally contrasted with the traditional uses of computers. Computers' propensity for abstraction and disengagement from the physical world is a key challenge for the incorporation of digital artifacts. Scholars like Suchman and Agre have argued that all research practices, "even the most analytic, [are] fundamentally concrete and embodied"[43]. They encourage a basic shift from the design of large singularly powerful or intelligent artifacts to those which make use of and function with the networks of interactions constituting their target environments. Instead of designing technology strictly in the laboratory and in the manner of a disembodied brain, it becomes necessary to explore and design within the specific sites or sociological contexts the devices are used.

As Agre notes, an artifact developed in a computer science laboratory incorporates assumptions, values, and challenges from its environment, and these may be at odds with those encountered by prototyping directly in the field[1]. This schism hinders a tool's physical and scientific efficacy. The technology might not function properly due to changes in moisture, power availability, space requirements, or the non-participation of the animals. Lehner elaborates on this necessary step forward:

> Ethologists should be more than collectors and analyzers of data; they should seek to 'understand' their animal subjects at a higher level than quantitative analysis can provide [17:5].

Thus, good digital ethological tools are tasked with not only collecting experimental data but also fostering exploration and reflection among the scientists. These can for be data collection and scientific gathering, but they might also be tools, like Silver describes, which aim to instead focus scientists' "attention back on nature… and how to build with it, nurture it, and form an intimate relationship with it" [41]. Creating tools appropriate for the fullness of ethological work becomes a key task.

RESEARCH CHALLENGE

Digital technology is increasingly being leveraged into ethological practice without critical analysis. The challenge of this research becomes how to develop constructive methods for incorporating the affordances of digital media to serve ethology.

Current intersections of digital media and wild animal behavioral research are often ad hoc partnerships between technologists and biologists that occur out of necessity. Combining these practices is largely something that is forced to happen, rather than synthesized through analysis and design. This blunt imposition of powerful, new technologies runs the risk of razing the values and methods important to the field. Computational projects can often subjugate partnering fields to computers' own specific methodologies due to restrictions and cultural practices specific to the digital medium. Finding a way to critically develop this framework for this unique combination of fields requires a specific methodology.

METHODOLOGY

Scope and Timeframes

The historical and theoretical backgrounds highlight the key challenges between ethology and digital media. This backdrop set the stage for direct research embedded with contemporary ethologists at their field sites. STRI[53], a worldwide hub of wildlife experimentation, served as an ideal location for this project, as it allows unique access to both interesting wildlife and a vibrant community of diverse field biologists [55]. Ethnographic data was collected via photo, video, and participant surveys from volunteer participants.

The primary phase of this work was carried out with multiple collaborators at STRI from 2012 (pilot season), 2013, and 2014. Data was analyzed and synthesized during 2014, and evaluated iteratively throughout three additional field expeditions from 2014-2015.

Research Structure and Modalities

Digital Naturalism's interdisciplinarity and intertwined biological, technological, and cultural factors necessitate the creation of a customized research structure. This section rapidly explains the origins and synthesis of a hybrid set of methodologies and the approach used throughout this investigation (deeper discussion found in [31:160]).

Finding a research paradigm and practical methods that could tackle the multitudinous factors involved required the assembly of many different fields and practices. Since a standard methodology did not already exist to meet these needs, one had to be customized from the several disciplines concerning science, technology, and design.

Because any hybrid approach risks being unwieldy, the approaches used throughout Digital Naturalism's creation are organized into a structure. This structure demonstrates the full spectrum of critical techniques utilized from general philosophical tactics to specific, concrete methods employed. The organization of this research is also presented to frame the overall project and indicate why certain design and analysis decisions are made.

Practical ↔ Conceptual					
	Paradigm	Qualitative Action Research			
	Approach	Science and Technology Studies			
	Strategies	Critical Making		Performance Studies	
	Methods	Case Studies	Questionnaires	Workshops	Activities
	Analysis	Thick Description			

Figure 2 – Customized research structure for overall "Qualitative Action Research."

In general, this work follows a philosophical paradigm of qualitative, Action-research. Following Qualitative research philosophies[42], the historical and contemporary values and practices of the primary stakeholders, the ethologists, are analyzed in multiple ways. From the Action Research side [18], the ideas collected from this process are then developed into new practices and tools which are iteratively evaluated with the scientists. Following the views of Lewin and Torbet, the point of this work is to function not as a "one-off" series of projects with self-contained solutions, but rather as a cyclical process of both studying, intervening, and changing a situation[47]. Thus as hybrid, "Qualitative Action Research," this research seeks to analyze thick webs of data[6] that are iteratively tested with the intention of bringing about direct changes in its examined field.

At more pragmatic levels, techniques and strategies from Science and Technology Studies (STS) are utilized for "critical elucidation" [15] of the interplay between the networks of scientific tools, biological traditions[16]. To tailor this analysis for ethology's particular challenges involving tool-making and behaviors, Digital Naturalism conducts this STS research via strategies from Critical Making and Performance Studies.

Ethology is a science deeply engaged with both tools and performances. Critical Making techniques, such as combining critical discussion with hands-on construction[36] of scientific tools will be helpful when working with the scientists to analyze the impact and potential digital technology has on their instruments. Performance studies[39] lend approaches to physically examine the interlinked behaviors of the scientists, animals, environments, and tools involved with ethology, while offering ways to generate and understand novel phenomena among these actors[38].

Digital Naturalism's specific toolkit of research methods included traditional ethnographic instruments along with many interventionist, exploratory tools. Questionnaires and Case Studies (in the form of audio-video interviews and design documentaries[35]) were used to elicit information and let participants reflect. Hands-on activities like workshops, performances, and technological probes then supplemented and tested the information gathered ethnographically.

Analysis

This research structure generates research massive amounts of highly qualitative data. Geertz's methodology of thick description [8:4] has become a standard technique for such analysis. A thick description examination presents a detailed account of the situation being investigated and key themes are identified [6:272]. Since, as Geertz notes, qualitative research writings are necessarily "interpretations," the purpose of describing the collected data "thickly" is to present a broader context against which the audience can form their own opinions [8:14]. The purpose of thick description is not to instantly prove an idea, but rather to discover and progressively validate new concepts from complex situations. The conclusions from the research are never justified in any absolute sense, but rather on the basis that the documented actions and decisions made by the researcher "can be seen as 'reasonable'" [6:273].

RESEARCH

Ethology Ethnography: Principles and Practices

Through surveys, interviews, and documentation, this research collected information on the scientists' general demographics and research styles, along with details on their research values and technological utilization.

Demographics and Research Styles

The ethologists studied possessed all researched the behaviors of non-humans in natural environments (typically the Panamanian rainforest). Beyond this, the researchers at STRI studied many different ecosystems with varying degrees of experience.

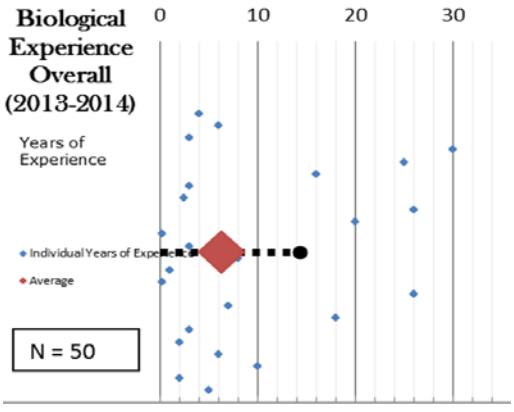

Figure 3 - visualized results of the experience demographics of the researchers studied

From the 50 researchers surveyed, 9 were Undergraduates, 6 were Master's students, 18 were PhD students, and 16 were independent researchers or professors. Participants' total number of years working directly in biology was also surveyed with responses ranging from several months to decades. Overall, the average respondent on the survey was a PhD student with a little over 6 years of biological research experience.

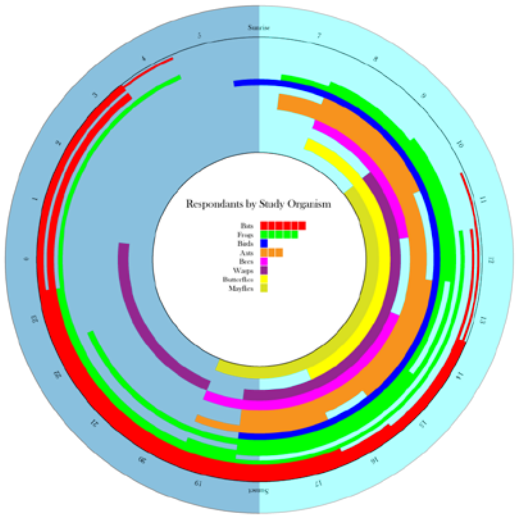

Figure 4 - Average working schedule of scientists at STRI with respected to their research organism (n = 19)

The daily schedules of the researchers are linked to their topic of study. One frog scientist pointed out she never sees her roommate due to different study organisms. In addition to this organismal and temporal diversity researchers all noted that they spend some part of their time in the field and some in the laboratory, that is, no current research is *entirely* lab or field based.

Ethological Values: Case Study – Warkentin Lab

The broader community ethnography was supplemented with four, multi-year, in depth case studies with different biologists and labs. There was Marting and his Azteca ants[20]; Karen Warkentin and her tree frogs[49]; Lipshutz studying Jacana birds[23]; and STRI's Bat Lab with Rachel Page[26] and Barrett Klein[14]. Each case study was unique and shared important perspectives about ethological fieldwork and exploration. This paper will quickly highlight one of the four.

Warkentin's lab pursues an interesting system of frog embryos that sense vibration from predators before they are even born[50]. At her Panama field site at STRI, she experiments with tadpoles and a large, programmable vibrating device that simulates predator behavior [2]. Interviews and shadowing reveal many of the same principles shared by foundational ethologists along with several additional concerns.

For instance, she prizes field-ready tools, like textile-cages, which can deal with the harshnesses and mobility needs of fieldwork. She describes, *"The beauty of a sewn cage is it's like a tent… you can take it down, pack it in a box, throw it in the laundry… transport it to a remote field site."* In order to address her particular research questions, being in natural fieldwork settings is mandatory. She needs to spend time away from her university lab to access rare creatures whose behaviors are adapted to their unique environments in Panama. Warkentin points out, *"I can't ask that question in Boston. I don't have a lab colony."*

Figure 5 – Warkentin's customized tadpole-interaction tools

Particularly important is how her lab identifies their work as being inquiry-driven. Instead of relying on a particular tool, they start with a question and develop tools and skills to answer this question. Warkentin's student, Cohen, explains in an interview, *"Some labs are 'Technique Labs.' They …model their work off an interesting technique that scientists had developed. Unlike the technique lab, [we] start with a question and need to then discover and refine the skills necessary to answer this question."* To support this inquiry-based work, Warkentin's lab focuses on customized, hand-crafted tools. She notes, *"I study frog embryos, and that's not something there's standard tools for."* Thus, they often have to craft their own devices themselves. Like she puts it, *"there are a lot of questions that, in order to ask, we need to make stuff."*

This arduous work of both conducting research and building one's own tools requires rapidly prototyping and test dozens of iterations of their equipment on-site in Panama – *"We go through design iterations and figure out how to make something that will enable us to ask the question."* Being able to prototype onsite helps the scientists adapt the tools to specific experiments and research questions. It also speeds up their work and maintains valuable time in the field:

> *If every design iteration requires a trip to Boston in between to manufacture something… it takes forever. Any material that can let me make prototypes down here [in Panama] and let me test it with eggs is going to speed up my research. For example, is this [design] a better idea or this*

[design]? I don't know now, but I'll know in a couple of days, right, as opposed to next year.

Building portions of the custom interfaces onsite enables Warkentin to avoid one of the biggest problems she sees in scientific tools: where something "*looks really elegant from an engineering perspective, but it actually doesn't work for the frogs.*" Overall, it's Warkentin's lab's emphasis on question-based research that drives their practices and technological use. This type of open-ended inquiry is supported by valuing such factors like onsite rapid prototyping, adaptability of tools, field-readiness, and bespoke tools.

		Foundational Ethologists (Literature)	Contemporary Ethologists (Ethnography)
Motivations	Being in Nature	■	■
	Being with Animals	■	■
	Open-Ended Inquiry	■	■
Analysis	Intuitive Analysis	■	■
	Augmented Interaction	■	■
	Augmented Observation	■	■
Tools	Instrument Feedback		■
	Field-Readiness		■
	Bespoke Tools	■	■
	Technological Agency	■	■
	Onsite Rapid Prototyping		■
	Adaptability		■

Figure 6 – Ethological values for research and technology shared in foundational literature and ethnographic research

These key ethological values were supported and expressed by the STRI community at large and the other case studies. These concepts were compiled and compared with similar findings in the foundational literature and used to develop workshops, activities, and novel technological devices during the next, "probe" iteration of the research.

Technological Probes

Building from the previous ethnographic work, technological projects are created to probe even deeper into digital media's potential impact on ethological practice. Workshops, projects, and performances are conducted in the jungle with the researchers at the STRI to investigate pragmatically how digital media can support specific principles of ethological work. Participants engaged with these probes were then interviewed and surveyed to reflect on key aspects of the activities or devices that supported ethological values. Participants were also invited to speculate on further augmentations or additions to the activities that would also enhance their practice.

Workshops

During the three field seasons at STRI, this research conducted four official community workshops (along with dozens of informal ones). These workshops followed a "critical making" style where participants were prompted into discussing biological, technological, and cultural influences in tandem with the construction process.

Figure 7 –Crafting, programming, and play testing digital firefly costumes in the rainforest.

For instance, during the Firefly Suit workshops, participants learned how to make and modify their own digital devices to interact with the lightning beetles in the dark forest.

They could embodily test and discuss behavioral concepts (such as firefly mating behaviors) in the forms of emergent games with the insects and each other. One participant described the experience: "*…now I realize I am not limited by the current selection of commercial tools available to conduct research, but I can build my own to cater to my specific research questions.*" It is these combined experiences with animals, ecosystems, technology, and critical discussion that let the scientists gain new insights about their creatures while granting them agency to understand their work can expand.

Projects

The behaviors and abilities of the nearby jungle creatures motivated several independent projects with participants to explore new digital means of natural interaction. These projects sought to follow design styles of the early, explorative devices from foundational ethologists involving dynamic stimuli placed directly in the creatures' environments. For instance, David Best's simple "robotic" hawkmoth (a box that lit up when a bird approached), consisted of little more than a lightbulb and a transparency sheet, but it enabled Best and Tinbergen to ask questions interactively about the bird's behavior [44:128].

Figure 8 – Projects: Ant-Morse Code, Leaf-cutter poetry, modular insect sensor prototypes, and Stereo Smelling devices.

Some project examples include explorations of dynamic ant interaction with an ant-Morse code messaging device[29]. A simple programmable gate forms an open-ended tool that lets participants raise questions by attempting to send messages through bustling swarms of ants. Leaf cutter cut-up poetry explored how to induce ants to carry surrogate materials (false food) for both engineering novel tracking devices and using the ants themselves as a media platform. The modular insect sensor series of prototypes [30] studied the values Warkentin previously espoused for getting rapid feedback by designing close to nature. The Stereo Smelling project explored concepts that other ethologists (like Uexküll[48] and Ryan [37]) advocated concerning embodied sensory augmentation. Stereo Smelling featured temporally isolated sensory prosthetics to let scientists feel, first hand, what it is like to have insect antennae and navigate pheromone trails.

Once again these projects tested and revealed more key features for digital-ethological tools, such as the value of open-ended tools that raise questions, and the rapid feedback afforded by designing close to nature.

Performances

With the community as a whole, or in small groups, this research also ran performances involving the animals and tools. Performance is a valuable tool for conducting scientific exploration. Scholars like Crease cite performance's ability to both probe and reflect upon scientific phenomena in research [5].

Figure 9 - Performances for probing natural systems and reflecting upon technological devices. (Ant-ice interaction in *Jungle Fluids* and Robotic puppet in *Leaf 5 Lover*)

Some performances were designed to explore new interactions and behaviors with the creatures. For example in the Jungle Fluids[32] performance (based on a "happening" by Alan Kaprow[40]) we exposed jungle creatures to new foreign stimuli (ice and extreme cold). This random, but systematic, probing revealed previously unknown behavioral phenomena where the ants would ferociously attack the ice until frozen solid, and then their sisters would rescue them by shaking and licking until they had thawed. This project illustrates performance's quality for "poiesis" described by Crease[5]. Creating these arbitrary sculptures generated novel ethological behaviors, such as the ants pulling each other to safety, which can then be further addressed scientifically.

These performances also benefitted scientific reflection. The act of conducting a prescribed ritual, as Schechner and Turner argued [38], brings one to a liminal space of reflection and analysis. This ability helped scientists step outside their own research and re-evaluate the assumptions built into the design or their experimentation. In a project called *Leaf 5 Lover*[21], scientists used their bodies and digital and analog technology to act out hypotheses for behavioral models in order to analyze their own early research ideas. Using a giant robotic Ant puppet and the emergent behavior of dozens of other participants, this performance explored scientist Marting's concepts of the defense behaviors of a tree-dwelling ant (*Azteca constructor*)[20]. After the performance the participants gathered around a real-life *Azteca-Cecropia* tree to witness the original system from which this play was adapted. Having just physically embodied the phenomena, many participants feedback shared the performance helped them better understand and empathize with the actions of the animals.

The performances again illustrated the usefulness of design features such as open-ended designs and getting feedback from nature, but they also highlighted the value of designing experiences that promote embodiment and immerse scientists' attention in these behavioral actions.

	Technological Probes	Speculative Desires
Practical Technological Engagement	■	
Tools for Reflection	■	
Peer Feedback	■	
Tool Feedback		■
Design Feedback from Nature	■	
Immediate Reference	■	
Integrating Natural Materials	■	
Environment Access		■
Sensory World Access	■	■
Animal Computer Feedback	■	■
Immersed Attention	■	
Raises Questions	■	
Open-Ended Design	■	

Figure 10 – Positive ethological attributes for digital devices found in technology activities and speculative reflections

Overall the technological probe periods further confirmed the values of workshops, prototypes, and performances as tools for both discovery and analysis. They also elucidated key features for technological design and interaction such as feedback from the tools and nature, tools that raise new questions, technology with open-ended designs, and tools that promote embodiment and access to the sensory worlds of other creatures.

FRAMEWORK

Synthesis

Following a qualitative analysis style, Digital Naturalism synthesizes its final design framework by combining the key principles of past and present ethologists with the field-

tested features of the technological probes. These facets were grouped into commons categories and distilled into key tenets.

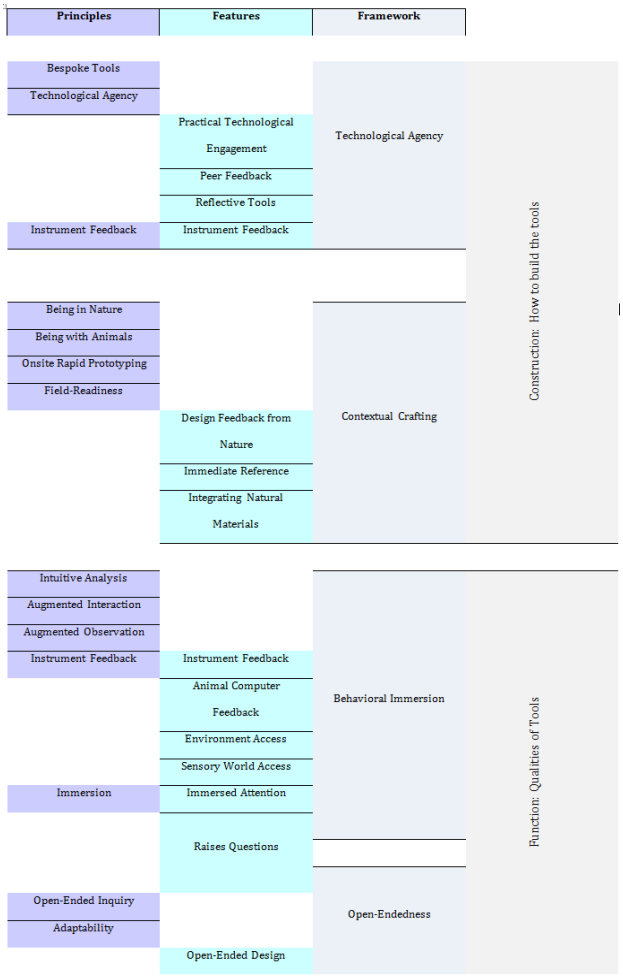

Figure 11 - Synthesis of framework from research concepts

The result of distilling this research is the discovery of four primary concepts that can guide digital technology's design to support ethology. The target of any design framework is to provide a concise set of ideas which, when followed, improve the capabilities of the resulting products. In the same way that Murray's Four Affordances [24] try to guide designers of digital media as a whole, the Digital Naturalism framework presents key principles for developing digital media which aim to serve an ethologist's practice while helping designers avoid potential pitfalls.

Digital Naturalism's resulting four tenets are Technological Agency, Contextual Crafting, Behavioral Immersion, and Open-endedness. They urge designers to A) make tools that are understandable and manipulable, B) build tools in natural environments, C) viscerally engage human and non-human participants, and D) design improvisational tools that raise questions. The first two concepts of agency and context guide ***how to make the tools***, and the second two concerning immersion and discovery describe the key ***functions of the instruments***.

Digital Naturalism Design Framework

Construction	Technological Agency	Promote transparency of the tools' functions.	
	Contextual Crafting	Build the tools in the wild.	
Functions	Behavioral Immersion	Create embodied, dynamic interactions with animals	
	Open-Endedness	Design non-specific, adaptable, improvisational instruments	

Figure 12 - Framework for promoting discussion and design of digital media artifacts for ethological work

Technological Agency

Making tools that foster a scientist's own Technological Agency helps give them the power to shape the tools according to the requirements of their original research question. Designing for Technological Agency means to create tools that are open, understandable, and manipulable.

Giving naturalists agency over their instruments is essential to the integrity of their work. It ensures scientists' experiments are driven by their research questions and helps eliminate erroneous assumptions involved with their tech. This is especially important in digital tools, where functionality can be locked-away in machine code. The ideal digital naturalist is a fully independent explorer of both biological and technological worlds. In collaborations, though, some techniques can help all parties have agency over their tools. Aim for simple, modular tools that let one manipulate the code without reprogramming. Furthermore, always encourage documentation and sharing of designs.

Contextual Crafting

Crafting digital devices within the context of their use can help speed up iterative development, and ensures the devices have appropriate features for use.

Contextual Crafting encourages researchers to physically create devices as close to the target environment as possible. Ethologists study animals in the wild because their behaviors evolved to fit the idiosyncrasies of the environment. Tools similarly incorporate assumptions about the environments in which they were made. Building tools in the wild ensures their field-readiness and suitability for the research site and animals. Building in proximity to the field and incorporating natural materials fosters the idea of "making as exploring"[28][33] which speeds iterations and inspires design insights from the field. Perhaps foremost,

this concept maintains naturalist's precious time spent in the field, thus promoting fostering serendipitous inspiration and discovery. Lastly, tools that are built in the field can also be repaired in the field, preventing naturalists from being stranded with broken tools.

Behavioral Immersion

The design principle of Behavioral Immersion encourages the development of tools which engage a scientist's own sensory abilities and promote the researcher's capability for intuition analysis.

Digital ethological tools should immerse the researchers in the behaviors of an organism or functions of an environment. A scientist's early exploration is heavily dependent on immersing oneself in the overload of multifaceted stimuli of the environment and their animal's behavior. Behavioral Immersion augments ethologists' interpretive abilities by allowing them to deeply engage this data with their whole bodies. One can cultivate immersion by remapping one's own sensory modalities to the outputs of sensors studying animals or environments. Prolonged stimulation of body parts (like the tongue or back) in coherent ways taps into the brain's plasticity and develops engagement[13]. Similarly, one can also design for feedback systems between the computers and animals themselves to elicit novel responses.

Open-Endedness

Targeting Open-Endedness in the functionality of ethological tools promotes adaptability and serendipitous discovery of new behavioral phenomena.

A key task of scientific exploration is to increase chances of serendipitously stumbling across interesting new phenomena. Naturalists' tools should be designed for Open-Endedness and spur the curiosity and undirected exploration integral to their work. Open-ended digital tools for scientific exploration can be thought to embody questions rather than only deliver answers. Tools with simple functions allow researchers to quickly re-arrange devices and poke and probe in new ways. Making adaptable, improvisational tools spurs curiosity by encouraging the interactor to create novel combinations of behavioral stimuli. Having tools that are only partially built further encourages such open-ended questioning and discovery.

EVALUATION

This research continued with additional layers of review and testing to fully evaluate the usefulness of this framework (again, full analysis available in [31]). Numerical data shown displays an average diamond mark graphed with their standard deviation of the total responses.

Community Evaluation

Final questionnaires were designed to gauge the impact of this research conducted with the STRI community. Researchers who had participated in Digital Naturalist activities, such as workshops, performances, or projects, were asked to evaluate their experiences. They were also invited to submit feedback critiquing the methods employed by this research.

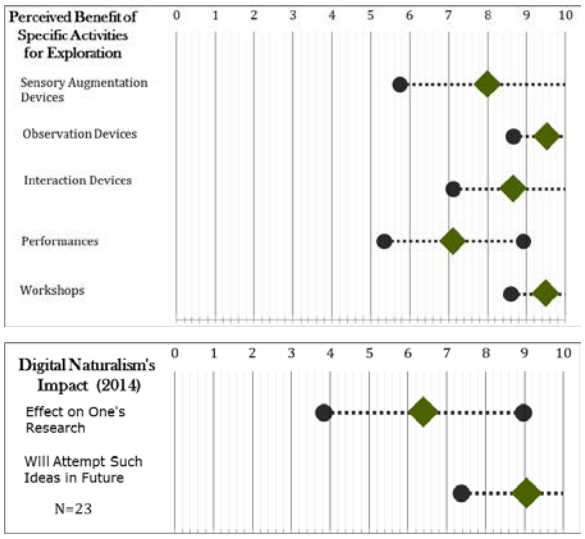

Figure 13 – Summary of participant responses concerning the benefits of Digital Naturalism's methods and impact. Details marked on scale of 10(positive effect) 1(negative effect) and 5 (no effect)

In general, participants claimed at least some perceived benefit of the digital naturalist activities and devices they experienced during this work. The participants were, however, plus and minus in noting the direct impact Digital Naturalism had on their own work. A follow up question inquiring on their attempts to incorporate the ideas shared in their future work proved overwhelmingly positive. These results indicate that the scientists' current projects were often already too far along to rework these new ideas for digital media into experiments, but aim to do so in their future practice. Several written responses confirm the delayed impact of Digital Naturalism. For example, as one scientist says, "*The robotics workshop opened my eyes to the world of Arduinos! I hope to incorporate these into future research, even if not research associated with STRI.*"

Field Evaluation: Hiking Hacks

Continuing this research's "Action Research" style, a final series of participatory, mobile workshops were designed based on the newly developed framework. These atypical workshops specifically harnessed the concepts of Technological Agency and Contextual Crafting from the framework to combine backpacking excursions into the wilderness with participatory, critical making workshops with digital technology. These mobile digital-ethological workshops, dubbed "Hiking Hacks," took place in Panama, Madagascar, and the United States for 2-4 weeks at a time.

Figure 14 - digital prototyping in nature - "Hiking Hacks"

Following these expeditions exploring digital natural prototyping and interaction, participant's responses were gathered once more. This final test assesses the design framework as a useful tool for designing digital media for ethological exploration.

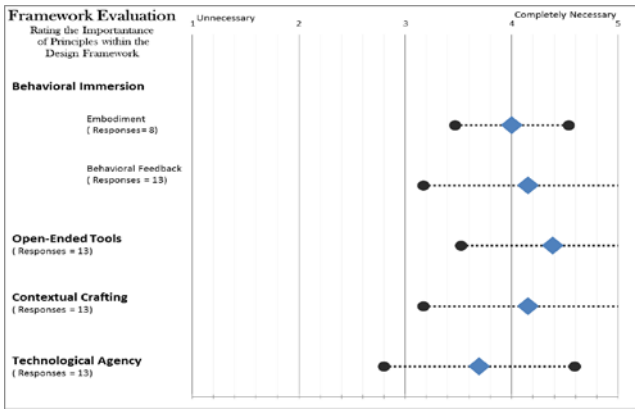

Figure 15 – framework evaluation by "hiking hackers"

The full framework was utilized during the Hiking Hacks to design activities and projects and then re-evaluated by participants. This testing served to judge the framework's efficacy at promoting digital-ethological exploration.

Overall, the workshop's situated experience gave greater insight to multiple ways of designing and conducting research. As one participant states, "*I like the backward structure of starting in the field and working backwards to make a lab… [it lets me] see the advantages of both places*." Building, repairing, and testing digital tools within the animals' natural environment proved to not only be feasible, but also functional.

These evaluations demonstrate that targeting these concepts facilitates the design of digital artifacts which uphold the values of ethology from the ground up.

CONTRIBUTIONS

Little groundwork has been previously laid for this research's specific intersection between digital media and ethology. For this reason, many other contributions to these parent fields also had to be developed along the way.

First, it provides an iteratively evaluated design framework for digital-ethological tools. It also shares a design for a pragmatic hybrid research structure for studying inter-mixed technological, cultural, and scientific factors utilizing real-world performance and construction.

The hands-on work with scientists also led to the design, analysis, and documentation of several new digital media tools for studying and interacting with animals, some of which have already been taken up by ethological researchers themselves [20]. Digital Naturalism's "contextual crafting" tenet has also directly motivated outside research such as Perner-Wilson's "Wearable Studio Practice" [9,34] and "Hacking the Wild," a television show for *Discovery Networks*[22]. Finally, this research outlines a new form of mobile, participatory design workshop, the Hiking Hack. These new theoretical models, analyses, designs, and pedagogical forms can become useful for other research conducted at the intersections of biology, media, engineering, and design.

CONCLUSION

Digital Naturalism shares how to design and utilize a novel media framework from important features of ethology and digital media. This structure develops and exemplifies a means of creating, evaluating, and sharing new media forms which connect digital and biotic behaviors. By helping ethologists design and build their own computational tools, this research strives to extend the ethologist's tool-making traditions into the digital realm. This framework for Digital Naturalism thus serves as a foundation for deeper collaborations between the human, digital, and biological worlds. Designing devices that promote enjoyment and engagement with non-humans can not only strengthen the design of digital media, but also foster greater empathy and appreciation for the natural world.

This preliminary research reveals many fruitful, new avenues of exploration. Continued Hiking Hacks and design research involving different biomes and cultures around the world will provide a small push in the broader struggle of using digital media to escape an anthropocentric worldview. Ethologist Bernd Heinrich describes weariness of traditional research that perhaps new media forms can help escape:

> Often I have been frustrated with the journal articles that come out of the research because only the finished results are given. All the excitement of the process has been squeezed out so that the results will conform to certain expected standards... My hope is to capture... the sounds and sights, the endless chores and happy accidents, the obsessions, the wonder of it all[10].

Hopefully more people will be inspired to push digital media out of the lab and into the wild.

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