“If Human Ears Were Tuned to Bat Frequencies": Inaudible Sound and the Sciences of Bat Echolocation

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Abstract

This report provides draft excerpts from my PhD dissertation titled "The Inaudible Sounds of Science and Medicine: Animals and Media from the Galton Whistle to Bat Echolocation," a chapter of which explores the laboratory work of Donald R. Griffin – and especially the emergence of the concept of bat echolocation – as it contributed to a sonic history of "ultrasound" and other typologies of liminal sound vibrations. Such "inaudible sounds" repeatedly defied amplification (efforts to make them louder); their frequencies were too high or too low to vibrate the human eardrum. But humans have long suspected that insects, bats, dogs, and other animals could hear them and communicate through them. The following research on bat echolocation in the Griffin laboratory is one aspect of a much more comprehensive historical project, which platforms nonhuman listeners in 19th- and 20th-century experimental contexts as they repeatedly pushed the limitations of human hearing. Broadly speaking, the dissertation suggests that animal figures are useful vectors for exploring an expanded history of sounds, including high-pitched frequencies, in science and medicine. My objective is to better understand how scientists designed media and choreographed animal listeners in order to make meaning from the sounds they could not hear on their own. I am most invested in understanding how humans exploited, collaborated with, and coexisted with animals to make sense of the insensible – or, to understand the unheard bestial worlds of communication.

In this report, I draw on material from the Donald R. Griffin Papers, held at the Rockefeller Archive Center, which includes a vast array of Griffin's laboratory notebooks, correspondences, sound films, newspaper clippings, and publications. The analysis spans the years between Donald Griffin's first experiment on bat navigation in the dark (1938) – conducted during his early graduate training years – and his postwar research on the physical principles of bat pulses into the 1960s. More specifically, I characterize the ways in which various forms of media were deployed in experimental settings to study bats and the inaudible sounds emitted by them for orienting their bodies in flight. Scientists and collaborators of the Griffin lab relied on an array of mixed media,

from the sound transposing devices of Harvard physicist George W. Pierce, to mechanical-visual apparatuses such as cathode-ray oscillograms and sound spectrographs, through to hand-written laboratory notes and printed correspondences and – ultimately – the bats themselves, to answer their questions. Furthermore, I explore the epistemic techniques of listening for sound and silence in the Griffin laboratory, in which the ears and eyes of scientists interfaced with special acoustic media to produce certain knowledges about bats and their patterns of flight. This project also engages with the highly militarized scientific contexts that constituted Griffin's work on bat echolocation.

Introduction: Weaponized Ultrasonics, Underwater Media, and Bats

World War II and the immediate postwar years ushered in a boom in the field of modern ultrasonics, from which both Griffin's research on bat echolocation and various attempts at weaponization of the sound spectrum emerged. "If human ears were tuned to bat frequencies," Donald Griffin once told a reporter, "a bat flying near one's head would sound as loud as a fighter airplane."[1] The sciences of bat echolocation and sonar pulse-echo were entwined creatures -- both born from military institutions and wartime knowledge regimes; both defined by historically specific sociotechnical attempts to transmit, transpose, and communicate across underwater terrains, inside anechoic chambers, and through established listening cultures of scientific communities – primarily by harnessing inaudible sound vibrations. At one point during the height of WWII, bat bodies in flight became reimagined as material war vectors, capable of carrying "small incendiary bombs into buildings and other inflammable property in enemy territory."[2] Although he would later regret the decision, citing serious practical and ethical concerns, Donald Griffin consulted on this "bat bomb" project in collaboration with Dr. Lytle S. Adams, in which hibernating bats would be transported behind enemy lines, released, and allowed to scatter with explosives strapped to them. The plan was never executed but is particularly illustrative of the pervasiveness of militarized discourses as they infiltrated even zoological and biological thought and praxis.

In fact, many electroacoustic technologies used to hear supersonic bats came directly out of commitments to projects such as underwater signaling and communications control during the interwar and WWII years. Griffin began his lifelong professional preoccupation with bats at Harvard University in the late 1930s, amid the peak of wartime psychoacoustics and industrial attempts to manufacture intelligible speech. An early experiment in 1938 used a Sonic Amplifier, a product of piezoelectric research and military involvement in the war effort to expand underwater acoustic signaling programs. When Griffin returned to his study of acoustic orientation as a means of bat perception after World War II, he became ever more determined to graphically depict –

presumably with more accuracy – the "actual sound waves upon which the bats relied so heavily for their orientation."[3] During the height of research on bat echolocation in the 1940s and 1950s, Griffin explored a variety of mixed auditory and visual modes of observation, and integrated new electroacoustic media into his laboratory practices. These devices included the Pierce Sonic Amplifier, which converted inaudible sounds into audible ones, as well as oscillographs and spectrographs – both of which displayed visual inscriptions of the inaudible sound waves. In the late 1950s, Griffin also began to incorporate tape recordings of bat sounds, which could be played back at reduced speed, thus "afford[ing] a literal translation of bat pulses into the range of human hearing."[4]

Despite this heavy reliance on machines to interpret imperceptible vibrational phenomena, including sounds, a full understanding of bat echolocation also required embodied notations of the sensory remnants that could not be explicated by media technologies alone. This most closely resembles what Daston and Galison refer to as "trained judgment" in the visual context, or "the cultivation of a kind of *physiognomic sight* – a capacity of both maker and user of… images to synthesize, highlight, and grasp relationships in ways that were not reducible to mechanical procedure."[5] Trained ears and trained eyes validated the presence of bat voices even in the absence of sound. In this way, perhaps paradoxically, even silences became possible indicators of inaudible sound waves. Although Griffin certainly implemented the transcription of inaudible bat voices onto paper, he still used mediated listening and unmediated listening to recognize patterns, to interpret the imperceptible, and to contextualize his visual experiences during encounters with his bats. To amplify and extend Daston and Galison, "learning to recognize the scientifically novel was a matter of training the eye" and – in the science of bat echolocation – the ear.[6]

Spanning the years 1938 to 1960, this report considers Griffin's laboratory and its research on acoustic bat orientation as it transitioned from the Second World War to the Cold War logics of weaponized vibrations and pervasive automation. In her history of infrasound, Sophia Roosth has argued that *especially* in Cold

War contexts, liminal sound vibrations manifested in and on the human body as various iterations of extracochlear perceptual experience – including nausea, dizziness, and confusion. Tactile and affective traces of the imperceptible served as indexical reminders of an atmosphere teeming with potential low-frequency vibratory threats to the body, as "sinister or malevolent forces" of nuclear war.[7] High-frequency inaudible waves, too, spawned similar uncertainty. Physicists and pioneers of modern ultrasonics watched as the eerie "death whispers" of supersonic beams killed fish, mice, and other model organisms. Ultrasonic beams were inaudible but tactile: "if the hand was held in the water near the plate an almost insupportable pain was felt, which gave one the impression that the bones were being heated."[8] Military officials warned that the inaudible sound vibrations of jet-propelled aircrafts could potentially manifest in human bodies as vague constellations of fatigue, nausea, confusion, or giddiness.[9] In other words, between WWII and the Cold War, as Griffin's research was repackaged in new military contexts of uncertainty, it is perhaps unsurprising that Griffin relied on a variety of mediated and unmediated body techniques to observe his bat subjects.

Furthermore, the relationship of human listening techniques and the development of underwater audio media from WWII to the Cold War era was hardly a straightforward trajectory towards increasingly automatic, disembodied submarine warfare. Historian of science John Shiga has attended to the shifting sensory, technological, and infrastructural terrains of ocean navigation, military communications, sonar, and the "construction of a new technical-natural object – the underwater ear."[10] He argues compellingly that the development of sonar systems initially required the creation of new modes of listening for American naval scientists, which in the case of early hydrophone systems established a sincere trust in the sense of hearing as a valid form of surveying and comprehending the ocean environment. But a reassessment of the human operator's ability to consistently interpret echoes around WWII undercut previous efforts to valorize hearing. Naval scientists increasingly relied on other ways of monitoring underwater terrains, and grew suspicious of human audibility and perception which, in turn, "propelled and shaped global ocean surveillance systems during the Cold War, when underwater warfare strategy turned to the mobilization of automated sensing machines to monitor the ocean for us."[11] In line with these important works on the weaponization of the sound spectrum, this account suggests that the inaudible sounds of bats from 1938 to 1960 were almost always surrogates for militarized ambitions and fears. Repeatedly processed as audible and visible constructs, the inaudible sounds of bats became imbued with highly politicized connotations of unheard weapons, subaqueous communications, and more efficient telecommunications infrastructures.

"Our Bats Were Talking in Ultrasonics"[12]: Sorting Out Echolocation

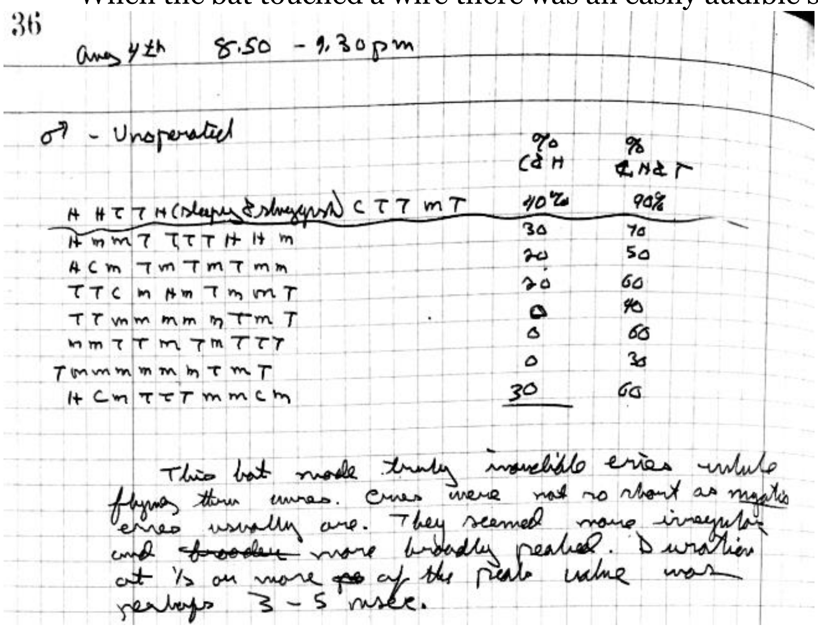
In 1938, graduate student Donald Griffin brought some bats to George W. Pierce, professor of physics at Harvard University. As they placed the bats in proximity to Pierce's newly built Sonic Amplifier – then the only known device in the world capable of translating high-frequency, inaudible ultrasound into audible beats – and tuned the microphone, what they heard shocked them. They demonstrated that seemingly silent bats were in fact 'crying,' emitting notes at the remarkable rate of 45,000-50,000 vibrations per second. Though such high-speed cries eluded Griffin and Pierce's attempts to hear with their naked ears, they revealed themselves in the laboratory as sonic materials susceptible to quantification, comparison, and analysis. "We were surprised and delighted to hear a medley of raucous noises from the loudspeaker," Griffin reflected in his monograph *Listening in the Dark,* published in 1958, and yet he cautioned that "just because the loudspeaker of the sonic detector popped and rattled we must not leap to the conclusion that our bats were talking in ultrasonics."[13] Hearing the transposed sounds of bat voices was certainly a promising start, but proving the ultrasonic chatter of bats and showing its involvement in flight patterns would require more experimentation. Such an investigation called on a combination of acoustical and visual media, and highly attuned scientific listeners.

Over the next three years, armed with a new medium capable of translating silent bat voices into audible sounds, Griffin and his colleague in biology, Robert Galambos, set out to answer why bats emitted these supersonic sounds, and how they learned to fly in the dark. "Anyone who has ever watched a bat in flight has been impressed by its agility and the quickness with which it dodges any solid object in its path," insisted Griffin and Galambos in their 1941 report on the auditory theory of bat obstacle avoidance.[14] Followed by this musing was substantial experimental evidence documenting the localizing powers of the bat ear, in which bats situated their bodies in space by hearing their own supersonic notes reflected off of obstacles. Griffin would later coin this process *echolocation*, a concept adopted and further developed by a wide variety of experts to describe techniques of acoustic orientation. By using the Sonic Amplifier to transpose unsound into sound audible to the scientific listener, Griffin's experiments elucidated the relationship between the apparent silence in the laboratory and the unheard echo-locative technique of flying bats. For more than two decades after successfully eavesdropping on his bats, Griffin continued to use his ears to listen in his laboratory – for silences, for repetitive 'audible clicks' that fused into "a faint buzz," for the pings of bats hitting the meticulously strung barriers of wires, for the rustling, grinding, and popping noises of electroacoustic machines, and for the rattling of transposed bat chatter. Indeed, what he heard and what he did not hear both contributed to his experimental practice.

The experimental arrangements of Griffin and Galambos were far more sophisticated than the initial experiment conducted by Pierce and Griffin three years prior; testing bats one at a time, in trials of 200 or more, these experiments meticulously logged flight patterns of many bats in various states of sensory deprivation – some blinded, some deafened, some half-deafened, and others gagged. The ultimate goal was to prove that normal bats could emit and hear their own ultrasounds, and that they used these sounds to perceive their surroundings. As noted above, Griffin would ultimately coin this perceptive process *echolocation*. Although they relied on the Sonic Amplifier to ensure that bats were emitting ultrasounds

Figure 1. "This Bat Made Truly Inaudible Cries," Aug 4, 1945, Lab Book 1: Dec 7 1944- March 23, 1946, Notebook entry page 36, Box 16, Folder 152, Donald R. Griffin Papers, Rockefeller Archive Center.

inaudible to the human ear, many experiments relied on another type of audible detection. Griffin and Galambos strung a series of wired obstacles from wall-to-wall, a barrier so challenging that "no bat avoided it completely." According to a 1941 account published in *The Journal of Experimental Zoology*, as each bat flew through the barrier, "a count was kept of the number of hits and misses… When the bat touched a wire there was an easily audible sound; and even when a wing tip brushed lightly against it, a wire would continue to vibrate perceptibly after the bat had passed." [15] What counted as statistical evidence of deviation from normal flight – or, what proved that bats were sufficiently deprived of hearing their own ultrasounds – was an audible indicator of collision.



Cracking the case of bat obstacle avoidance and logging any discrepancies required careful, repetitive listening practices and trained scientific ears, as well as meticulous paperwork. Griffin's laboratory notebooks are archival testaments to the multisensory observational practices that scientists used to explain the orientation behaviors of bats and, more broadly, they are indicative of the techniques that experts used to explain inaudible sounds. Under a running tally of "hits," "misses," and "turns," Griffin wrote notes about the character of bat cries, which incorporated both unmediated ear work and observations about oscillographic traces: "this bat made truly inaudible cries while flying thru wires. Cries were not so robust as myotis [bat] cries usually are. They seemed more irregular and more broadly peaked" (Figure 1).[16] Despite the incorporation of mechanical graphic media, Griffin also drew on the trained judgment of his own auditory impressions, which characterized discrepancies between the experience of total silence, faint audibility, and audible sounds.

Making adequate sound recordings of the ultrasonic bat voices, which could be stored, played back, and circulated, almost always posed a challenge for Griffin and Galambos. Commercially available sound recording products were hardly ever equipped to capture the sound waves outside of the audible spectrum, which is one of the reasons why scientists who studied echolocation were bound to ephemeral audible translations of inaudible sound. Ultrasounds constantly seemed to defy modern recording equipment as well as attempts to manipulate it, or to slow it down. Writing in 1944 with an update on his "work on the leathery-winged mammals which have carried us to such dizzy heights of fame and renown," Galambos expressed his reservations to Griffin: "your suggestion is that supersonics be recorded on the sound track and played back at slow speed. With it I find this fault: I question that even post-war electronics can cause the recording lamp to flicker at 50kc – filaments wouldn't go on and off that fast to record that many streaks on film."[17] Sound-recording media could not keep up with the high-frequency

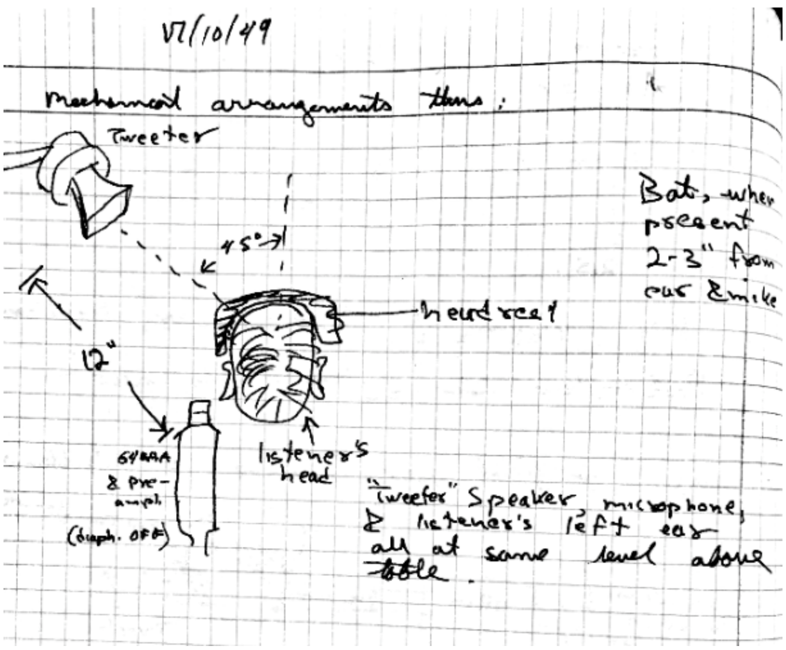


Figure 2. "Mechanical Arrangements Thus," October 17, 1949, Lab Book 5: July 16 1943 – May 3 1950, Notebook Entry p. 48, Box 16, Folder 156, Donald R. Griffin Papers, RAC.

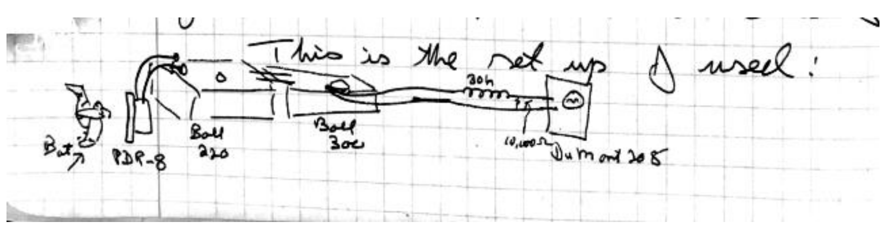


Figure 3. "This is the Set Up I Used," July 30, 1946, Lab Book 2: March 28 1946 – Dec. 26 1946, Box 16, Folder 153, Donald R. Griffin Papers, RAC.

pulses of bat “barking.” Furthermore, commercially available microphones were most sensitive to sounds in the audible spectrum and, because of this attunement, ineffectively transduced higher-frequency sounds into electrical pulses. Working out which microphones “worked” in certain experimental settings required oftentimes elaborate choreography with various electroacoustic equipment, bats, and trained human listeners (Figure 2 & 3).

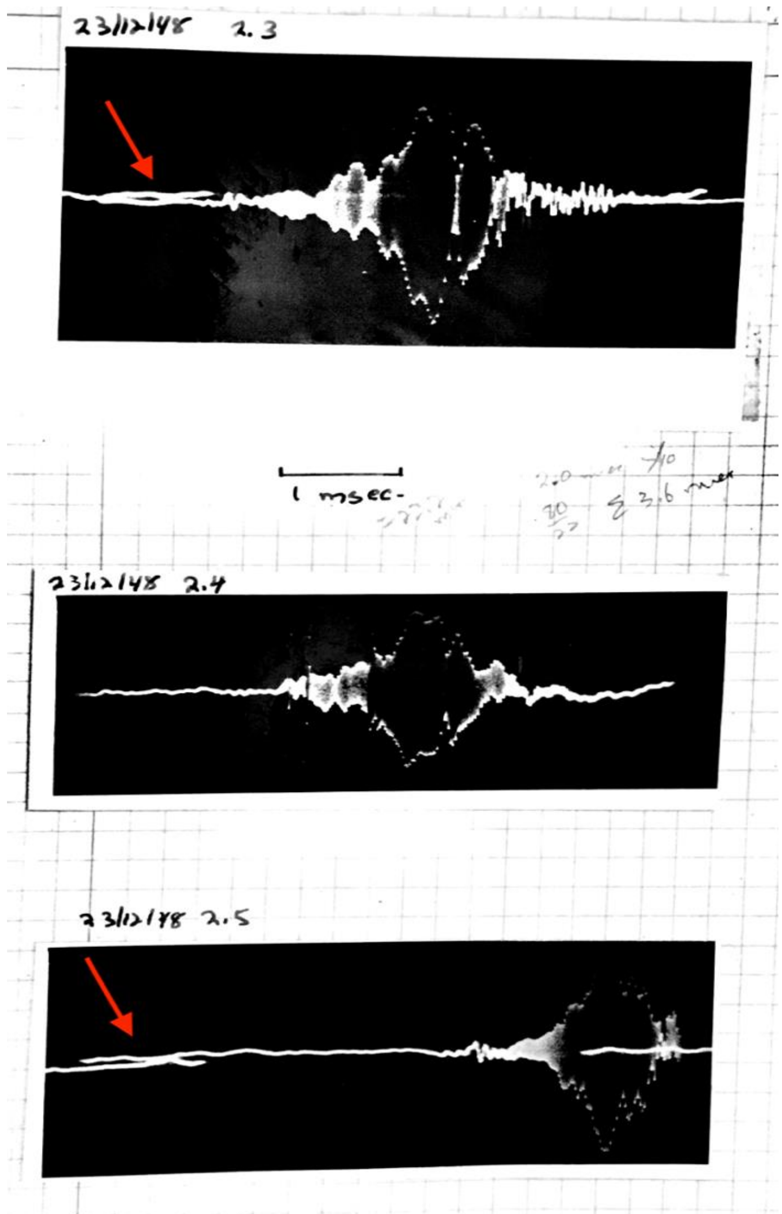
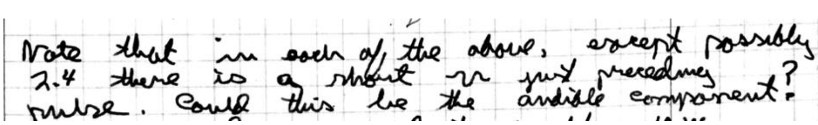


Figure 4. “Could This be the Audible Component?” Dec 23, 1948, Cathode-ray oscillograph photo of ultrasonic bat pulses, Lab Book 4: 7 Dec 1948 – July 1949, Notebook Entry December 23, 1948, Page 46 & 47, Box 16, Folder 155, Donald R. Griffin Papers, RAC. [Red arrows not in original document, emphasis added.]



Despite the fact that a vast array of electroacoustic media entered the Griffin laboratory from 1938 to 1960, processing and automizing the registration of inaudible sounds, closer attention to Griffin's correspondences and laboratory notebooks suggests that he persistently collated the mechanized visual and audio outputs of media machines with his own perceptual experiences. Despite an increasing reliance on mechanical and automatic recording devices to comprehend the presence of and potential for unheard sounds – including, especially, ultrasound – various forms of embodied representation endured. The scientific investigation and observation of inaudible sound was irreducible to mechanically derived transcriptions alone. In Griffin's laboratory notebooks, for instance, photographs of sound waves recorded by cathode-ray oscilloscope were often accompanied by hand-written notes in the margin, which designated the level of audibility of the sound pulses. One problem that Griffin and his colleagues encountered after WWII was an audible click made by the bats, which did not seem to coincide with the overall *inaudibility* of the supersonic bat cries. What was the relationship between the bat's audible click and its inaudible cries, which could only be heard through a machine that transposed them into audible beats? One solution was to write the waves down using a cathode-ray oscillograph. "Note that in each of the above, except possibly 2.4 there is a short [wave symbol] just preceding pulse. Could this be the audible component?" Griffin wrote, probing at the relationship between waves he could see in the photograph and sounds he heard (or did not hear) as bats flew past his ear.[18] Even when the waves were automatically transcribed by oscillography – that is, even when machines seemed to do all of the work of registration – their visual inscriptions still had to be reconciled with Griffin's own ears. Griffin manually recorded his own perceptual experiences by scrawling them underneath mechanically generated figures (Figure 4).

Although automatic visual, wave-based representations gradually predominated post-war understandings of inaudible sounds in the 1950s and 1960s United States, scientists and engineers still drew on embodied perceptual work to study them in the laboratory. What I mean by 'embodied perceptual work' is a wide range of scientific practices that do not involve procedural uses of acoustic or visual media. Examples include, for instance, unmediated

Figure 5. Orienting Bats to Microphones. Griffin's experiments often involved complex technical choreographies; here, we see a scientist in Griffin's laboratory holding a bat in flight above a microphone, which is transducing the sounds into electrical signals. This whole process is being photographed frame by frame to gauge orientation of the bat, in an effort to study the angles of the bat ultrasonic signals. Furthermore, these photograph sequences are sliced and pasted into Griffin's laboratory notebook. April 12, 1950, Lab Book 5: July 16 1943 – May 3 1950, p. 127, Box 16, Folder 156, Donald R. Griffin Papers, RAC.

earwork, in which techniques of listening with the naked ear for both silence and sounds became instructive in working out echolocative phenomena. Griffin also relied on non-mechanical scribbles in laboratory notebooks to denote auditory techniques and impressions of the loudness, pitch, and duration of sound pulses. To communicate his findings outside of his own laboratory records, he described his perceptual experiences of inaudible sounds and sent them through the mail to other scientists for verification. For instance, Griffin spent a great deal of time confirming with colleagues the shared perceptual reality of what he suspected were audible components accompanying the (inaudible) supersonic bursts of bat cries – barely perceptible traces of powerful inaudible pulses that followed. "I still feel that what you describe as the ticking or rattling sound is the same as the sound which we have called the audible click or the buzz," Griffin wrote to a colleague, trying to process audible from inaudible markers.[19]

Other body techniques involved in exposing the inaudible regimes of bats in the laboratory, which did not rely on mechanized registrations alone, were related to configuring, tuning, and directionally accommodating media to register the inaudible sounds in the first place. Such postural and positional protocols must not be overlooked. Even when electroacoustic machines were used to transpose inaudible sounds into audible beats, as in the case of the Sonic Amplifier, Griffin and other scientists had to manually tune the frequency dial according to the fleeting positions of flying bats in order to properly detect the echoes. By restricting the received sounds by frequency band, Griffin could selectively amplify, sonify, and ultimately determine the acoustic nature of the bat voices. Furthermore, failure to appropriately orient the parabolic horn, which collected the bat voices, when the bats were flying led to initially flawed conclusions. After accounting for the "extremely directional position of both the bat's emitted beam and the microphone," and relying on new protocols for positioning the parabolic receiver on the Sonic Amplifier, Griffin and his colleague G.W. Pierce reversed their initial findings that bats did *not* use supersonic sounds to fly. "Only when the bat was pointed directly at the microphone did we detect its sounds."[20] Further, the experimental choreography that took place as both visual inscriptions and auditory translations were made – including the painstaking arrangement of uncooperative "talking" bats, expert scientific listeners, and an oftentimes labyrinthine arrangement of electroacoustic equipment – required much more spatio-temporal acuity than is permitted by a 2-D visual representation (Figure 5). In fact, visual inscriptions were nearly unintelligible in the absence of established laboratory cultures of listening and previous auditory findings.[21] Even as Griffin was carefully observing the ultrasonic pulses of bats being written onto paper by machines, he was diligently listening to them fly around his laboratory.

***Ticklaut*, or the Audible Click**

While Griffin and Galambos were busy choreographing experiments with advanced electroacoustic equipment and soundproof rooms, Dutch zoologist Sven Dijkgraaf was making careful observations of bats in flight without any acoustic media technologies at all – and he was doing it during the German occupation of his home in the Netherlands. Due to interference with established scientific communication channels, Dijkgraaf, Griffin, and Galambos all remained unaware of each other's research until after the war.[22] Remarkably, across the Atlantic, Dijkgraaf used his naked ear to conclude that bats used their own emitted sounds to avoid obstacles in flight. Although he could not hear these inaudible sounds directly, Dijkgraaf learned to trace bat flight patterns through an audible indicator, which he called *Ticklaut,* or ticking sound. Before emitting their ultrasounds, bats emitted a series of rapid successive sonic pulses – ticking sounds – audible to the human ear; when these sounds merged together into a faint buzz, Dijkgraaf called them *Ratterlaut,* or rattling sound. He noticed that *Ticklaut* occurred right before a bat "took off" to fly and immediately preceding a difficult problem of orientation, such as the approach of an obstacle. Griffin compared these "faint audible components" which were often conflated with "the fluttering of the wings" to "the ticking of a lady's wrist watch."[23]

By all accounts, *Ticklaut* was a difficult sound to hear. It was faint and barely audible, straddling the divide between human audibility and inaudibility. Griffin found himself "lost in admiration"[24] with Dijkgraaf's keen sense of hearing paired with acute listening practices, Griffin admitted in 1958 that, at least in the field:

> Perhaps my hearing is less acute, or perhaps low enough ambient noise levels are more common in Europe than in America; but I have very seldom been able to hear the audible clicks or *Ticklaute* [sic] from bats under natural conditions. Occasionally as a bat flies past at close range in a cave or building I can hear its audible clicks, but unless I hold a bat in my hand close to another person's ear I can seldom convince him that the faint spitting or clicking sound does not originate from the fluttering of its wings. Few summer evenings are free enough of the noise of insects or the rustling of leaves to allow me to hear the audible clicks of bats as they fly past unless they almost touch my head, whereas with suitable apparatus the ultrasonic pulses can be detected at 100 feet or more. Sounds so weak as the audible clicks could scarcely generate useful echoes from small obstacles.[25]

Griffin and Galambos published their own findings on the audible click in 1942. Their attempts to *directly* listen to the click unaided were "easily overshadowed or masked by such faint noises as the flutter of a bat's wings in flight, or the scratching of its body as it crawls… Another sound which confuses the pictures is the spitting and biting of the teeth together which our bats often exhibited."[26] Relying on the aid of the Pierce apparatus in addition to their own ears, they concluded that bat supersonics hardly ever occurred in normal bats without the presence of the "click… heard as a buzz or whirr when a flying bat swoops close to an observer's ear." In other words, "the click and the supersonic… always appear together."[27] Whether *Ticklaut* was in fact "a different component of the same physical bundle of sound waves" or an entirely separate sound pulse altogether was a question that occupied Griffin's attention for some time.

The first step of investigating *Ticklaut* was to confirm that Griffin, Galambos, and Dijkgraaf were indeed listening for the same sounds emitted by their bats. The difficulty of repeating the same experiments on echolocation using different listeners, different media technologies, and different species of bats – not to mention in different countries with different laboratories and natural soundscapes – was a major feat. "To satisfy my curiosity in this matter I wonder whether we can, by correspondence, convey to each other the loudness of these audible clicks made by the bats," wrote Griffin to Dijkgraaf in 1945:

> I doubt that you will have access to any physical instruments which would measure this sound in a manner which I could duplicate here, for this is a rather difficult task. Probably we can best use descriptive terms, at least to approximate the level of the bats' cries. I should say that our bats made clicks considerably fainter than the ticking of an ordinary watch, perhaps as quiet as a very high quality watch. If one whispers the consonant 'k' just as faintly as possible without making it unintelligible to another person whose ear is six inches from your mouth, I should think that would also duplicate the loudness of the bat's click as we have heard it. I should be much interested to hear your description of the sounds you have heard from the bats.[28]

Dijkgraaf replied, in turn, and largely confirmed Griffin's descriptions of the intensity of the clicking: "I can hear the sharp clicks easily every time the animal flies towards me or close past me, in this room (5 ½ x 5 ½ m) at a max distance of about 70 cm, in spite of the rather loud street noises penetrating the room… I think the intensity of the sound is of the same order as the ticking of my watch." Dijkgraaf did include a word of caution: "I must admit that I have a fairly strong hearing, as you may see from one of the papers that I'm sending you… I heard a couple of years ago sounds produced by v.Frisch's 'Elritzen' (little fishes), that most people could hardly perceive."[29] Despite a minor discrepancy in concepts of "normal" hearing – Griffin insisted that as far as clinical audiograms could tell, his hearing was in fact average – the two scientists agreed that they were indeed probably hearing the same sounds.

But one important difference remained between the two scientists' conclusions, which threatened to subvert the theory that inaudible sounds guided bat orientation while the audible components were mere byproducts of the supersonic bursts. Dijkgraaf still believed that *Ticklaut*, or the audible click, was the primary means for acoustic orientation, whereas Griffin and Galambos insisted that the "audible click is merely the transients generated by the sharpness of the supersonic pulse."[30] After this exchange, the two scientists turned toward photographic evidence of wave forms (unfortunately, these photographs do not remain in the archival correspondence). Dijkgraaf conceded that "your photographs have convinced me indeed that the bat's cries are entirely supersonic and I can agree with you in assuming that the audible click may be caused by the abrupt beginning or ending of the supersonic cry."[31]

But by 1947, Griffin confessed that he still remained uncertain about the physical properties of the sound wave that Dijkgraaf called *Ticklaut*. "I am still not sure whether the audible click is simply a small asymmetry in the supersonic pulse or a faint low frequency wave occurring just before or just after it."[32] He could not reconcile the audible traces with written ones. In 1949, Griffin wrote to Dijkgraaf about improving his oscilloscope apparatus for seeing the supersonic waves: "I think I can now see in oscilloscope pictures the low frequency components of the bats' pulses of sound. These are very weak compared to the high frequency waves; but there seems always to be at least one or two irregular waves of roughly 10 kilocycles frequency just before the main pulse…. I still have no way of correlating very well the loudness of a pulse to my ears and the picture obtained from the oscillograph."[33] The question remained whether Dijkgraaf was hearing a meaningful audible pulse, separate from the supersonic cries and the audible clicks of Griffin's bats, that helped his bats navigate around obstacles. And, further, were Dijkgraaf and Griffin observing the same or similar *Ticklaut*?

Although Griffin had refined the photographs captured by his cathode-ray oscillograph, a media technology that wrote the bat voices onto paper, by winter of 1950, he was suggesting to Dijkgraaf that this visual evidence was, in fact, not enough to rest his case on the topic of *Ticklaut*. When he showed the oscillograph reproductions of the audible click to an expert who had also visited Dijkgraaf's laboratory, his friend seemed "quite sure that my bats made considerably fainter audible sounds than yours." Even after convincing visual evidence was produced, the question of the level of audibility of *Ticklaut* – which was now an established index of ultrasonic bat pulses – troubled Griffin, who soon found himself asking whether or not Dijkgraaf would mind trading bats, sending them across seas and through customs. "Ideally," he confessed, "we should both exchange bats and let me study yours with my apparatus; but I am afraid bringing or shipping bats into the United States would encounter customs complications because of the strict prohibitions against importing fruit bats from the Old World Tropics." Griffin settled on possibly sending some of his bats with a friend who would bring them by ship to Holland, where Dijkgraaf could examine them in his laboratory and report back after comparing the loudness of *Ticklaut*.[34] On January 27, 1951, Dijkfgraaf's reply put the topic to rest: "thank you very much for the bats… as to the cries I could not find any marked difference between your species and [mine]."[35]

We have seen above with the example of *Ticklaut* that graphic representations of bat voices did not capture the subjective impression of sounds made by listener, and that Griffin struggled to correlate his mechanically-produced visual data with his own listening ear. Further, the example of *Ticklaut* suggests that photographic evidence alone was not sufficient to decipher audible and inaudible components of echolocative pulses. Instead, Griffin and his colleagues who studied bat echolocation relied on a combination of earwork and eyework – as well as acoustic and visual mediation – to decode inaudible bat pulses. In addition, descriptors of hearing, observing, and other embodied registrations became important modes of comparison between experiments, which could not rely on the intrinsic repetition of mechanically processed traces. The automatically derived visual inscriptions of unsound certainly informed theories of echolocation, but they could not stand in for them entirely. Working out the lines between perceptibility and imperceptibility in bats and their acoustic orientation required an assemblage of empirical strategies.

Conclusions

The Rockefeller Archive Center's holdings – including the reports, laboratory notebooks, newspaper clippings, and correspondences contained within the Donald R. Griffin Papers – allow for a reappraisal of the relationship between human ears, media technologies, and animal listeners in the postwar scientific context. I have used Griffin's laboratory-based work on bat echolocation to demonstrate such a reappraisal. I argue that despite the incorporation of mechanical visual and electroacoustic media into Griffin's laboratory protocols, for the purpose of interpreting, measuring, and quantifying high-pitched bats voices, Griffin continued to use unmediated listening techniques in his experiments. He recorded embodied notations of acoustic experience in his laboratory notebooks – scrawling them in the margins of his notebooks or underneath photographs of mechanical inscriptions, qualifying and contextualizing them according to what he heard or did not hear in the laboratory as he watched his bats fly.

At the same time, this analysis takes seriously the various ways in which new arrangements of electroacoustic media were incorporated into experimental protocols, and in fact restructured scientists' perceptions and imperceptions of high-frequency sound waves. Considering the work of fleshy bat sensoria – in their fullest expressions, as emitters and receivers of sounds inaudible to humans – I show that new mediatic configurations never totally replaced animals; they just rearranged them. No longer were the high-pitched squeaks of bats used to describe or estimate thresholds of human audibility – as *the sole* vectors for registering and interpreting inaudible sounds. Instead, bats became essential organic appendages to the mechanization of inaudible sounds, as their voices were translated, written down, and subjected to new proceduralized regimes of quantification – which continued to work in tandem with auditory perceptual work in the experimental context.

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[1] "Science: Bat Sonar," *Time Magazine,* May 1, 1950.

[2] "Memorandum to Mr. Thomas R. Taylor Regarding the Use of Bats and Other Mammals as Vectors of Incendiary Bombs," submitted by Donald Griffin, date unknown, Box 14, Folder 140, Donald R. Griffin Papers, Rockefeller Archive Center (hereafter RAC).

[3] Donald R. Griffin, *Listening in the Dark; the Acoustic Orientation of Bats and Men* (New Haven: Yale University Press, 1958), 84.

[4] Griffin, *Listening in the Dark,* 319.

[5] Lorraine Daston and Peter Galison, *Objectivity* (Cambridge, Mass.: MIT Press, 2007), 314.

[6] Daston and Galison*, Objectivity,* 344.

[7] Sophia Roosth, "Nineteen Hertz and Below: An Infrasonic History of the Twentieth Century," *Resilience: A Journal of the Environmental Humanities* 5, no. 3 (2018): 119.

[8] Robert Williams Wood, *Supersonics, the Science of Inaudible Sounds* (Providence, RI.: Brown University, 1939), 36. Furthermore, Wood observed that if the ultrasonic waves were transmitted through glass rods, "drawn out into a long thread of the diameter of a horsehair… the heat developed… is so great that a groove with seared edges is left in the skin. A week later bright red spots similar in appearance to blood-blisters developed, which did not disappear for several weeks. These were perhaps due to an effusion of blood from capillaries deep down in the skin, which were ruptured by the vibration." Wood, 72-73.

[9] ED Dickson and DL Chadwick, "Observations on Disturbances of Equilibrium and Other Symptoms Induced by Jet-Engine Noise," *J Laryngol Otol.* 65, no. 3 (1951): 154–65. The claim that ultrasound was a harmful (if not lethal) byproduct of mechanical and electrical engineering developments was contested. Responding to an article about "the deadly effect" of airplane noises and supersonic vibrations on small chickens and young foxes, one physicist and aviation expert dashed off a letter to the editor in the *Washington Post* arguing that no matter the toxicity of inaudible waves, they were at the very least evidently survivable. "Nature is replete with supersonic vibrations, inaudible to the human or animal ear," he said, "and the human race, through countless generations, seems to have gallantly withstood the impact of Michelson rays from outer space, atomic bombardment, cardiac pulsations, variable barometric pressure … and a host of other vibrations." See Edwin Fairfax Naulty, "Humanity Has Withstood through the Centuries the Effect of Audible and Inaudible Vibrations -- Invention Will Do Away with Airplane Noises," *The Washington Post (1923-1954)*, June 10, 1929. See also Frank Thone, "Death Rays? No!," *The Science News-Letter* 27, no. 728 (1935): 186–88.

[10] John Shiga, "Sonar: Empire, Media, and the Politics of Underwater Sound," *Canadian Journal of Communication* 38, no. 3 (September 14, 2013), 358.
[11] Shiga, "Sonar," 374.
[12] Donald R. Griffin, *Listening in the Dark; The Acoustic Orientation of Bats and Men* (New Haven: Yale University Press, 1958).
[13] Donald R. Griffin, *Listening in the Dark: The Acoustic Orientation of Bats and Men* (New Haven: Yale University Press, 1958), 67. You can listen to the transposition of these bat cries – from inaudible pulse to audible beat – in archival footage recorded in Cambridge, Massachusetts in 1940. The footage was made into a short video clip by neuroscientist Bradley Voytek and overlayed with narration by Robert Galambos. See Bradley Voytek, "Robert Galambos – History of Bat Echolocation," Youtube, published May 31, 2011, accessed January 3, 2021, https://www.youtube.com/watch?v=Qdu4bSVazco.
[14] Donald R. Griffin and Robert Galambos, "The Sensory Basis of Obstacle Avoidance by Flying Bats," *Journal of Experimental Zoology* 86, no. 3 (1941): 481–506.
[15] Griffin and Galambos, "The Sensory Basis of Obstacle Avoidance by Flying Bats," *Journal of Experimental Zoology* 86, no. 3 (April 1941): 484.
[16] Lab Book 1: Dec 7, 1944 - March 23, 1946, Notebook Entry p. 36, Box 16, Folder 152, Donald R. Griffin Papers, RAC.
[17] Letter from Donald Griffin to Robert Galambos, Aug. 15, 1944, Box 4, Folder 31, Donald R. Griffin Papers, RAC.
[18] Lab Book 4: 7 Dec 1948 – July 1949, Notebook Entry December 23, 1948, Page 47, Box 16, Folder 155, Donald R. Griffin Papers, RAC.
[19] Letter to Sven Dijkgraaf from Donald R. Griffin, March 18, 1946, Box 3, Folder 20, Donald R. Griffin Papers, RAC.
[20] Letter to Sven Dijkgraaf from Donald R. Griffin, March 18, 1946, Box 3, Folder 20, Donald R. Griffin Papers, RAC.
[21] Cultures of listening, in this case, refer to a wide array of what Karin Bijsterveld has called "sonic skills," which include "not only listening skills, but also the techniques that doctors, engineers, and scientists need for what they consider an effective use of their listening and recording equipment." Bijsterveld argues that "to understand listening for knowledge, therefore, we need to study not only the skills related to listening proper, but also those that ensure sounds can be amplified, captured, reproduced, edited, compiled, accessed, and analyzed." Karin Bijsterveld, "Listening for Knowledge: Introduction," in *Sonic Skills: Listening for Knowledge in Science, Medicine and Engineering (1920s-Present)*, ed. Karin Bijsterveld (London: Palgrave Macmillan UK, 2019), 1–28.
[22] "Dear Dr. Griffin and Dr. Galambos," wrote Dijkgraaf in July 1945, "After the Germans had occupied our country[,] we did not receive any more American journals. So I was completely unaware of your excellent work on obstacle avoidance in flying bats, when I started some years ago a series of experiments in order to solve this old problem. I took special interest in it since I studied the mechanisms of obstacle perception in blinded fishes.... In the following time I have studied especially 1. Object perception by means of what I called the 'rattling sound' in not-flying bats, including object discrimination; 2. The part played by the rattle-mechanism and other sense organs in the behavior of bats (perception of food, orientation in space etc.)." Letter To Donald Griffin and Robert Galambos from Sven Dijkgraaf, July 30, 1945, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[23] Griffin, *Echoes of Bats and Men,* 30.

[24] Griffin wrote to Dijkgraaf on September 26, 1945: "I am lost in admiration at the manner in which you solved this problem without the aid of apparatus to assist you in the detection of the bats' cries, or better their clicks or ratting sounds." Letter to Sven Dijkgraaf from Donald R. Griffin, Sep 26, 1945, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[25] Griffin, *Listening in the Dark: The Acoustic Orientation of Bats and Men,* 76.

[26] Letter to Sven Dijkgraaf from Donald R. Griffin, Sep 26, 1945, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[27] Galambos and Griffin, "Obstacle Avoidance by Flying Bats: The Cries of Bats," 477; 480.

[28] Letter to Sven Dijkgraaf from Donald R. Griffin, Sep 26, 1945, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[29] Letter to Donald Griffin and Robert Galambos from Sven Dijkgraaf, July 30, 1945, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[30] Letter to Sven Dijkgraaf from Donald R. Griffin, March 18, 1946, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[31] Letter to Donald Griffin from Sven Dijkgraaf, May 10, 1946, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[32] Letter to Franz P. Mohres from Donald R. Griffin, December 30, 1947, Box 8, Folder 79, Donald R. Griffin Papers, RAC.

[33] Letter to Sven Dijkgraaf from Donald R. Griffin, July 21, 1949, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[34] Letter to Sven Dijkgraaf from Donald R. Griffin, Nov 15, 1950, Box 3, Folder 20, Donald R. Griffin Papers, RAC.

[35] Letter to Donald Griffin from Sven Dijkgraaf, Jan 27, 1951, Box 3, Folder 20, Donald R. Griffin Papers, RAC.