Hearing Aids and the History of Electronics Miniaturization

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Electrical hearing aids were the principal site for component miniaturization and compact assembly before World War II. After the war, hearing aid users became the first consumer market for printed circuits, transistors, and integrated circuits. Due to the stigmatization of hearing loss, users generally demanded small or invisible devices. In addition to being early adopters, deaf and hard of hearing people were often the inventors, retailers, and manufacturers of miniaturized electronics.

In the April 1965 issue of *Electronics*, Gordon Moore announced an exponential increase in the number of components that could be "crammed" onto integrated circuits (ICs). This ongoing small-scale process, he predicted, would result in a corresponding acceleration of technological breakthroughs in computing, medicine, and communications. "The object," Moore explained, is "to miniaturize electronics equipment to include increasingly complex electronic functions in limited space with minimum weight."[1] Smaller parts meant smaller equipment as well as the promise of increased reliability and processing speed. Moore's law famously became a self-fulfilling prophecy, a prescription for his company (Intel) and the rest of the microelectronics industry to double the number of components on a single chip every one to two years.[2]

Although Moore dated miniaturization to the development of integrated electronics in the 1950s, other engineers and historians have located the origins of the phenomenon in discrete components. In *Crystal Fire: The Invention of the Transistor and the Birth of the Information Age*, Michael Riordan and Lillian Hoddeson track what they call the "relentless progress of miniaturization" following the 1948 invention of the transistor.[3] To the contrary, Eric Hintz claims that the "button" mercury battery preceded the transistor and "was just as important, if not more so, for the progress of miniaturization."[4] In 1961, James Nall of Fairchild Semiconductor insisted that "printed electronic circuits and subminiature tubes encouraged our modern day electronic revolution"—he defined miniaturization as "a media in which there is a high degree of order and efficiency."[5] That same year, George Senn and Rudolph Riehs of the US Army agreed that "the philosophy of miniaturization" took hold during World War II, as subminiature vacuum tubes began to be adopted for a range of devices.[6]

In fact, the language and ideals of miniaturization can be traced to the first decade of the 20th century, just prior to the development of electronics. In philosophy and literary studies, Gaston Bachelard and Susan Stewart describe the *miniature* as a universal aesthetic and perceptual category, characterized by cuteness and charm, manipulability and control.[7] Doubtless, electronic miniaturization shares some of these qualities; however, it is historically framed by the modern industrial ideals of efficiency, rationalization, mechanical reproduction, mobility, individualism (and the rising interest in "personal" technology), and global communication.[8] And as Nall indicates, the phenomenon cannot be understood by looking at discrete components; it is a theory of infrastructure for electronic media. The interconnections between components have been miniaturized in conjunction with the components themselves; the steady increase in circuit complexity was always tied to new methods for compact assembly.[9]

Today, Moore's law is frequently reduced to the "prediction that the speed of computers will double every year or two."[10] Processing speed—due to number of transistors and their proximity to one another—was a

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relative latecomer to the ''philosophy of miniaturization,'' which slowly accumulated features, starting with small size, and eventually including density, ruggedness, reliability, reduced power requirements and decreased production costs. In 1965, moreover, Moore had anticipated transformations across electronics quite broadly, from computing to telephone systems to radar.

''Personal portable communications equipment''—one of Moore's forecasts—predates computing and in many respects facilitated the emergence of microelectronics.[11] The hearing aid—the first such ''personal portable'' device—was a key site for component innovation during the first half of the 20th century. Many histories of microelectronics emphasize military demand beginning in World War II.[12] Yet as Michael Brian Schiffer has demonstrated, the interwar consumer market for portable radios fed components into military communications.[13] ''Only the hearing aid''—which began to be miniaturized as early as 1900—''drove miniaturization harder''[14] (see Figure 1). In the opening decades of the 20th century, subminiature vacuum tubes originated in the hearing aid industry, as did strategies for compact assembly and the ''wearability'' of electronic devices.

Ross Bassett has described Moore's law as ''technological trajectory,'' a focusing mechanism that ''took advantage of an existing technological base and developed with relentless incrementalism.''[15] Hearing aids were critical to the establishment of this base. Before the personal computer or other personal electronics were obvious commodities—and before reliable production techniques had made miniaturization economical—hearing aids incubated the technique and the ''philosophy'' of miniaturization.[16] Hearing aids were always ''personal''—tools for daily life that were carried on the body and intimate to an individual user.

During World War II, Handie-Talkies and other lightweight electronics equipment for military use became crucial to component miniaturization (although they arguably did not require the drastic size reduction demanded by hearing aid users). Technologies developed during the war—such as the button battery and printed circuit—later made their first commercial appearances in hearing aids, as would the transistor and IC. With its relatively simple circuitry, the postwar hearing aid served as a testbed for mass production techniques, component

Figure 1. ''Trumpet to Transist-Ear.'' Maico advertised hearing aid miniaturization as continuous and progressive. (Courtesy of the Kenneth Berger Hearing Aid Museum and Archives)

longevity, and consumer interest in miniaturized products.[17] It also served as a standard of reference for other industries interested in miniaturization.[18]

New components could be introduced to this ''luxury'' consumer product with little regard to increases in cost. Although demographic trends (and methods) have varied across the 20th century, today the National Institute on Deafness and other Communication Disorders (NIDCD) maintains that nearly 30 million Americans have either permanent hearing loss or deafness.[19] This broad statistic includes members of Deaf culture who use sign language as well as hard of hearing individuals who experience their hearing loss as an impairment. Approximately one in five wears a hearing aid—a fact attributable to personal preference, device performance, social stigma, and cost.[20] Throughout the 20th and 21st centuries, hearing aids have only rarely been covered by health insurance. Lack of regulation, outright corruption, and the willingness of well-off (or occasionally desperate) customers have led to persistent overpricing of these devices.[21]

Beyond portability, the predominant trend in hearing aid design has always been invisibility, which propelled extreme miniaturization of components and assembly, even in the absence of immediate functional or economic gains.[22] The paradox of hearing aids is that they are designed to rehabilitate an invisible impairment, yet the devices themselves visibly mark and even socially disable their wearers. Although hearing aid users did not always demand miniaturized components outright, the longstanding "cultural imperative" of an in-the-ear or otherwise undetectable device motivated innovation in the early 20th century and, later, made hearing aids a ready site for the refinement of materials developed in scientific or military contexts.[23]

William Aspray and Martin Campbell-Kelly have demonstrated that in the 1950s and 1960s, when electronics and computing were separate industries, "computers appropriated the new electronics technologies as they became available."[24] Transistors were initially used within computers as substitutes for hot, fragile vacuum tubes. However, electronics and computing truly converged in the 1970s with the development of the microprocessor. With the IC thus transformed into a programmable "computer on a chip," hearing aids no longer remained at the fore of miniaturization. For one thing, the microprocessor was more than just a revamped vacuum tube; new algorithms for speech processing had to be devised to make use of this technology.[25] In this case, more importantly, the imperative for invisible aids undermined early adoption—Moore's law held true for ICs, but the first digital hearing aids themselves were many times larger than analog models.

The long history of miniaturization calls into question its "relentless progress"—the notion that technical changes in electronics are somehow autonomous or continuous. The exponential line of Moore's law is often extrapolated from microprocessors to devices and used to predict accelerating, technology-induced changes in human capabilities and social norms. Size reduction has been the overall trend in communications equipment, but it never held to a straight course. For the case of hearing aids, stronger amplifiers sometimes entailed an increase in component or circuit size, and different models of mechanical, electric, and electronic devices coexisted rather than cleanly succeeding one another. Consumers have always been forced to weigh trade-offs among cost, function, size, and style.

More importantly, although the enduring stigmatization of deafness often led to unhappy relationships between individuals and their prosthetics—and sometimes to fraudulence in the hearing aid field—it did not necessarily result in passivity or dependence. Deaf and hard of hearing people played shaping roles as early adopters, inventors, retailers, and manufacturers of miniaturized components—even though advertisements and the popular press have historically portrayed "the deaf" as patients, "guinea pigs," recipients of charity, or hapless consumers of technology. Even in the vast literature on "users" in technology studies over the past 30 years, people with disabilities have only rarely been ascribed the competence or the relevance to figure centrally in narratives of technological change.[26]

Concealed Trumpets and Tubes

The first dedicated hearing aid firm, Frederick Rein of London, began to manufacture ear trumpets, hearing fans, and conversation tubes in 1800.[27] Trumpets and tubes "amplified" by collecting and concentrating sound waves that would otherwise disperse. As such, their design was an ongoing compromise between amplification and portability—the longer the trumpet and the wider its bell, the greater the magnification of sound.

In Europe and the US, the number of hearing aid firms increased at the end of the 19th century, matched by a rising emphasis on concealment.[28] Age-related hearing loss was, at the same time, becoming pathologized due to new audiometric techniques. Moreover, in 1880 the International Congress of Milan endorsed oralism as the most effective pedagogical strategy for deaf schools—a censure of sign language, which amounted to a vote against deafness in all its forms. More broadly, the emerging ideals of mechanized communication and rationalized design dictated the treatment of hearing loss with unobtrusive technical aids.[29] Finally, as argued by many disability historians, urbanization and the growth of the middle class encouraged 19th-century individuals to take advantage of anonymity and manage their self-presentations. For people with disabilities in particular, becoming "unremarkable" was an aid to social mobility.[30]

Beyond portability or wearability, then, invisibility was established as the design standard for hearing aids. Trumpets, tubes, and other mechanical hearing devices might be disguised as clothing, accessories, or furniture. In the last quarter of the century, "inserts," "invisibles," and artificial eardrums became tremendously popular, despite their limited efficacy. Cathy Sarli and a team of researchers from the Central Institute for the Deaf recently measured the gain from a range of 19th-century instruments; they concluded that "the majority of the population wanted and would pay for increasingly inconspicuous devices even if they were of little benefit to their hearing.''[31]

Micro-Telephones

The transition to electroacoustics began with the invention of the telephone, the first device to convert a perceptible wave phenomenon into electrical form and back again. The earliest electrical hearing aids were ''small telephone systems,'' as Harvey Fletcher of American Telephone & Telegraph (AT&T) explained to members of the American Society for the Hard of Hearing during a lecture in 1936.[32] Telephone technology would vastly increase the number of ways and the precision with which an acoustic signal could be manipulated. Control over loudness, frequency, or distortion entailed a multiplication of the components in a hearing aid circuit. Thus, electrical hearing aids exhibited the familiar tension between amplification and wearability, to which was added the question of compact assembly.[33]

Immediately after Alexander Graham Bell filed his patent in 1876, a myth surfaced: the telephone was little more than a hearing aid, invented by Bell for his wife or his mother.[34] The telephone was, in fact, almost immediately converted into a ''deaf aid.'' Some found that their hearing was improved over the telephone, as compared with direct conversation. A variety of personal experiments ensued. J.C. Chester, a hard of hearing man from Montana, made the newspapers for attaching a telephone to a dry battery, wrapping its wires around his waist, and carrying it about with him, receiver-to-ear. The *Buffalo Times* reported—in 1897, before any similar portable technologies were available—''It looks peculiar, but it does not hurt.''[35]

By 1882, Dr. James Alexander Campbell of St. Louis, Missouri, included the phone alongside his list of mechanical ''helps to hear'' because, he theorized, ''it extends the ordinary range of hearing so marvelously.''[36] Hoping to learn of new adaptations of telephone technology, Campbell sent an inquiry to Thomas Edison, who had attributed his recent invention of the carbon transmitter to his own hearing loss. ''When Bell first worked out his telephone idea,'' Edison explained,

> I tried it and the sound which came in through the instrument was so weak I couldn't hear it. I started to develop it and kept on until the sounds were audible to me. I sold my improvement, the carbon transmitter, to the Western Union and they sold it to Bell. It made the telephone successful. If I had not been deaf it is possible and even probable that this improvement would not have been made. The telephone as we now know it might have been delayed if a deaf electrician had not undertaken the job of making it a practical thing.[37]

Figure 2. Frederick Alt's Micro-Telephone (1900). This hearing aid looked too much like a telephone for most users. (Courtesy of Becker Medical Library, Washington University School of Medicine)

The carbon transmitter worked as an amplifier, using a weak speech signal to vary a larger electrical current. As such, it eventually became the basis for long-distance telephone repeaters and hearing aids. However, when Edison replied to Campbell in early 1881, he admitted that he had ''tried a great many experiments in the line you speak of; none have been sufficiently satisfactory as to make a commercial introduction.''[38]

In 1898, Miller Reese Hutchison used a carbon transmitter to build a portable amplifier for a college friend. This resulted in the *akouphone*, the first dedicated electric hearing aid—and one of the first ''mobile'' phones. There was a constant traffic between hearing aids and the broad field of electroacoustics. Hutchison, who became chief engineer of Edison Laboratories, employed long wires to install one of his later hearing aid models (the Acousticon) as an intercom in the House of Representatives.[39]

Frederick Alt, working at Adam Politzer's otology clinic in Vienna in 1900, assembled another early hearing aid for his patients. Named the Micro-Telephone, it was made up of a simple circuit: a battery, a smaller carbon transmitter, and an earphone receiver or two (see Figure 2). It still looked like a telephone, however. For most users, this was a drawback in the years before "personal technology" became a conceptual given.

Frances Warfield, a regular contributor to the *New Yorker* and a member of the New York League for the Hard of Hearing, wrote two influential memoirs about her hearing loss and reluctance to wear a carbon-transmitter aid in the first decades of the 20th century. The New York League was founded as an advocacy group by former students of the Nitchie School of Lip-reading in 1909, and its members soon began pressuring AT&T to build electronic audiometers and hearing aids.[40] Nevertheless, Warfield did not want to look like "a walking telephone." Her boyfriend thought telephones were "noisy and unsightly"—so much so that he hid his living room phone within a cabinet.[41]

Warfield's family friend, Aunt Mary, had encountered a great deal of discrimination while carrying her enigmatic "black box," owing to a prevalent apprehension of electrified technologies:

> The first "black box" portable, about 1910, she recalled, had weighed about seven pounds...Made people stare and point and ask impertinent questions. Once, during World War I, on a vacation trip to Atlantic City, she'd been arrested as she strolled on the boardwalk, on suspicion of being an enemy spy; the Shore Patrol thought her black box must contain a wireless set.[42]

And yet, as Warfield explained, Aunt Mary's living room was a virtual museum of hearing aids. Her combination of desire and dissatisfaction made her the ideal consumer—committed to the technology, while always willing to upgrade.

Aunt Mary also warned Warfield that stigma attached to the companions of a hearing aid wearer—"people don't like to be seen with a deaf person. Makes 'em feel too conspicuous."[43] When sociologist Erving Goffman developed his elaborate theory of stigma in the 1960s, he drew heavily on Warfield's memoirs. He defined stigma as "an attribute that is deeply discrediting." Extrapolating from the case of hearing impairment to all possible attributes, he noted that a stigma "interferes directly with the etiquette and mechanics of communication."[44] Based on Warfield's anecdotes, Goffman argued that assistive technologies—such as hearing aids—tended to become "stigma symbols," themselves discrediting.[45]

Rosemarie Garland Thomson has remarked upon the tremendous power of these symbols, which are often the most tangible manifestations of stigma, to generate secondary injuries. "Hearing impairments corrected with mechanical aids are usually socially disabling, even though they entail almost no physical dysfunction."[46] Thus, those who wear aids have generally chosen to "cover" or minimize their impairment by choosing ever-smaller or less-conspicuous devices.

Although electrical aids had the distinct advantage of providing greater amplification per size, as compared to mechanical models, they were still too eye-catching for people like Warfield.[47] Electrical hearing aid companies responded by making earphone receivers smaller so as to be worn on headbands, rather than held up to the ear. Beginning in 1925, Western Electric sold "midget" eartip receivers, made from lightweight Permalloy.[48] By the late 1920s, Hearing Devices Corporation marketed in-the-ear "Tom Thumb Earpieces" with their Audiphone. According to Michael Brian Schiffer, these types of insertable "ear plug" receivers "were first widely used in hearing aids."[49] Microphone transmitters also continued to shrink in size and were soon lightweight enough to be clipped to clothing. Some carbon aids were built into purses and shopping bags, or disguised as other new technologies, such as cameras.

Personal Electronics, Circa 1920

Even as the first electrical hearing aids were being developed, the "age of electronics" had already begun. Electrical experimenters noticed early on that the filament of Thomas Edison's light bulb gave off electrons when heated. By building a network of wires and metal plates around it, they were eventually able to harness the behavior of those electrons and modulate them with other electrical signals. John Ambrose Fleming, who worked with Thomas Edison, was one of the first to turn a light bulb into a "valve" for controlling the flow of electrical current. Stuart Bennett has attributed Fleming's invention to the man's hearing loss; he explained that in 1904 "Fleming was becoming slightly deaf and was therefore beginning to look for a means of visually detecting the receipt of radio signals."[50]

In 1908, Lee De Forest patented a triode tube, with three electrodes, to modulate electron flow; it even amplified weak electrical signals with comparatively little distortion.[51] Variations on these vacuum tubes, as they became known, eventually made long-distance telephony and wireless speech transmission possible (and later, other forms of radio). Vacuum tubes would also serve as switches in the telephone network and in early digital computers. The loudness and clarity of tube-based electroacoustic devices led to a boom in portable and other consumer technologies. At the same time, vacuum tubes were accompanied by their own set of problems, which applied renewed pressure to the issue of miniaturized components and interconnections. Tubes were relatively fragile, they took time to warm up, and they gave off an uncomfortable amount of heat. When incorporated into portable technologies, their power requirements meant too-frequent battery changes. Finally, as part of the growing ability to process signals, tubes entered into complex circuits that were increasingly difficult to construct and repair.

Naval engineer Earl Hanson patented the first vacuum-tube hearing aid, the Vactuphone, in 1920, motivated by his mother's deafness.[52] Globe of Boston sponsored his research and contracted Western Electric (the manufacturing branch of AT&T) to mass produce the seven-pound device. The Vactuphone used a telephone transmitter to transform speech into an analogous electrical signal, which then modulated a larger current of electrons in the vacuum tube. This amplified signal was converted into louder speech at the receiver. Globe advertised the Vactuphone as a gateway to an unprecedented world of sound: "Listen to distortionless speech and hear sounds that even normal and healthy ears have not heard since the world began."[53]

Prompted by Alfred DuPont's request for an amplifier, AT&T commenced its own hearing aid development program in 1922.[54] Bell engineers came up with a "binaural" set for DuPont, having two separate transmitters and two receivers. This hearing aid became the basis for the Western Electric Audiphone, their first commercial device, which at 220 pounds and $5,000 reached a very small market (see Figure 3). The immensity of the Audiphone was due to the quantity and size of its vacuum tubes, as well as its circuit of additional components. Electronic hearing aids increasingly manipulated signals. They included, for instance, rheostats and resistors for volume and feedback control, and electrical filters for selecting out particular frequencies—to tailor amplification to a particular audiogram.

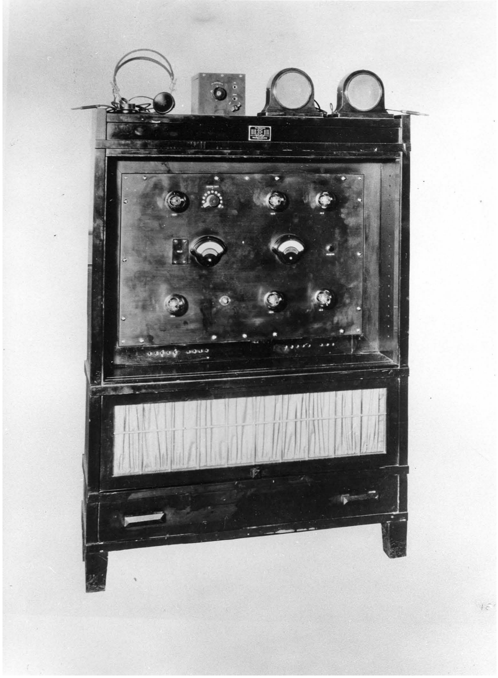

Figure 3. Western Electric's first commercial hearing aid, the 10-A Audiphone (1923). The Audiphone weighed 220 pounds and cost $5,000. (Courtesy of AT&T Archives and History Center)

Within a year, Western Electric condensed this apparatus down to 35 pounds, including batteries for the first time. One's hearing could then be transported in what looked like a small suitcase. During World War I, the firm had developed smaller vacuum tubes for Army "trench sets." These tubes were designed to decrease battery requirements in the field, not to miniaturize portable wireless equipment, which remained fairly bulky—often transported by mule or by truck.[55] Commercially, this research yielded the "peanut" amplifier in 1919 (also known as the midget, miniature, or minimized tube).[56] By the end of 1924, Western Electric incorporated a version of the peanut tube suitable for speech amplification into a seven-pound Audiphone, which also required fewer batteries (see Figure 4).[57]

The clarity of vacuum tube sound reproduction, the tubes' ability to provide up to 70 decibels of amplification (as opposed to the 15 decibels of most carbon aids), the reputability of manufacturers such as

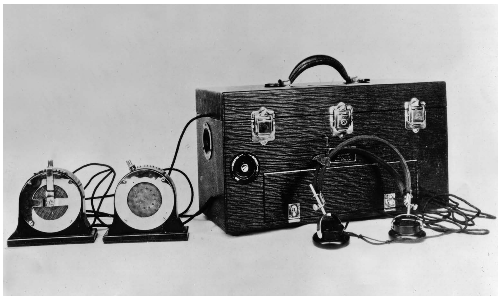

Figure 4. The WE 24-A Audiphone (1924). One of Western Electric's first portable models. (Courtesy of Kenneth Berger Hearing Aid Museum and Archives)

Figure 5. "Wearable" Sonotone vacuum tube hearing aid. The advertisement glamorizes product concealment. (Courtesy of Kenneth Berger Hearing Aid Museum and Archives)

Western Electric, and the influence of hard of hearing activism attracted a widening array of customers in the 1920s and 1930s, including many who would not have otherwise considered wearing a hearing aid.[58] This technological expansion, moreover, affected the classification of deafness. In a stark example of "the co-construction of users and technologies," Michael Reis has linked the availability of strong, portable and wearable hearing aids to the diminishing populations at deaf schools in the 1930s, as newly "hard of hearing" students used technology to "mainstream."[59]

Anthropologist Ruth Benedict wrote in her diary in 1926 about ordering a vacuum tube aid to use during Franz Boas' lectures at Columbia: "Got earphone from Western Electric for trial and didn't have nerve to take it out in class!"[60] She returned it the next day. For many users, the desire for a powerful aid was still checked by dissatisfaction with conspicuous devices. Those who did adopt these early vacuum tube aids described them as at once assisting and interfering with social affairs. Poet and essayist Persis Vose, who personified her aid into the good-tempered "hearing assistant" Algy, admitted that the two of them were as often the objects of mean and thoughtless jibes as pleasant inquiries.[61]

Wearable Technology

Vacuum-tube hearing aids gradually became more popular in the 1930s, with the advent of wearable models. These multipack aids distributed the amplification circuit about the user's body: batteries were carried in a pocket or strapped to the leg, microphones with amplifiers were hidden elsewhere beneath the clothing, and all this equipment was connected by thin wires to a tiny earpiece (see Figure 5). The "hidden" microphones meant that sounds were muffled by clothing, which itself added rubbing noises. Usually fastened at chest level, these microphones gathered speech from an unusually low auditory perspective. There was constant demand for in-the-ear microphone-receiver combinations, a variation on 19th-century "inserts" and "invisibles." This cultural imperative would not be met until after World War II, when circuitry, amplifiers, and batteries were further miniaturized.

Marie Hays Heiner, member of the Cleveland League for the Hard of Hearing, described her initial response to a multipack aid in her memoir *Hearing is Believing*:

> How could this contrivance ever underwrite a human function? The first time I put it on I felt deformed. Here, to my twisted thinking, was the outward evidence of my physical lack. Could I bear to advertise it to the whole world?[62]

She purchased it anyway, drawn by things like the sound of rain, the squeaking of her theater seat, and the voices in the new sound films.

Heiner eventually incorporated her hearing aid into her fashion, and even glamorized its concealment in her writing. Once, at a party, another hard of hearing woman asked her how she wore it. They withdrew into a bedroom together, and Heiner began ''uncovering and revealing'' her hearing aid—''the batteries fastened like a garter,'' the microphone tucked under the ruffles of her blouse, ''the tiny wire covering a scant space of bare neck before it was lost in my hair along with the sound conducting medium.''[63] (Her acquaintance, who apparently was not moved, concluded, ''Well, I'm not ashamed of my hearing aid.'')

Manufacturers similarly labored to overcome negative stereotypes of hearing aid use while maintaining an emphasis on concealment. Thus, many advertisements featured alluring women with electronics components hidden among their undergarments.

Even Frances Warfied eventually consented to wear a hearing aid, despite its dreaded visibility, convinced by the sound quality from vacuum tubes:

> A Nitchie School acquaintance whom I ran into at Schrafft's in 1938 had just gotten this latest model; she told me she sewed her batteries in the hem of her skirt. I could see that her hemline was whopper-jawed; the batteries must have weighed half a ton. She felt like a new woman, she said; this vacuum tube aid was so clear and quiet that it made the old carbon model seem like amplified bedlam. She was enmeshed in a web of dangling black wires and cords, and from her ear jutted the hearing-aid receiver, like a big black widow spider. But she was beaming and seemed to hear awfully well.[64]

Threatening and unfeminine, each component of this hearing aid was still too large—and too mechanized. The amplifier and an extra battery made these aids more bulky than their carbon counterparts. In the office of the hearing aid dealer, at last, Warfield decided to purchase the smallest possible aid—a carbon model—even though it was noisy and weak.[65] All in all, vacuum tube sound was unquestionably superior, but as late as 1939, AT&T engineers predicted that carbon makes would continue to lead in sales based on size alone.[66] (For this reason, Western Electric had begun to manufacture carbon aids in 1926, after launching several vacuum tube models.) Vacuum tube aids were also more expensive, and tubes went dead without warning and became hot after long periods of use.

Smaller wearable aids were eventually made possible by the development of ''subminiature'' vacuum tubes by Norman Krim of Raytheon. Krim, a former student of Vannevar Bush, was assigned to research new outlets for even smaller tubes in 1937. With the keys to the Massachusetts Institute of Technology library, Krim pored over the electronics journals every evening after work. At the end of a week, he came to the conclusion that hearing aids were the perfect market; the hard of hearing population numbered in the millions, and women seemed to detest wearing the heavy microphone-amplifiers and strapping battery packs to their legs.[67] If a tiny, efficient tube requiring fewer or smaller batteries could be produced, the profits would be enormous. By 1938, his team at Raytheon announced a new line of subminiature tubes, and it rapidly won them 95% of the hearing aid manufacturers.

Compact Assembly

The shrinking of amplifiers and their power requirements formed just one aspect of the hearing aid's overall miniaturization. Manufacturers also looked for ways to space components as closely together as possible and eliminate superfluous connecting wires. In the hearing aid industry, every fraction of an inch seemed to carry an enormous marketing advantage. For at least 50 years, telephone engineers (and inventors in other fields) had proposed replacing wires with patterns of stenciled metallic ink or etched metal.[68] During World War II, Paul Eisler, an Austrian refugee and engineer in London, established a technique for printing and mounting components on a single board, by using a lithograph machine to stamp interconnections on a piece of foil. Printed circuits were smaller and sturdier than assorted

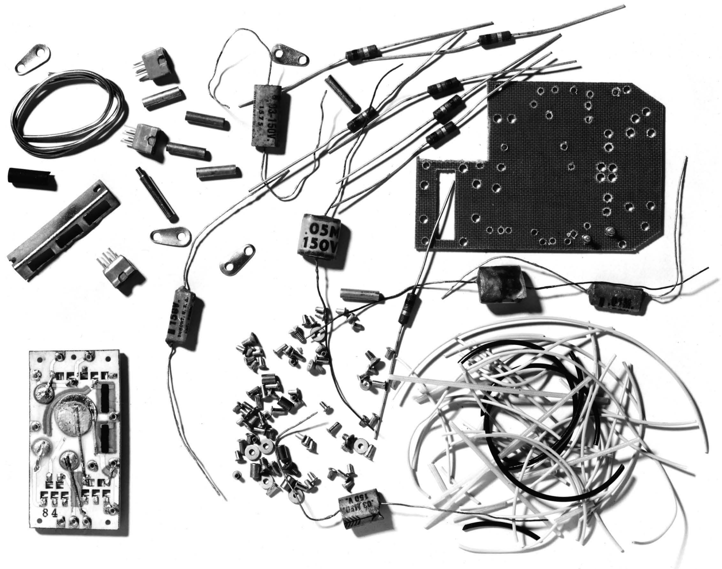

Figure 6. Solo-pak hearing aid printed circuit (left lower corner), compared to previous hard wires and discrete components. (Courtesy of Kenneth Berger Hearing Aid Museum and Archives)

wire connections. Moreover, mechanizing the assembly of circuits was likely to increase productivity and reliability.

Eisler began working as an engineer for Odeon Theatres in 1936. He had previously invented a method of graphical sound recording that was never put to use, and the possibilities for inscription continued to preoccupy him. In formulating his circuit board, Eisler's primary analogy was the printed book:

> My idea was that the printed circuit technique should be able to bring this network into existence as one integral structure, more or less simultaneously, in the manner of the inscriptions on a printed page or in the manner of a number of superimposed pages, as in a brochure. Even those elements which could not be printed by it, whether because they were irreducible to print or because their specifications were not fully understood, might at least be assembled into the rest of the printed network to some advantage.[69]

Unable to find an electronics firm willing to sponsor his project, Eisler turned instead to Henderson & Spalding, one of the oldest lithographers in England. They hired him to fix their Technograph (a "music typewriter"), and he was allowed to use the offset-lithography press for his own experiments. Substituting a sheet of foil for traditional paper, Eisler successfully printed the connections between the elements of a simple radio circuit. Eisler believed that, ultimately, components could be printed along with their connections, and a circuit could be formed from stacks of double-sided, interconnected layers.

US scientists immediately developed his idea for military radios. An adaptation of the printed circuit idea was also applied to the *proximity fuze*, a detonator in the nose of projectiles that automatically triggered an explosion when it sensed proximity to a target. Printed circuits proved to be small, moisture resistant, and unaffected by rough movements. Proximity fuzes were powered by subminiature vacuum tubes; Percy Spencer of Raytheon claimed that he was inspired to invent the fuze after using a "hearing aid tube" to build a model airplane for his son.[70]

The Centralab branch of Globe Union assembled printed circuits for the US military. After the war, they immediately switched to commercial manufacture for hearing aid companies. Joseph Knouse, who had directed the production of vacuum tubes for proximity fuzes, became head engineer of the hearing aid firm Allen-Howe.[71] He sent specifications to Centralab for printed circuitry to replace the 173 separate items (and 65 soldered connections) that comprised the modern hearing aid (See Figure 6). In this case, most of the "wires" were silk-screened with silver or carbon ink, and resistors were sprayed on through a stencil (using metallic paint), but condensers, batteries, and tubes were mounted by hand.

What became known as "the hearing aid approach" for working with microelectronic components served as an early model for other industries, which in turn developed new techniques for printed circuitry.[72] As one example, the US Army's Diamond Ordnance Fuze Laboratory (DOFL) launched its microelectronics program by exploiting the hearing aid approach to miniaturization. DOFL engineers later switched to what they called "microminiaturization," with the production of a "microtransistor" and the use of photolithography.[73]

Allen-Howe's new hearing aid, the Solo-pak, was as small as a cigarette case. Allen-Howe designed the aid to have 48 possible settings: three different types of receiver, controls for volume and frequency, and different "strengths" of vacuum tubes. Although it was advertised as "easy to repair" by simply replacing the circuit wafer, the possibilities for tinkering by individual users were greatly

Figure 7. Advertisement for the Solo-pak printed circuit hearing aid. "Proved in battles across the world." (Courtesy of Kenneth Berger Hearing Aid Museum and Archives)

reduced.[74] This would become an ongoing paradox for "personal" electronics—devices that allowed a preset range of customization, but were no longer easily reconfigured at the hardware level.

In January 1948, *Radio-Craft* reported:

> The hearing-aid field is obviously a "natural" for the printed circuit. Its inherent advantages are especially applicable to that instrument. But it will not be long before the printed circuit makes its appearance in other equipment, where either ruggedness under rough usage, or vibration, compactness, or trouble-free operation are important.[75]

Hearing aid users had long since established many of these parameters for portable electronics. Nevertheless, Allen-Howe's advertisements portrayed the hearing aid as entirely derivative, drumming up altruism and redemption with their slogans for the Solo-pak: "You're the Target!" "First Peacetime Use!" and "Science turns deadly weapon into aid to deaf" (see Figure 7). Here, disability functioned to rehabilitate military equipment, and the local treatment of hearing loss served as a metonym for a more general postwar restoration. Yet certain components of the proximity fuze, such as subminiature vacuum tubes, were in fact indebted to the hearing aid industry.[76] In these advertisements, toughness and heroism are attributes to be granted by technology.

Other firms followed Allen-Howe with printed-circuit devices of their own. As in the past, the miniaturization process was linked conceptually to disability, namely through the figure of the "midget." Advertisements for new "Midget Instruments" capitalized on the noteworthiness of disability, while distancing it from deafness (see Figure 8). In what disability theorist Rosemarie Garland Thomson singles out as an exotifying visual rhetoric, "the hyperbole and stigma traditionally associated with disability" was used to generate a "new and arresting image" for advertisers.[77] The particular novelty of the "midget" is nonthreatening: as Thomson explains, this "miniature" is charming, it "delights and titillates," and it "invites stewardship and appropriation."[78]

In this manner, when Solo-pak adopted P.R. Mallory's "button" batteries, Allen-Howe renamed them "midgets." Acousticon likewise advertised their B batteries in 1946 as "Tom Thumbs." And in an article cutely titled "Midget Electronics," *The Wall Street Journal* announced "another industrial era—electronics miniaturization" on 3 December 1947.


June 1948
in by Bate

Local Dealer . . . CLARENCE B. PLACE, GENERAL MANAGER of the AUDIPHONE COMPANY of WESTERN STATES . . .

is shown holding one of the new UNEX MIDGET INSTRUMENTS comparing the size of the tiny instrument with the small hand of Chico, southern California's famous pint-sized page boy of the Hotel Imig Manor at San Diego.

Midget Size

The manufacturer states that it is the world's smallest, lightest, high fidelity one-piece hearing-aid ever made. Being much thinner than all other one-unit hearing-aids. The actual measurements of the case are: 3$\frac{5}{8}$" long, 2$\frac{3}{8}$" wide and 11/16" thick. Placing an ordinary business card over the instrument will almost completely conceal it. Its weight without batteries is 2 1/64 ozs. and 4$\frac{5}{8}$ ozs. with batteries. This is quite a weight reduction below that of the first vacuum tube set which weighed about nine pounds.

Printed Circuit

The circuit utilizes the revolutionary "Printed Circuit" for high resistance to humidity failure, electronic elimination of loud audio shock, and instant finger-tip selection of frequency range. The Microphone, a new developed "Sensitone" floats on bubbles of rubber behind a recessed aperture to assure quiet operation and high fidelity. A unique preformed sub-chassis provides perfect shielding for high-gain amplification and prevents degenerative interstage coupling.

Smart Appearance

This little gold finished instrument looks as smart as a lady's compact or cigarette case, but is smaller and lighter than most.

Removable Chassis

The chassis can be quickly removed and replaced in less than five minutes. This feature provides constant hearing for the deafened in event of instrument failure. This makes possible speedy, local service.

Reasonable Price

These new Unex Midget Instruments are priced at about one-half the price of most hearing-aids. Only $95.00, fully guaranteed for one year, including personalized service. Convenient terms can be arranged.

Your money will be refunded if not satisfied after 3 days trial.

Demonstrations are being conducted now at the AUDIPHONE COMPANY'S convenient ground floor location, 252 South Main Street Salt Lake City, Utah., Phone 4-5659.

Figure 8. "Chico" demonstrates the UNEX printed-circuit "midget instrument" (June 1948). (Courtesy of Kenneth Berger Hearing Aid Museum and Archives)

With the printed circuit, for the first time, amplifiers, batteries, microphones, and other components could be housed together in a small case—to be worn in the pocket, hidden in the hair, or disguised as a tie-clip or pen. "Monopacks" brought modernist design to hearing aids. They were made from industrial metals and colored plastics, patterned with clean lines. Michael Brian Schiffer has demonstrated the predominance of hearing aids in the early imagination of portable electronics; one of the first pocket radios, using subminiature tubes, failed to sell because it looked too much like a one-piece hearing aid. Schiffer further argues, regarding the immediate postwar period, "After the privations of the war, Americans were not enthusiastic about drastically downsized products of any kind."[79] Hearing aids thus remained at the fore of personal technology—a reliable market for miniaturized components, a proving ground for the methods and merits of compact assembly.

Transist-Ear

In 1948, Bell Laboratories held a press conference about a new component for amplifying and switching signals—the transistor.[80] Invented by John Bardeen, Walter Brattain, and William Shockley, transistors would ultimately be longer lived, sturdier, and less expensive to produce than vacuum tubes. The early transistors, however, had many defects, at times discovered or worked out in the hearing aid market.[81]

The reporters who attended the press conference were generally unmoved, but Norman Krim saw the future of hearing aids in these amplifiers: because of their smallness, because they required less battery power and no warm-up time, and because they promised to generate less distortion and heat. AT&T offered royalty-free licensing of transistor technology for anyone working on hearing aids.[82] With its 95% market share in hearing aid amplifiers, and with Krim as vice president of the tube and semiconductor division, Raytheon opened a production line of point-contact transistors that year.[83] Most, however, were immediately shipped back by the hearing aid companies, "because of their inability to withstand a slight mechanical shock."[84]

By 1951, Raytheon engineers learned to manufacture (or "grow") the more stable junction transistor. Krim then embarked on a national tour of the dozen or so of the largest hearing aid companies (including Zenith, Sonotone, Telex, Maico, and Radio Ear). In two weeks, he secured $3 million in transistor orders.[85] With this guarantee, Raytheon approved equipment for a new transistor project and became the first company to mass-produce junction transistors.[86] George Freedman, who trained with Shockley, managed development and manufacturing. Freedman decided to employ hearing aid wearers, exclusively, to fabricate Raytheon's transistors. According to a short biography by journalist George Rostky, "All the people hired for Freedman's production line were deaf; all wore experimental transistorized hearing aids."[87] Nationwide, in 1953, 200,000 transistorized hearing aids were purchased.[88]

That April, Zenith concluded that their new transistorized hearing aids were cursed with a short lifespan. Zenith's president, Eugene McDonald, Jr., had lost most of his hearing in a car accident 10 years earlier. After spending nearly $200 on a hearing aid in 1943—which he later learned was made up of the same parts found, for a tenth of the cost, in radios or telephones—McDonald ordered his company to add vacuum tube hearing aids to their catalog.[89] Zenith released its first aids during World War II, with an exemption from production bans because the company agreed to hire deafened workers. B.J. Farwig, a hard of hearing sales manager, reported:

> When it began to manufacture hearing aids the company at once began to profit. Word got out that any hard-of-hearing person who sought work at the plant would not only get a job but a hearing aid. The result is that today hundreds of hard-of-hearing workers are on the Zenith Corporation's payroll.[90]

Switching to transistorized aids in the next decade, Zenith customers discovered that the body's humidity caused the transistors to fail in a matter of weeks.[91] This inability of germanium to withstand heat and moisture, along with military concerns about its reliability for missile electronics, fed the search for other semiconductors.[92] In the *New York Times*, hearing aid wearers were described as the "human guinea pigs" of transistorization.[93] Hard of hearing people, who were in fact actively making both transistors and hearing aids, had become screens for cultural fears about dependency and control over emerging technology.[94]

When a journalist for *Fortune* magazine named 1953 "the year of the transistor," he cited the replacement of vacuum tubes by transistors in hearing aids, over a period of just 18 months.[95] The *Johns Hopkins Science Review* aired an episode about "The Mighty Midget" that year, in which Bell scientist Gordon Raisbeck introduced the transistor to a television audience. After demonstrating the "miracle" of a transistorized hearing aid on a hard of hearing woman, host Lynn Poole announced, "No one really knows what this will be used for in the future...but one use we do know, and that is, that it is used today in hearing aids." The first all-transistor hearing aid models became available in 1953—the Microtone Transimatic and the Maico Transist-ear—which were still one-piece "body aids." As Braun and MacDonald caution, transistorization

> should be seen in the context of the very radical changes that had been taking place in hearing aids since the late thirties. Hearing aids were reduced in volume and weight very much more between 1938 and 1945, for example, than in the following eight years, despite the use of transistors...the introduction of the transistor to hearing aids really did no more than permit the continuation of a trend towards miniaturization that had been evident long before the transistor's invention.[96]

Texas Instruments produced a silicon transistor in 1954, and Raytheon began to lose ground as the world's largest manufacturer of transistors. TI had entered the semiconductor field in 1952, with an interest in military and telecommunications markets. In the short term, the company hoped to compete in the hearing aid field because those consumers were willing to purchase transistors at an initial high price ($10 to $16).[97] As TI refined its mass-production techniques, they used the hearing aid industry as a quality indicator. According to an anniversary pamphlet held in the TI collection at the Smithsonian, "The ability to mass-produce grown-junction germanium transistors was sufficiently convincing so that, somewhere in the fall of 1953, Sonotone ordered...7500 of them. So, [our] claim to be able to mass-produce was confirmed."[98] The next year, TI put silicon transistors into mass production and brought out the first of many new consumer electronic devices—the transistor radio.

Meanwhile, William Shockley prepared to open his own semiconductor firm. He followed the early successes of transistorization in the hearing aid industry and studied the gap between the transistorization of hearing aids and portable radios to forecast the rapidity of the phenomenon's spread.[99] As manufacturing improved, he kept track of the rates of transistor replacement by hearing aid wearers to estimate the component's longevity.[100] Shortly after the invention of the

The integrated circuit found its first commercial application in hearing aids.

junction transistor, Shockley unsuccessfully pressed Raytheon for $1 million in exchange for establishing a transistor lab at one of their sites.[101] Moving instead to California, he convinced Beckman Instruments to sponsor Shockley Semiconductor in 1956. Fairchild Semiconductor eventually splintered from Shockley's firm, and later generated many of the founding companies of Silicon Valley.[102]

In Conclusion: The IC and the Microprocessor

In 1957, continued miniaturization enabled the first one-piece hearing aid that could be worn at the ear: the Otarion Listener. A pair of "hearing glasses," the electronics were still too large to fit entirely in the ear. Lee De Forest appeared as a spokesperson for Otarion in the *Saturday Evening Post* that year (see Figure 9). He had already been associated with the hearing aid industry for decades. In the late 1920s, Hearing Devices Company of New York advertised a "Lee De Forest Audiphone," designed by the inventor of the vacuum tube himself. Two decades later, De Forest contributed to amplifier design and fitting procedures for the National Hearing Aid Laboratories of Los Angeles.

Near the end of his life, De Forest began to wear a vacuum-tube hearing aid. (He often wrote to Krim about his dissatisfaction with Raytheon tubes.) When Otarion released the transistorized Listener, De Forest switched to this device and offered his official endorsement:

> The LISTENER is without question the finest hearing aid I have ever worn. Nothing compares with it for the quality of hearing it gives. The advantage of ear-level hearing and the elimination of irritating clothing noises make the LISTENER a pleasure to wear. In fact, it overcomes all of the objections I previously had to wearing a hearing aid.

The Listener, Otarion advertised, "defies detection." The very notion of eyeglass aids—the covering of hearing difficulties as those of vision—suggests that deafness continued to carry a special burden even after decades of improvements to hearing aid technology. Visual deception was, moreover, part and parcel of electronics. Even a hypervisible apparatus concealed a world of components; the phenomenology and politics inhering in instrument design for the most part disappeared.

In 1958, the year after the Listener's release, Jack Kilby designed an IC at TI in which all components were created out of the same block of material (in this case, germanium). Kilby had previously silk-screened hearing aid circuits at Centralab of Globe Union, and he represented that firm during a 1952 tour of the new AT&T transistor factory in Allentown.[103] By 1960, Kilby was himself a hearing aid user, at that time wearing an eyeglass aid.[104]

Robert Wolff, a Centralab supervisor, remarked on Kilby's success with the miniaturization of hearing aid circuits: "He was responsible for our first really small transistorized hearing aid."[105] Braun and MacDonald have contended that this "was work which provided Kilby with an awareness of the desirability of integration."[106] Integration meant reduced size and power consumption, decreased manufacturing costs, greater ruggedness, and—most importantly, according to Braun and MacDonald—increased reliability. The humidity sensitivity of the Raytheon transistor units in Zenith hearing aids led Kilby, in 1953, to investigate ways to more effectively "house," "snap," or "seal" transistors within printed circuits.[107] Regarding the "packaged transistor amplifier" that resulted from this research, Centralab advertised, "no bulky components extend from the body of the amplifier, all are enclosed in virtually a single surface."[108]

Characteristically, the IC found its first commercial application in hearing aids.[109] Over the next 20 years, the miniaturization of ICs was understood to have new advantages, particularly in cases where transistors were used as on/off switches for digital signaling and binary calculation, rather than just as amplifiers. As Ross Bassett has carefully detailed, "the density of MOS [metal-oxide-semiconductor] circuitry led to low-cost semiconductor memory and the microprocessor, making a personal

Figure 9. Lee De Forest wears the Otarion Listener "hearing glasses." Saturday Evening Post advertisement (1957).

computer possible."[110] Paul Ceruzzi has likewise summarized:

> The force that drove the minicomputer was an improvement in its basic circuits, which began with the integrated circuit (IC) in 1959. The IC, or chip, replaced transistors, resistors, and other discrete circuits in the processing units of computers; it also replaced cores for the memory units.[111]

The long-term result of continued miniaturization, predicted by Moore, was a surge in portable and otherwise personal technologies, not to mention the propagation of objects that performed multiple, increasingly complex functions—things which remembered, reacted, and processed worldly phenomena. "Digital electronics… proliferated into almost every area of American life, through the small unseen computers that do their work in appliances and automobiles as well as through personal computers."[112]

Nevertheless, as I have argued, the IC was not the origin of electronic miniaturization. Hearing aids, particularly in their evolution as "small telephone systems" in the 20th century, provided a site for the development and testing of miniaturized components and assembly techniques as early as 1900. The "philosophy of miniaturization," as a theory of electronic design, only slowly accrued its current characteristics, spreading from portable electroacoustic technology to other domains. It was not immediately apparent that personal electronics would become a widespread consumer desire, nor even that the miniaturization of telephone and computer infrastructure was cost-effective—or necessary. By the late 1950s, as Gene Strull of Westinghouse recalls, a majority of people finally became "enamoured with miniaturisation. That was the key word, how tiny it could be…it caught the imagination of the public and of the Military as well."[113]

Computers-on-chips ultimately circulated back into hearing aids, transforming them from simple amplifiers to devices capable of "signal processing for speech enhancement, noise reduction, self-adapting directional inputs, feedback cancellation, data monitoring, and acoustic scene analysis, as well as the means for a wireless link with other communications systems."[114] Although microprocessors were available in the early 1970s, computerized hearing aids did not become common for another decade. For one thing, as Harry Levitt explains, only at the end of the 1970s were there chips "capable of processing audio signals in real time."[115] For another, even in the early 1980s, to use a digital hearing aid one would "need a friend with a wheelbarrow…to carry the instrument."[116]

Today, the imperative of invisibility largely persists as a design standard for hearing aids, with the demand for miniaturization often limiting device functionality. Recent examples of fashionable earpieces compete with new models of "completely-in-canal" invisible aids.[117] As a long view of hearing aids makes plain, hearing loss has been stigmatized despite the increasing commonness of the diagnosis, and despite the fact that moderate hearing loss can be remedied by technical means. Just as inexplicable is the obduracy of the stigma that adheres to the technology itself—when hearing aids have otherwise represented the leading edge of personal electronics, and when they exist as one configuration of the same components found in so many other appliances.[118]

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References and Notes

1. G.E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics,* vol. 38, Apr. 1965, p. 1.
2. D. MacKenzie, *Knowing Machines,* MIT Press, 1996, pp. 54–59. Moore's initial prediction was one year, but in practice the doubling has occurred every 1.5 to two years.
3. M. Riordan and L. Hoddeson, *Crystal Fire: The Invention of the Transistor and the Birth of the Information Age,* W.W. Norton, 1998, pp. 205, 9.
4. E.S. Hintz, "Portable Power: Inventor Samuel Ruben and the Birth of Duracell," *Technology and Culture,* vol. 50 Jan. 2009, pp. 24–57. Although the button battery was produced before the transistor, to claim that it was more important to the history of miniaturization—and to the development of electronic devices such as the calculator—is to misunderstand the technique of miniaturization and its advantages. With the transistor, especially as it evolved into the microprocessor, smallness was linked not only to literal size, but to increased density, processing speeds, and reliability.
5. J.R. Nall, "Miniaturization for Military Equipment," *Miniaturization,* H. Gilbert, ed., Reinhold Publishing, 1961, p. 14. Nall acknowledged the tradition of watch making as a nonelectronic example of the same "media."
6. G. Senn and R. Riehs, "Miniaturization in Communications Equipment," *Miniaturization,*

H. Gilbert, ed., Reinhold Publishing, 1961, 94.

7. G. Bachelard, ''Miniature,'' *The Poetics of Space,* M. Jolas, trans., Beacon Press, 1969; S. Stewart, *On Longing: Narratives of the Miniature, the Gigantic, the Souvenir, the Collection,* Duke Univ. Press, 1993.
8. M.B. Schiffer, notes the rise of assorted ''pocket'' devices in the early 20th century for Americans who were newly mobile due to cars and increased leisure time. M.B. Schiffer, *The Portable Radio in American Life,* Univ. of Arizona Press, 1991, p. 38.
9. E. Mollick explains that ''the increase in chip density'' is today attributable to a number of factors, including circuit design, substrate materials, techniques for increasing surface area, and techniques for reducing the width of etched connections. E. Mollick, ''Establishing Moore's Law,'' *IEEE Annals of the History of Computing,* vol. 28, no. 3, 2006, p. 63.
10. Mollick, ''Establishing Moore's Law,'' p. 62.
11. Standard surveys of mobile phone and mobile media history similarly argue that portable handsets were the result of miniaturized electronics, rather than considering the ways that portable electroacoustic media drove component miniaturization. See, for instance, R. Ling and J. Donner, *Mobile Communication,* Polity, 2009, or G. Goggin, *Cell Phone Culture: Mobile Technology in Everyday Life,* Routledge, 2006.
12. T. Misa explains that military interest in miniaturized electronics began with the walkie-talkie in the late 1930s. T. Misa, ''Military Needs, Commercial Realities and the Development of the Transistor,'' *Military Enterprise and Technological Change,* M. Roe Smith, ed., MIT Press, 1985, pp. 253–287. See also C. Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970,* MIT Press, 2005.
13. Miniature tubes and other ''diminutive components'' specifically ''made possible military transceivers of unprecedented portability,'' such as Handie-Talkies. Schiffer, *The Portable Radio in American Life,* p. 130.
14. Schiffer, *The Portable Radio in American Life,* p. 123. Although the dream of a pocket radio dates to the 19th century, Schiffer argues that radios truly began to be miniaturized during the Depression. ''Prior to this time [the 1930s], there had been no effort to reduce the size of volume controls, tuning capacitors, intermediate frequency transformers, and so forth. But once it became a priority, miniaturization was readily accomplished.'' Interestingly, miniaturized radios were less expensive; the opposite was often true for hearing aids (Schiffer, p. 103).
15. According to Ross Bassett, this incrementalism was not necessarily linear. Bassett, *To the Digital,* p. 284.
16. Or what E. Braun and S. MacDonald call ''the general ethos of miniaturisation.'' E. Braun and S. MacDonald, *Revolution in Miniature,* Cambridge Univ. Press, 1982, p. 94. By 1959, industry experts recognized that ''more advances have been made in the miniaturization of hearing aids than in any other consumer product.'' D.A. Findlay, ''Miniaturization of Consumer Products,'' *Miniaturization,* H.D. Gilbert, ed., Reinhold, 1961, p. 183.
17. Whereas the military demand for reliable electronics encouraged the development of the planar transistor in 1959, early and even provisional versions of the transistor (as well as other components) found their way into hearing aids. Thank you to the anonymous reviewer who pointed this detail out to me.
18. ''The standard of reference for most miniaturization steps is the original vacuum-tube circuitry represented by the full size octalbase vacuum tube and its associated circuitry. The first stage of miniaturization—which usually means a size reduction of the order of 10 times—was effected by the use of subminiature vacuum tubes, printed wiring, some component size reduction, and more efficient component integration.'' J.J. Staller and A.H. Wolfsohn, ''Miniaturization in Computers,'' *Miniaturization,* H.D. Gilbert, ed., Reinhold, 1961, p. 115. The article by Nall in the same volume also places hearing aids at the start of a timeline that leads to ICs.
19. J.F. Battey, ''Testimony to the Senate Subcommittee on Labor-HHS-Education Appropriations,'' Nat'l Inst. on Deafness and Other Common Disorders (NIDCD), 26 Mar. 2007, http://www.nidcd.nih.gov/about/plans/congressional/battey20070326.htm.
20. ''The Basics: Hearing Aids,'' NIDCD, 2010, http://www.nidcd.nih.gov/health/hearing/thebasics_hearingaid.asp.
21. Quackery was less rampant in the field of electrical hearing aids than in that of ''deafness cures.'' Nevertheless, the longstanding lack of legal and medical oversight in this industry has often permitted the fraudulent marketing of inexpensive as well as expensive aids. Am. Medical Assoc. Bureau of Investigation, *Deafness Cures,* Am. Medical Assoc., 1912.
22. To be sure, hearing aid miniaturization has often resulted in decreased amplification and/or options for customization.

23. I intend both meanings of ''cultural imperative'' here: the general definition of a compulsory cultural norm, as well as M.B. Schiffer's concept for ''a product fervently believed by a group—its constituency—to be desirable and inevitable, merely awaiting technological means for its realization.'' M.B. Schiffer, ''Cultural Imperatives and Product Development: The Case of the Shirt-Pocket Radio,'' *Technology and Culture,* vol. 34, no. 1, 1993, pp. 98–113.
24. ''In the early 1970s, these electronics-based industries, and the traditional computer industry, were quite distinct sectors, with very little crossover between them. By the late 1970s, however, they would all converge around a single product—the personal computer—built around the microprocessor, which was a true computer.'' W. Aspray and M. Campbell-Kelly, *Computer: A History of the Information Machine,* Basic Books, 1997, p. 199.
25. In Braun and MacDonald's account, the history of miniaturized electronics switches from ''market-pull'' to ''technology-push'' with the transistor. Similarly, Bassett argues that with the microprocessor ''digital electronics…proliferated into almost every area of American life, through the small unseen computers that do their work in appliances and automobiles as well as through personal computers.'' Bassett, *To the Digital,* p. 251.
26. For a survey of this literature, see N. Oudshoorn and T. Pinch, eds., *How Users Matter: The Co-Construction of Users and Technologies,* MIT Press, 2003, especially the introduction.
27. For a more detailed discussion of mechanical hearing aids, and their significance to the history of electroacoustics, see M. Mills, ''When Mobile Communication Technologies Were New,'' *Endeavour,* vol. 33, no. 4, 2009, pp. 141–147. R. Hüls offers a broad history of hearing aids in *Die Geschichte der Hörakustik,* Median-Verlag Heidelberg, 1999. See also K. Berger, *The Hearing Aid: Its Operation and Development,* Nat'l Hearing Aid Soc., 1970.
28. C. Sarlie, et. al., ''19th-Century Camouflaged Mechanical Hearing Devices,'' *Otology and Neurotology,* vol. 24, no. 4, 2003, pp. 691–698.
29. On the history of mechanization and rationalization across many domains of human life, see S. Giedion, *Mechanization Takes Command: A Contribution to Anonymous History,* Norton, 1969.
30. See S. Mihm, '''A Limb Which Shall be Presentable in Polite Society': Prosthetic Technologies in the Nineteenth Century,'' *Artificial Parts, Practical Lives: Modern Histories of Prosthetics,* ed. K. Ott, D. Serlin, and S. Mihm, eds., New York Univ. Press, 2002, pp. 282–299; D.D. Yuan, ''Disfigurement and Reconstruction in Oliver Wendell Holmes's 'The Human Wheel, Its Spokes and Felloes,''' *The Body and Physical Difference: Discourses of Disability,* D.T. Mitchell and S.L. Snyder, eds., Univ. of Michigan Press, 1997, pp. 71–88; R. Garland-Thomson, *Staring: How We Look,* Oxford Univ. Press, 2009.
31. Sarli et al., ''19th-Century,'' pp. 692–693. Here they restate the argument found in S.D. Stephens and J.C. Goodwin, ''Non-electric Aids to Hearing: A Short History,'' *Audiology,* vol. 23, no. 2, 1984, pp. 215–240.
32. This lecture was itself broadcast through a ''group hearing aid.'' H. Fletcher, ''Alexander Graham Bell—The Inventor—The Teacher,'' talk before 16th Ann. Conf. Am. Soc. for the Hard of Hearing, 27 May 1936, p. 9, series UA 029, box 2, folder 2, Harvey Fletcher Papers, L. Tom Perry Special Collections, Brigham Young Univ. The description of hearing aids as ''miniature telephone systems'' pervaded Bell publications. See also W.L. Tuffnell, ''The Ortho-Technic Audiphone,'' Bell Laboratories Record, vol. 28, Sept. 1939, pp. 8–11.
33. Schiffer describes a similar tension between power and size in the portable radio field. Schiffer, *The Portable Radio in American Life,* p. 15.
34. A.A. Hayden, ''Hearing Aids from Otologists' Audiograms,'' *J. Am. Medical Assoc.,* vol. 111, no. 7, 1938, pp. 592–593.
35. J. Sterne, also discusses this ''living telephone.'' J. Sterne, *The Audible Past,* Duke Univ. Press, 2003, pp. 81–82; from the *Buffalo N.Y. Times,* 24 Jan. 1897. Clipping held in ''Hearing'' file, audiology folder, Medical Sciences Division, Smithsonian Institution Nat'l Museum of Am. History.
36. Campbell, *Helps to Hear,* p. 89.
37. D.D. Runes, ed., *The Diary and Sundry Observations of Thomas A. Edison,* Philosophical Library, 1948, p. 53. Edison was involved in a lengthy patent dispute with E. Berliner over the carbon transmitter; the patent was eventually awarded to him by the American and British courts.
38. Edison went on, ''I do believe that it is a possibility to utilize the results so far attained in the art of telephony, in the condition [i.e. deafness] you name.'' Campbell, *Helps to Hear,* pp. 104–105. By 1878, Siemens was in fact selling the Phonophor, a telephone amplifier attachment, by which ''many people

with impaired hearing could understand speech better when telephoning than in normal conversation.'' Siemens Timeline, Siemens file, Berger Archives. On similar attachments in the U.S., see W.P. Banning, ''Bringing Telephone Service to the Deaf,'' *Bell Telephone Quarterly,* vol. 4, Jul. 1925, pp. 203–210.

39. ''Congressional Speeches over the Telephone,'' *New York Times,* 20 Jan. 1907, SM6. Hutchison also developed a means of miniaturizing the sound film recording process, so that a wider range of frequencies per second could be played back. ''New Film Enlarges Range of 'Talkies,''' *New York Times,* 27 Jan. 1931, p. 4. Furthermore, he invented the electric automobile horn, which prompted his friend Mark Twain to comment on the vicious circle of modern amplification, ''You invented the Klaxon horn to make people deaf, so they'd have to use your acoustic devices in order to make them hear again.'' ''Miller Hutchison, Inventor, 67, Dead,'' *New York Times,* 18 Feb. 1944, p. 17.
40. For more on the relationship between the New York League for the Hard of Hearing and AT&T, see M. Mills, ''Deafening: Noise and the Engineering of Communication in the Telephone System,'' to be published in *Grey Room,* spring 2011, p. 43.
41. F. Warfield, *Cotton in My Ears,* Viking Press, 1948, p. 137.
42. F. Warfield, *Keep Listening,* Viking Press, 1957, p. 41. Hearing aids aroused many suspicions about new technology. In 1926, The *New York Times* reported on the dousing of a businessman's Acousticon by the city bomb squad—it was in a generic black case and seemed to be giving off a ticking noise. ''Acousticon in Bag Causes a Bomb Scare,'' *New York Times,* 22 Aug. 1926, p. 27.
43. Warfield, *Cotton in My Ears,* p. 88.
44. By identifying stigma with miscommunication, it could be argued that stigma theory itself reinforced the discredit attached to hearing loss and deafness. E. Goffman, *Stigma: Notes on the Management of Spoiled Identity,* revised ed., Touchstone, 1986, pp. 104, 49 (original ed. Prentice Hall, 1963). Adopting the language of communication engineering, Goffman further classified stigma symbols as ''information carriers,'' p. 45.
45. On hearing aids specifically, see Goffman, *Stigma,* pp. 92–93.
46. R. Garland-Thomson, *Extraordinary Bodies: Figuring Physical Disability in American Culture and Literature,* Columbia Univ. Press, 1997, p. 14.
47. At the same time, many users of ear trumpets chose not to trade them in for electrical aids: mechanical devices were inexpensive, sturdy, and did not contain parts (such as batteries) that had to be replaced.
48. ''The History of Western Electric Hearing Aids,'' p. 12, Western Electric file, Kenneth Berger Hearing Aid Archive, Kent State Univ.
49. Schiffer, *The Portable Radio in American Life,* p. 169.
50. S. Bennett, *A History of Control Engineering, 1800–1930,* Peter Peregrinus, 1986, p. 184.
51. By 1913, De Forest Radio, Telephone, and Telegraph—his vacuum tube-manufacturing company—was marketing the Audion using the terms of deaf oral pedagogy, which went hand in hand with the technification of communication: ''The wireless was born dumb. It could chirp like a bird or bark like a dog, but it couldn't talk like a human. . . . For speech to be transmitted there must be a continuous oscillation with the speech modulations impressed on it. . . . It was De Forest who made the wireless speak.'' ''He Made the Wireless Speak,'' pamphlet, box 18, item 161, p. 70, Lee De Forest papers, History San José. Reprinted from Radio Merchandising, Sept. 1926.
52. E.C. Hanson, ''The Vactuphone,'' *The Volta Rev.,* July 1921.
53. I. Gerling and M. Taylor, ''Quest for Quality and Consumer Appeal Shaped History of Hearing Aid,'' *The Hearing J.,* vol. 50, 1997, p. 42. Gerling and Taylor claim that ''In 1924, the Secret Service requested and was granted permission to use the Vactuphone for its Operations.''
54. H. Fletcher, the director of speech and hearing studies at AT&T, was also personally invested in the issues of hearing loss and assistive technology. He served for many years as the President of the New York League for the Hard of Hearing, and his own father was deaf. S. Fletcher, *Harvey Fletcher, 1884–1981,* Nat'l Academy of Sciences, 1992, p. 179.
55. ''Most of the military sets . . .,'' Schiffer explains, ''were technologically old-fashioned, consisting of cumbersome spark transmitters and receivers without audions.'' Trench Sets were trunk-sized; Pack Sets were carried in backpacks. More powerful military portables were larger and required truck transportation. In 1922, however, various firms began to assemble compact radios with ''efficient'' designs. For further details about portable radios during and after World War I. See

Schiffer, *The Portable Radio in American Life,* pp. 28–30, 67.

56. On peanut tubes, see D. Vermeulen, ''The Remarkable Dr. Hendrik van der Bijl,'' *Proc. IEEE,* vol. 86, no. 12, 1998, pp. 2445–2454.
57. All these renovations were tested on family members and friends of Bell System employees. ''Material Given to Some Western Electric Employees in 1933,'' Kenneth Berger Hearing Aid Archives, Kent State Univ.
58. Just prior to the Depression, Sonotone and Acousticon each sold approximately 60,000 aids annually. ''Material Given to Some Western Electric Employees in 1933,'' p. 3, Western Electric File, Berger Archive.
59. M. Reis, ''Student Life at the Indiana School for the Deaf During the Depression Years,'' *Deaf History Unveiled: Interpretations from the New Scholarship,* J. Vickrey Van Cleve, ed., Gallaudet Univ. Press, 1993, p. 201.
60. M. Mead, ed., *An Anthropologist at Work: Writings of Ruth Benedict,* Houghton Mifflin Company, 1959, p. 74. Elsewhere, Mead discusses Benedict's style of ethnography and textual analysis in terms of her hearing loss. M. Mead, *Ruth Benedict,* Columbia Univ. Press, 1974, p. 30.
61. P. Vose, *Say It Again,* Southworth Press, 1931, pp. 13–14.
62. M. Hays Heiner, *Hearing is Believing,* World Publishing Company, 1949, p. 61.
63. Hays Heiner, *Hearing is Believing,* p. 66.
64. Warfield, *Keep Listening,* 43.
65. Subsequently, she continually tested and purchased new models.
66. K. Berger estimates that there were 50,000 carbon hearing aid wearers as late as 1944. Berger, *Hearing Aid,* p. 41.
67. N. Krim, personal discussion with M. Mills, 28 Feb. 2008. According to an earlier interview with M.B. Schiffer, Krim had also learned that a former Raytheon employee was making small hearing aid tubes for the British electronics firm Hi-Vac. Schiffer, *The Portable Radio in American Life,* p. 161.
68. For a good overview of a topic that has been overlooked by historians, see K. Petherbridge, P. Evans, and D. Harrison, ''The Origins and Evolution of the PCB: A Review,'' *Circuit World,* vol. 31, no. 1, 2005, pp. 41–45.
69. P. Eisler, *My Life With the Printed Circuit,* Lehigh Univ. Press, 1989, p. 27.
70. ''Model Airplane Tube Led to Proximity Fuse,'' *The Boston Globe,* 5 Jan. 1964. Clipping held in the subject files at the IEEE History Center.
71. Allen-Howe was itself a 1945 spin-off of Globe Phone (who marketed the Vactuphone in 1921).
72. Allen-Howe introduced their aid at a 15 Oct. 1947 symposium on printed circuits in Washington, DC, which was attended by nearly 1,000 engineers and scientists.
73. H. Gilbert, ed., *Miniaturization,* Reinhold, 1961, pp. 19, 21.
74. ''The Printed Circuit,'' Solo-Pak File, Kenneth Berger Hearing Aid Archives, Kent State Univ.
75. ''Smallest Hearing Aid Uses Printed Circuit,'' *Radio-Craft,* Jan. 1948. Clipping held in Solo-Pak File, Berger Archive. The *Volta Review* introduced printed circuit techniques (silkscreen, electroplating, photographic printing) to its readers even earlier. E.L.R. Corliss, ''Printed Circuits for Hearing Aids,'' *The Volta Rev.,* vol. 49 Sept. 1947, pp. 405–406, 444, 446.
76. Schiffer notes that advertisements for postwar portable radios often listed ''alleged war-derived improvements'' even though ''all were based on pre-war technologies.'' (This changed with the incorporation of the printed circuit into portable radios.) Schiffer, *The Portable Radio in American Life,* p. 141.
77. R. Garland-Thomson, ''The Politics of Staring: Visual Rhetorics of Disability in Popular Photography,'' *Disability Studies: Enabling the Humanities,* S.L. Snyder, B.J. Brueggemann, and R. Garland-Thomson, eds., Modern Language Assoc. of America, 2002, p. 69.
78. Garland-Thomson, ''The Politics of Staring,'' p. 69. G. Bachelard similarly argues, ''The cleverer I am at miniaturising the world, the better I possess it.'' Bachelard, *The Poetics of Space,* p. 150.
79. M.B. Schiffer, ''Cultural Imperatives and Product Development: The Case of the Shirt-Pocket Radio,'' *Technology and Culture,* vol. 34, 1993, p. 107.
80. One of their first publications on the topic, forecasting possible applications, was ''The Transistor,'' *Bell Laboratories Record,* vol. 26, 1948, pp. 321–324.
81. Braun and MacDonald note that the first transistors were actually noisier than vacuum tubes, moreover they ''could handle less power'' and ''were more restricted in their frequency performance.'' Braun and MacDonald, *Revolution in Miniature,* p. 49.
82. A Pacific Bell circular announcing these licenses to San Francisco customers noted, ''the telephone itself was a by-product of early experiments by Alexander Graham Bell who had a lifelong interest in the problems

of the deaf." "No Royalty Payments on Transistors in Hearing Aids," *Talk: News and Information about your Telephone Service,* Sept. 1954, pp. 86-050, box 11, binder, William Shockley Papers, Stanford Archives. Riordan and Hoddeson point out that J. Bardeen's wife "used one of the first transistorized hearing aids, supplied by Sonotone at Shockley's urging." Riordan and Hoddeson, *Crystal Fire,* p. 205.
83. N. Krim, email message to M. Mills, 18 Feb. 2008.
84. N. Krim, personal discussion with M. Mills, 2 Feb. 2008.
85. N. Krim, email message to M. Mills, 18 Feb. 2008. However, Raytheon continued to manufacture subminiature vacuum tubes for other purposes into the 1990s.
86. The start-up costs for this project were such that Krim considers himself to have "gambled the company" on transistors.
87. G. Rostky, "Hearing with Transistors," *The Transistor, A Biography,* CMP Publications, Raytheon Archives, 1997, p. 13.
88. Riordan and Hoddeson state that "when the hearing-aid market erupted in 1953, Raytheon quickly cornered it, supplying most of the amplifiers for the 200,000 transistorized hearing aids that sold that year." *Crystal Fire,* p. 226
89. For a discussion of Zenith's long-term cost-cutting, and its rise to the top of the hearing aid industry. See J.J. Nagle, "Hearing Aid Costs Challenged Again," *New York Times,* 20 June 1954, p. F1.
90. B.J. Farwig, "Zenith's $40 Hearing Aid Leads," *Sales Management Magazine,* 1 July 1944, p. 25. Many thanks to M.B. Schiffer for providing me with a copy of this article.
91. "The Transistor," *The Volta Rev.,* vol. 55, no. 6, Jun. 1953, p. 308.
92. "Transistors in Need of Improvement," *New York Times,* 19 Apr. 1953, p. E9.
93. "Zenith Finds Flaw in Transistor Aid," *New York Times,* 17 Apr. 1953, p. 33.
94. Krim often used the language of "early adoption": "The hearing aid manufacturers, always alert to the new developments in their field, will become the first in the electronics industry to give their consumers the advantages made possible by the development of the junction transmitters." "Transistors Set for Hearing Aids," *New York Times,* 26 Jan. 1953, p. 27.
95. F. Bello, "The Year of the Transistor," *Fortune,* vol. 47, Mar. 1953, p. 132.
96. Braun and MacDonald, *Revolution in Miniature,* p. 49.
97. J. McDonald, "The Men who Made TI," *Fortune,* Nov. 1961, p. 118.
98. P.E. Haggerty, "A Successful Strategy," 25th Anniversary Observance Transistor Radio and Silicon Transistor 17 Mar. 1980, p. 4, TI Manuscript Collection, Smithsonian Nat'l Museum of Am. History Archives.
99. See "Shockley Predicts Transistor Growth," *Television Digest,* 27 Oct. 1956, Shockley Papers, Stanford Univ. Archives.
100. "Beckman Backs Transistors: Shockley Semiconductor Lab to Develop and Produce Transistors, Other Solid State Electronic Devices," *Chemical and Eng. News,* vol. 34, 1956, p. 1067.
101. Rostky, "Hearing with Transistors," p. 11.
102. Andy Grove the founder of one of these companies—Intel—wore a hearing aid as a result of childhood scarlet fever. Grove often communicated with his vacuum tube hearing aid in novel ways, for instance hitting it against the conference table to indicate dissent. See T. Jackson, *Inside Intel: Andy Grove and the Rise of the World's Most Powerful Chip Company,* Dutton, 1997.
103. S. Leslie, "Blue Collar Science: Bringing the Transistor to Life in the Lehigh Valley," *HSPS,* vol. 32, 2001, p. 86.
104. For a photograph of Kilby wearing an eyeglass aid, see the cover of *Electronic Daily Magazine,* vol. 9, no. 1, Mar. 1960.
105. M. Wolff, "The Genesis of the Integrated Circuit," *IEEE Spectrum,* vol. 13, Aug. 1976, p. 46. This article places most of the "motivation to miniaturize" with the military.
106. Braun and MacDonald, *Revolution in Miniature,* p. 89.
107. "Subject: Transistor Development," Jack Kilby, to R.L. Wolff, 24 September 1953, p.2, "Kilby-correspondence with Centralab-to R.L. Wolff" folder, box 1, Jack Kilby papers, DeGolyer Library, Southern Methodist University.
108. *Packaged Transistor Amplifier* (pamphlet, n.d.), "Kilby-*Centralab Engineering Preview*" folder, box 1, Jack Kilby papers, DeGolyer Library, Southern Methodist Univ.
109. It was first sold commercially in a Zenith hearing aid. Air Force Systems Command, "Integrated Circuits Come of Age," pamphlet, p. 20. Clipping held in the subject files ("Integrated Circuit") at the IEEE History Center.
110. Bassett, *To the Digital,* p. 2.
111. P. Ceruzzi, *A History of Modern Computing,* 2nd ed., MIT Press, 2003, p. 178.
112. Bassett, *To the Digital,* p. 251.
113. Quoted in Braun and MacDonald, *Revolution in Miniature,* p. 93. They go on to argue,

"Commercial production processes were developed to supply components and were doing this so successfully by the late fifties and early sixties that the development of new processes to build larger components, even had these been electronically superior, would have been unacceptable."

114. H. Levitt, "A Historical Perspective on Digital Hearing Aids: How Digital Technology has Changed Modern Hearing Aids," *Trends Amplif,* vol. 11, no. 7, 2007, p. 7. Today, there is a return to analog circuitry in some hearing aids, such as the Lyric.
115. Levitt, "A Historical Perspective on Digital Hearing Aids," p. 11.
116. Levitt, "A Historical Perspective on Digital Hearing Aids," p. 12.
117. On the rising popularity of wireless earpieces, and their potential to decrease the stigma of hearing aids, see R. Jackler, "The Impending End to the Stigma of Wearing Ear Devices and its Revolutionary Implications," *Otology & Neurotology,* vol. 27, no. 3, 2006, pp. 299–300. Jackler predicts a future of widely used, customizable earpieces for amplification, digital audio, and computer interfacing. For prototypes of fashionable and conspicuous hearing aids, see the Web archive of the HearWear exhibit at the Victoria and Albert Museum, 2006, http://www.vam.ac.uk/vastatic/microsites/1498_hearwear/player.php.
118. K. Ott describes this as the "technological ghetto" of "assistive" technology. K. Ott, "The Sum of Its Parts: An Introduction to Modern Histories of Prosthetics," *Artificial Parts, Practical Lives: Modern Histories of Prosthetics,* K. Ott, D. Serlin, and S. Mihm, eds., New York Univ. Press, 2002, p. 21.

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