[Frontiers in Bioscience 12, 3152-3166, May 1, 2007]

General functions and specific applications of environmental sound research

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1. ABSTRACT

Environmental sound research is still in its beginning stages, although in recent years there has started to accumulate a body of research, both on the perception of environmental sounds themselves, and on their practical applications in other areas of auditory research and cognitive science. In this chapter some of those practical applications are detailed, combined with a discussion of the implications of environmental sound research for auditory perception in general, and finally some outstanding issues and possible directions for future research are outlined.

2. INTRODUCTION

In the past few years, there has been increasing interest in the study of environmental sounds (which are here defined as naturally occurring non-speech, non-musical sounds), a class of sounds which has been relatively underresearched compared to the major ones, speech and music. As a rough gauge of this, a Psychinfo search on "environmental sounds" returned only 152 records, 55 of which were from after 2001, with the earliest entry dating only from 1961. (In contrast, a search on "speech perception" returns 13803 records.) As described in greater detail in section 3, one of the reasons for the paucity of data on environmental sound perception is that historically, the foci of auditory research have been on either artificial, laboratory generated sounds, such as the pure tones and noise bursts used in psychoacoustic research, or on speech and music.

These two threads of auditory research have not converged as neatly as could be hoped for: for instance, speech has shown a greater resistance to degradation in the signal quality and missing parts of the signal than would be expected from the psychophysical literature(1, 2). Aside from the fact that deaf people fare poorly on both measures, puretone thresholds are often not reliable predictors of speech comprehension ability in individuals (e.g., (3-5)). One potential interpretation of this is that speech sounds comprise a unique class of sounds which is perceived differently from sounds that do not carry linguistic information. However, before concluding, as some in the speech community have, that "speech is special" (6) it should be considered whether the robustness of speech is more a function both of the complex spectral-temporal structure, which affords multiple cues with a high degree of redundancy, and of our strong familiarity with the sound structure and grammar of speech, which allows us to make reliable guesses as to the nature of missing parts, as in the high- versus low probability sections of the Speech in Noise (SPIN) test (7).

One way to approach this problem is to study sounds which have a similar spectral-temporal complexity to speech and are highly familiar to listeners, but lack the grammar and semantic content of speech. Environmental sounds, being produced by naturally occurring physical sources, have complex acoustic structure that reflects aspects of their sources, as shown in studies of bouncing and breaking bottles (8), footsteps (9) and hand claps (10). Many environmental sounds are also highly familiar – listeners can quickly and easily identify a wide range of environmental sounds (11-14). Some studies have shown that environmental sounds share many features with speech in terms of the effects of varying spectral or temporal resolution, and the frequency region carrying the greatest information (13, 15, 16), and in a multi-factorial study of a wide range of listening abilities the ability to identify environmental sounds tended to group with the ability to understand speech as opposed to more psychophysically oriented tasks (17). So it does seem that environmental sound share some critical features with speech. It has been proposed that the common factor between speech and environmental sounds appears to be an ability to make parts of wholes, i.e., the necessary abilities for both types of listening appear to be as much cognitive or central as peripheral (5).

In addition to providing a gateway into understanding speech perception, environmental sounds are also an important component of our everyday listening experience. One of the main benefits listeners with cochlear implants report is an increased ability to perceive environmental sounds (18, 19). Although appeals to evolutionary aspects of hearing are difficult to prove, it is hard to argue against the notion that the ability to identify sound sources preceded that of listening to speech or music (20). The communicative value of speech and the aesthetic pleasures of music have made those classes of sounds seem much more necessary; however, it would be a more difficult, dangerous and less meaningful world without the ability to recognize environmental sounds.

To the clinical researcher environmental sounds offer a rich variety of meaningful stimuli that are of interest both in their own right and for what they reveal about auditory and cognitive functioning. The clinical uses of environmental sounds are discussed in greater detail in Section 2, but it should be noted that environmental sounds have already been used as stimuli in evoked response potentials (ERP) studies (21), for assessments of cognitive functioning in autistic individuals (22), and as an alternative to pure tones for audiological assessments (23).

The remainder of this chapter will discuss the history of environmental sound research, current applications, some useful methodologies for those interested in utilizing environmental sounds, how environmental sounds research fits in with the current traditions in both hearing and psychological research, and some promising future directions for environmental sounds research. As more researchers delve into it, it is hoped that the heretofore underexplored area of environmental sound research will be able to come into its own as a distinct body of knowledge, interesting both in its own right and for the larger implications for sensory and cognitive studies.

3. PRACTICAL APPLICATIONS OF ENVIRONMENTAL SOUND RESEARCH

Environmental sound research, although still in its infancy, has been associated with a number of diverse practical applications including medicine, artificial intelligence, noise control and design of virtual auditory environments. In the medical fields, research has been directed primarily at restoring the ability to perceive the world through sound by the hearing impaired and development of novel diagnostic methods. Subjective evaluations of environmental sounds and their contributions to the annoyance in specific environments have been the subjects of noise control research (24-28). Experimental results regarding the effects of various types of sounds in the listeners' environment on communication and productivity have lead to efforts to develop a conceptual framework for designing listening environments or soundscapes (29). Finally, overlapping a number of research areas, are the attempts to formalize the relationship between the semantic and aesthetic properties of environmental sounds and their physical parameters (10, 16, 30-32). Understanding these relationships can provide a basis for sound recognition and identification by machines and for the design of novel information-carrying sounds.

3.1. Restoring the Awareness of Environment through Sound

Environmental sounds play an important role in animating the world around the listener and contribute to the listener's sense of situational awareness and well-being (33, 34). However, for a large number of hearing impaired individuals, the ability to perceive environmental sounds, and thus their awareness of the objects and events in their vicinity, is compromised. Although no quantitative model exists to determine the overall contribution of environmental sounds to the listener's perceived connection with the outside world, anecdotal reports from numerous newly implanted cochlear implant users convey a tremendous sense of excitement from their ability to identify environmental sounds (35)[1]. Surveys of cochlear implant users further indicate that environmental sound perception is one of their major concerns (18).

In contrast to cochlear implant users, who typically report significant gains in environmental sound perception post implantation, reported difficulties in environmental sound perception of hearing aid users, on average, do not seem to differ from individuals with a similar degree of hearing loss who do not use amplification.

A comparison of responses on an open – ended questionnaire of 120 individuals with hearing loss who were hearing aid candidates and never used hearing aids with those of 120 experienced hearing aid users revealed that, although the hearing aid candidates reported more problems with speech understanding, the number of problems with environmental sound perception was comparable between the two groups (36). In addition to a decline in the ability to perceive individual environmental sounds, hearing loss also has a negative effect on the identification of auditory environments or scenes (37). This is an expected outcome since identification of environments through sound requires the listener to be able to identify specific sounds that characterize the environment (38). Thus, inability to identify the sources of specific sounds may not only prevent the listener from reacting appropriately to specific sound producing events (e.g., fire alarms, imminent collisions), but may also impair orientation in an environment as a whole.

Presently environmental sounds are being used in the early stages of audiological rehabilitation following cochlear implant surgery. This practice is recommended in a number of professional publications (39, 40) as well as materials in audiology, e.g., "Learning to Hear" by the Hearing Restoration Fund[2] and Sound and Beyond™ by Cochlear Americas[3]. However, little research has been carried out to support or guide these practices. Furthermore, the majority of existing environmental sound tests has not been normed and varies widely in the number and types of sounds included, quality of the recordings, acoustic properties of the sound tokens, testing procedure and response format (i.e. open or closed set). These uncontrolled variables often make it difficult to unambiguously interpret available test results, which is a problem running through environmental sound research, as discussed in Section 5.

3.2. Diagnostic applications of environmental sounds

Encompassing a broad range of semantic and acoustic complexity, environmental sounds provide a unique set of materials to serve as diagnostic tools. They are sufficiently different from other auditory stimuli typically used for diagnostic purposes such as speech or acoustically simple stimuli (i.e., pure tones and wide band noises) to assess central and peripheral aspects of auditory processing. Because environmental sound testing need not involve complex language skills, environmental sounds can be used to test listeners with limited language proficiency such as children, foreign language speakers, or patients with linguistic or cognitive deficits (41-43). Moreover, the ability of environmental sounds to attract attention and amuse the listener makes them especially useful with these difficult to test populations. For example, the use of octave-band filtered environmental sounds was advocated as an alternative to pure tones in audiological tests for children, on the assumption that the sounds would hold the young children's attention more readily than pure tones, while at the same time providing an opportunity to assess frequency specific hearing thresholds (23).

A number of recent studies have investigated the differences in the central processing of speech, environmental sounds, and music (e.g., (44-46). The findings have been mixed: dissociations in performance have been found with both speech and music, although environmental sound recognition is more commonly linked with linguistic deficits (see (47) for an overview). This research is still in early stages; however, one potential diagnostic application of environmental sound tests among patients with central deficits is in being able to relate specific behavioral deficits to specific sites of lesions. In one case, it was noted that patients with impaired environmental sound recognition tended to have damage to the left posterior superior temporal gyrus and the inferior parietal lobe (43).

A different kind of diagnostic value associated with environmental sounds comes from their ability to convey information about sound sources. One of the most ancient tools of medical diagnosis, auscultation, involves trained listeners evaluating the functional state of internal organs such as the heart, lungs, or the gastrointestinal system through sound. Unfortunately, the cognitive aspects of medical auscultation have received considerably less attention than other well-known areas of expert listening such as music. Most present-day research on diagnostic bodily sounds is focused on the acoustic properties of sounds underlying pathological and normal states (48-50) and largely ignore their perceptual and cognitive aspects. Nevertheless, few existing studies indicate systematic differences between novices (i.e., medical students) and expert listeners (cardiologists) in the evaluation of heart sounds (51). Given an overall decline in the ability of medical professionals to provide accurate diagnosis through auscultation (52, 53), the cognitive mechanics involved in perception and learning of bodily sounds warrant further investigation.

3.3. Noise control and the design of acoustic environments

In addition to being a source of useful information about the listener's surroundings, environmental sounds are also known for their ability to elicit affective responses and have an impact on listeners' mood, overall satisfaction, and productivity (26). Environmental sounds can please or annoy the listener to the degree that cannot be predicted based on their gross physical properties such as frequency content or sound pressure level alone (26). In addition, the degree of annoyance can be influenced by the environmental context in which the sound is heard and listener expectations (54, 55). On the other hand, listeners' evaluation of the quality of an environment as a whole can be also influenced by its acoustic makeup. For instance, it was found that the sounds of 'downtown traffic', 'lawn mower' or 'a jet plane' were highly detracting in a wooded setting, while these sounds had a high to moderate enhancement on subjects' evaluations of the quality of a downtown site (24). A major aim of noise control research to date has been to determine the relationship between negative effects of ambient sound and its physical properties. Substantially less attention has been paid to the study of the positive effects of ambient sound and its ability to enhance performance and augment communication (29). Nevertheless, the knowledge about both the positive and negative psychological effects of environmental sounds can provide a basis for the effective design and control of indoor and outdoor acoustic environments, also known as "soundscapes," a term coined by Murray Schafer in his 1977 book (56).

3.4 Sound synthesis: auralization, audification and sonification

The advent of electroacoustic technology (a term referring to all instances of electrically mediated sound (29)) has opened an exciting source of seemingly unlimited possibilities in sound engineering and design. Physical characteristics of sound can be specified in minute detail and are no longer constrained by the physical properties of specific sound sources. Traditionally, in order to produce a specific sound one had to find an appropriate mechanical object which when acted upon in a specific way would produce the desired acoustic signal. Now the properties of the acoustic signal itself can be specifically prescribed and produced via the conversion of electric current to the mechanical vibration a loudspeaker's diaphragm. For example, FM synthesis allows the replication of greater effort on an instrument (e.g., striking a key on a piano with greater force) by concurrent changes in both the amplitude and bandwidth of the signal (57).

Advances in electronic sound synthesis have led to the development of a host of synthesis techniques aimed at the production of realistic environmental sounds such as footsteps, colliding balls, water and machine sounds (58-61). At the current time the algorithms available for synthesizing impact sounds are the most advanced and are gaining acceptance in psychoacoustics (62, 63). For more information, the website for the Sounding Objects project (SOb), www.soundobject.org, has a large repository of papers and reports in this area. These techniques find practical application in a variety of virtual reality interfaces and are typically grouped under the term 'auralization.' Auralization is defined as "the process of rendering audible, by physical or mathematical modeling, the sound field of a source in a space, in such a way as to simulate the binaural listening experience at a given position in the modeled space." (64) Thus, the practical need for perceptually accurate synthesis of environmental sounds has contributed to the interest in the relationship between the physics of the sound source, the characteristics of the acoustic signal, and its perceptual properties.

The development of sound synthesis has also lead to the appearance of a new class of electronic sounds which do not have a referent among "real world" mechanical objects. Perhaps the best known examples of such sounds are special effects produced by musicians (e.g., flanging) and movie and radio sound effects (e.g., laser guns firing, or "beaming up" people through space). However, in addition to being a source of amusement and aesthetic satisfaction, electronically synthesized sounds can convey useful information about inherently nonauditory objects, events, or processes. The terms 'audification' and 'sonification' refer to the process of conveying information through sound which is not speech and are described in some detail in the Proceedings of the seminal 1992 Sante Fe Institute Conference on Auditory Display (65). Usually it consists of converting some nonacoustic time-series data to sound or to some acoustic representation of specific properties of nonauditory objects and events that are not necessarily dynamic in nature. One of the more impressive examples of the use of audification mentioned in the Proceedings is diagnosis of a problem with the Voyager spacecraft by playing a large batch of telemetry and noticing a singular "machine-gun" like sound (62) pg. 35). In the same volume is a description of listening to data on seismic activity (66). Examples of sonification are sounds made by a computer to indicate a specific event (e.g. error, file open, new hardware found, etc.) known as earcons (67). A detailed imagining of the potential for sonification in all facets of daily life is provided by Albert Bregman in his introduction to the Proceedings describing a shoe salesman who uses sonification for sales analysis, inventory, and ordering food.

4. ENVIRONMENTAL SOUNDS AND LISTENING IN THE WORLD

There is little technical basis for telling whether a given experiment is an ecological normal, located in the midst of a crowd of natural instances, or whether it is more like a bearded lady at the fringes of reality, or perhaps like a mere homunculus of the laboratory out in the blank. - Egon Brunswik, The conceptual framework of psychology p. 204 (68).

4.1. Historical role of environmental sound research

A brief and highly overgeneralized history of hearing research can be thought of as having two major threads: one centered on the psychophysics of auditory perception, and the other focused on speech with a third, less extensive, thread focused on musical perception which is at various times closely linked with psychophysics and other times with speech. Speech research has been initially driven by the great practical importance of understanding speech perception whereas psychophysical research investigated the basic structure and function of the auditory system.

For over one hundred years the psychophysically-oriented investigators have been systematically manipulating acoustic parameters, some simple (e.g., frequency, intensity) and some more complex (e.g., rate and depth of modulation), with the aim of determining the sensitivity of the auditory system and its resolving power for changes in these parameters. The stimuli were largely laboratory-generated sounds such as pure tones, clicks and noise bursts whose acoustic properties (e.g., frequency, power, and duration) could be easily manipulated and controlled.[4]

In another, sometimes quite separate, division of auditory research were the speech investigators, who had always been concerned with sounds of extreme complexity. The meaningful dimensions for speech perception were

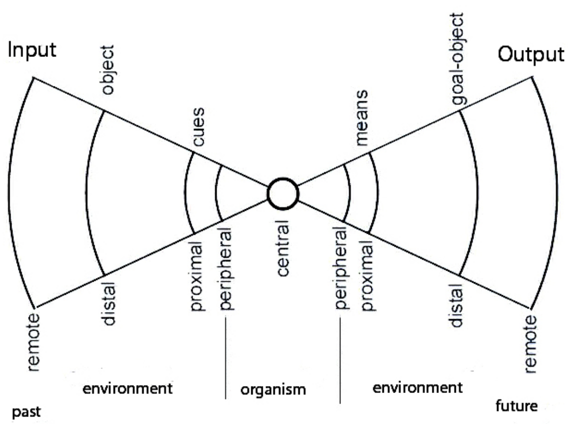

Figure 1. Brunswik's structure model

obviously not ones that changed uniformly with overall intensity (a sentence can mean the same thing whether spoken close to you or from far away) or pitch (men have lower pitched voices than women) so single acoustic parameters (e.g., overall energy or fundamental frequency) were often not very useful for predicting listeners' responses. From the beginning speech scientists focused on higher-order acoustic properties, such as the dynamic and static aspects of formant structure (69-71).

Between these two major traditions of auditory research, the study of environmental sounds has been largely overlooked. With few exceptions (72, 73), the perception of environmental sounds was not considered to be of practical use to speech researchers, because of the general assumption that there is little to be learned from environmental sounds that is applicable to speech. On the other hand, psychoacousticians have not often used environmental sounds in their research, in part because of the difficulty of characterizing them acoustically, and in part because it was thought that studying environmental sounds would not add useful information to the basic understanding of the auditory system.

4.2. Studying meaningful sounds

Some of the split between psychoacoustics and speech research is a result of the tension in research between internal validity and external validity. Speech research was driven by the great practical importance of understanding speech perception; the psychophysical research investigated the fundamental bases of the abilities of the auditory system. However, there are approaches that can bridge the divide. As noted by J.J. Gibson (who is usually associated with the idea), Egon Brunswik was one of the first to articulate that an organism has evolved to respond to meaningful stimuli in a meaningful way, and scientific research should reflect that by employing stimuli that are representative of the population of stimuli to which it has adapted (74). Brunswik termed this "representative design", although a more familiar and less well-defined term would be "ecological validity."

In auditory terms, we have evolved to hear meaningful sounds, which initially likely meant recognizing, as Lloyd Jeffress once stated informally, whether something could be eaten or was about to eat you. So one way of conceptualizing auditory perception is as a process of "tuning in" to the perceptually relevant properties of the distal stimulus in the patterns of activity in the auditory system, which can also be viewed as a problem of reverse engineering. Brunswik explicated this process in his structure model, shown in (Figure 1), which was instantiated for vision by Heider and Brunswik in their lens model (75). However, unlike in vision, where the retinotopic mapping is a relatively straightforward reproduction of what a camera might capture (although upside down and grainy), the transformations of the acoustic input by the auditory system are dramatic and still not fully understood.

To understand perceptual processing of meaningful sounds, it is necessary to understand the acoustic structure of sounds in the world. An attempt at this was made in two papers by William Gaver (59, 76), in which he detailed the physics of sound producing events, dividing them into a hierarchy based initially on the materials involved in the events, gases, liquids or solids. From these basic classes he developed complex interactions and a taxonomy of sounds, which is detailed in (Figure 2). Although he aimed to cover a broad range of sounds, by his own admission he excluded very important classes of sounds, such as vocalizations and certain electronically synthesized sounds[5].

This is a critical point because not all sounds are equally relevant for listeners. Studies of auditory scenes (77, 78) have shown that the majority of sounds in the world are inharmonic and relatively stationary, but on the other hand studies on the similarity of environmental sounds (79) indicate that the major features humans listen for in sounds are harmonicity and amplitude modulation, and, further, listeners make a strong distinction between harmonic and non-harmonic environmental sounds. That is likely because harmonic sounds, requiring a cavity or resonating structure of some sort, are almost always generated by biological sources or devices specifically designed to produce them (sirens, musical instruments). On the other hand highly periodic sounds with inharmonic spectra generally reflect machinery (80) and water sounds are characterized by slowly modulated broadband noises, often saturated with transient components (59). One notable feature of vocalizations is they are one of the few naturally occurring classes of sounds that modulate non-monotonically both in frequency and time because of the flexible properties of the vocal tract. Although speech may be modulated slowly in perceptual terms, according to Plomp (81), the fact it is produced by a physical source is remarkable, since most objects in the world, having mass and stiffness, are not nearly so malleable on the time scales of speech.

4.3. The problem of auditory scenes

Of course sounds are almost never presented in isolation but in an auditory scene in which temporally

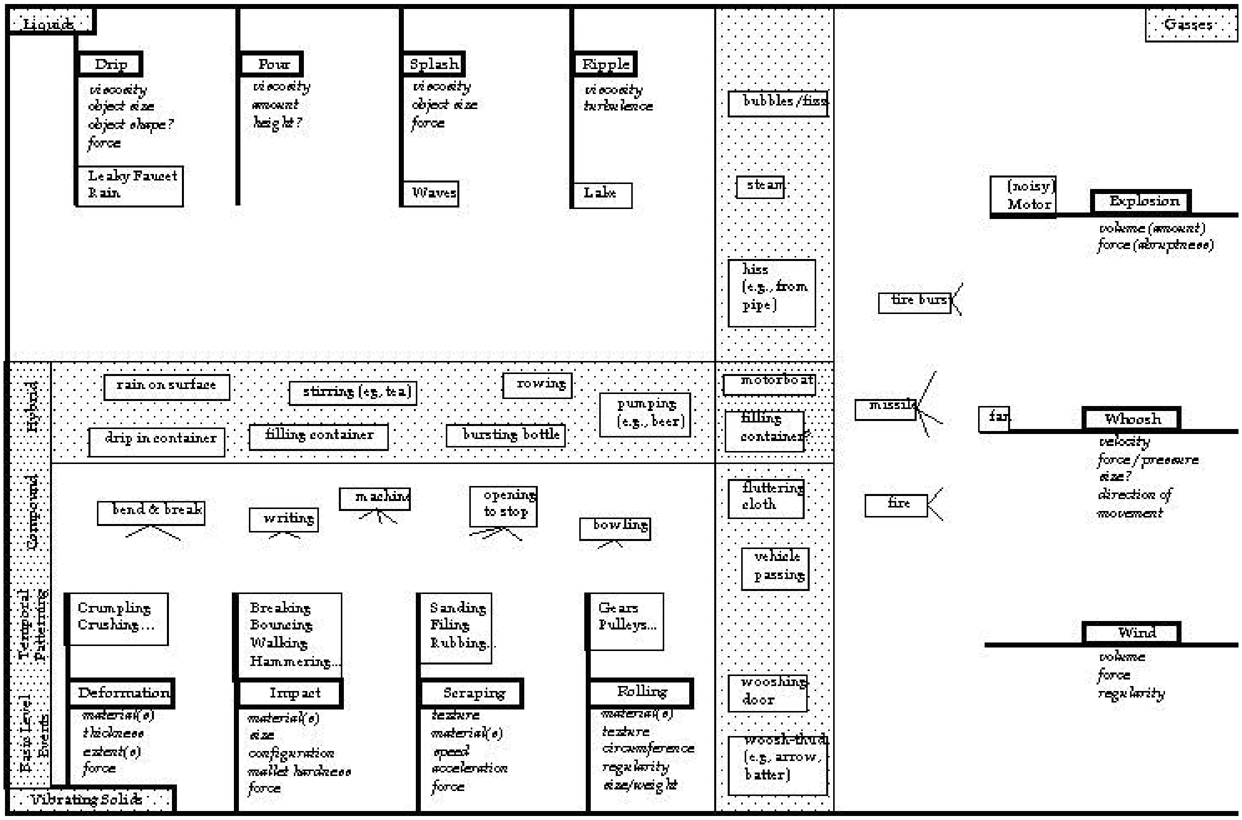

Figure 2. Gaver's (59) taxonomy of sounds.

linear mixtures of sounds enter the ear canal, and somehow are parsed by the listener. Bregman (82) described certain regularities of sound sources that can be exploited by listeners to separate out sounds, such as common onsets, coherent frequency transitions, and several other aspects. The issue of listening to one sound as opposed to listening to many sounds presents several problems because the acoustic features that are distinctive in isolation tend to disappear in sound mixtures. Nelken, Rotman & Josef examined the separability of frequency and time in a variety of naturally occurring sounds (83). In their analysis sounds which have coherent modulation across frequency bands over time are defined as being not separable (i.e., frequency is not independent of time). They found that single animal vocalizations, having FM components, are not separable in this sense; however a mixture of vocalizations will be separable because of the central limit theorem. A similar effect has been found with speech maskers. "Speech babble" consisting of eight or fewer voices tends to have large temporal fluctuations, resembling those of single speech, with a 4 Hz modulation spectrum peak (84) and speech-like spectra. However, above eight speakers the peak modulation frequency tends to move up to about 12 Hz and the spectrum approaches that of speech-shaped noise.

Part of the problem may lie in the general approach of hearing scientists of there being a signal and a masker, i.e., one relevant sound versus a background of stationary random noise, which brings to mind Brunswik's "bearded lady at the fringes of reality." As noted above, in the extreme case the long-term spectrum for large scale mixtures of sounds approaches a 1/f or "pink" noise with a flat envelope; but the world being unpredictable as it is, those relations are seldom stable and the actual background noise is seldom random or meaningless. Nelken, Rotman & Josef (83) observed in their mixtures of bird calls that the calls tended to come in clusters which added long term envelope fluctuations. In addition, sounds in real settings often have slow AM modulation because of microturbulence (78, 85). Nelken, Rotman & Josef hypothesized that these inherent fluctuations enabled recognition of individual vocalizations because of comodulation masking release (CMR): a single bird call will tend to be coherently modulated at quite a different rate than the background mixture, facilitating separation.

4.4. Coding in the auditory system

Learning the statistics of natural sounds is only one part of the puzzle. Understanding how the auditory system represents those sounds is critical, especially given the fairly radical transformations that occur in the auditory periphery (filtering in the outer and middle ear, bandpass filtering with nonlinearities in the cochlea, halfway rectification by the hair cells, and low pass filtering by the auditory nerve fibers). Some researchers have proposed complex time/frequency analysis in the cochlea (such as Patterson's Auditory Image model (86)) and the cochlea does seem to provide a good front end for many types of analysis such as detecting harmonic structure and coherent modulation across frequency bands. But since the cochlea itself has no receptors, many researchers have looked at the coding by the auditory nervous system for extraction of critical features. Nelken, Rotman & Josef (83) found evidence for CMR in the primary auditory cortex of cats. Reactions to complex modulation spectrum manipulations have been found in the forebrain of birds (87) and the auditory cortex of cats (88), leading some researchers to propose spectral temporal receptive fields in the auditory cortex, similar to visual receptive fields in the visual cortex (89, 90)

Since the auditory system evolved in response to properties of the sound environment, it is reasonable to assume that the system would be adapted to those, and measures of the information rate transmitted by auditory nerve fibers have shown that they transmit natural stimuli more efficiently than either white noise (91) or "non-naturalistic" sounds (92). Some researchers have attempted to find the optimal coding patterns for various types of natural stimuli, based on the notion of limited redundancy, that is, the messages carried by the individual nerve channels are as independent as possible (this approach is more applicable to stimuli in isolation than in mixtures; as mentioned in the Introduction in real-life situations, redundancy is desirable to provide robustness against signal degradation). This was proposed as far back as (93) and a fair amount of work in this area has been done on visual images (94). More recently a few researchers have applied this technique to environmental sounds: (95, 96) An intriguing finding was that the optimal coding strategy for vocalizations was quite different from that of non-vocal environmental sounds (97). For vocalizations, the optimal code resembled a Fourier transform, being more extended in time and frequency specific, where as for non-vocal environmental sounds it was more like a wavelet transform, being local in time. This is consistent with experimental data showing that harmonic sounds are regarded as perceptually quite distinct from non-harmonic sounds (79).

The findings fit quite nicely with the idea of the individual being well suited to the environment, and suggest that auditory research could benefit from more work designed to uncover the way humans and other organisms have adapted to the statistical regularities of the world of sound around us. Environmental sounds, as a class, are perhaps better suited to uncover these statistical regularities than speech. Containing both harmonic and transient components, speech is a more complex signal than most other naturally occurring sounds: the optimal processing strategy for speech was found to be a combination of Fourier and wavelet transforms (97). At the same time, speech is highly restricted both in terms of the possible sources and settings, and the skills involved in comprehending speech are not necessarily transferable to other listening tasks, such as for our ancestral hunter-gatherer trying to identify the source of the crunching sound in the bush ahead of him.

5. OUTSTANDING ISSUES IN ENVIRONMENTAL SOUND RESEARCH

Environmental sound research is at the stage similar to that of speech in the early part of the twentieth century, although fortunately the analysis tools at our disposal are much more powerful. There are several issues that need to be resolved, from the methodological to the theoretical. The most pertinent of these will be discussed below.

Very little in the field of environmental sounds research has been standardized, including the very language we use to describe them. Unlike speech and music, whose definitions are generally agreed upon, several different terms continue to be used to describe familiar naturally-occurring non-speech non-musical sounds, including "natural sounds", "familiar sounds", "everyday sounds" and "common sounds." The term "environmental sounds" seems to be the most common although it does suffer from some problems, namely it can be both too general (defining the "environment" is difficult; strictly speaking, all sounds occur in some environment) and too specific (many people automatically assume this means sounds associated with outdoor settings, such as forests). However, given the body of research that has used this terminology, it may be difficult to change now and perhaps in time the term will achieve general acceptance and its meaning will be more or less immediately obvious, at least among researchers.

Even strengthening the above definition, it is not clear that environmental sounds constitute a unitary group. As described earlier, there is considerable evidence that vocalizations and other harmonic sounds are treated as a unique class perceptually. However, one common thread of environmental sounds as defined here is that the goal of listening to them is to identify the source of the sound, unlike with speech perception where the source is usually assumed to be a vocal tract, and the important information is the semantic content of the signal (although speaker identification may involve some of the perceptual processes involved in environmental sound identification as well). Similarly with music it can be argued that the task of the listener is to extract the aesthetic structure, rather than identify specific instruments. Only infrequently does one listen to a piece of music to determine what instruments are being played, although inability to perceive variation in instruments' timbre may potentially interfere with music appreciation (98).

One implication of this is that for both speech and music, and environmental sounds there are different sets of relationships between temporal structure and semantic or aesthetic content, most likely due to the differences in the underlying atomic units of perceptual analysis (e.g., phonemes for speech, notes for music, and TBD for environmental sounds). A large number of environmental sounds can be identified at durations as short as 500 ms (30). In addition, temporal ordering is more important for both speech and music than for identifying a large number of environmental sounds, which are remarkably resistant to time distortions such as reversal (99). This applies more generally to sounds which are extended in time and have distinctive spectra (e.g., bowling, baby crying). The identification of impulsive sounds with strong transients such as hammering or footsteps is greatly hampered by time reversal windows as short as 30 ms.

The methodologies used to study environmental sounds are still in the early stages of development. Many experiments have used a single type of sound, such as the studies mentioned in the Introduction involving footsteps (9), struck objects (100, 101), hand claps (10) and bouncing and breaking bottles (8). This has the advantage of restricting the set of relevant variables immensely, and some of the factors involved in identification of a particular sound or physical feature of a source have been discovered in this manner (a more thorough description of this literature is in (102), pg. 30-47), although it is not clear whether these factors are applicable to a wide range of sounds. A few researchers have conducted studies using multiple exemplars (>40) of environmental sounds (13, 14, 30, 103) in which the goal was at least partly that of developing a standardized, normalized corpus which would theoretically be representative of all environmental sounds but the necessarily tedious work of replication and verification has yet to even start.

Part of the problem is the lack of urgency (and hence funding) for developing such a corpus, since difficulty in perceiving environmental sounds is rarely an explicit cause for concern among people, despite the cochlear implant satisfaction studies cited earlier – few people seek help because they cannot identify specific sound sources (e.g., birds chirping). Unlike difficulties in speech and music perception which are generally more apparent, there does not seem a direct way to assess effects of inability to identify common environmental sounds on quality of life.

Difficulties in perceiving environmental sounds may be further obscured by individuals' listening habits. Unlike speech or music, listening to environmental sounds is rarely an explicitly sought goal among people in industrialized societies (specific instances, such as auscultation, described in section 3, being an exception (29)). In daily life, environmental sounds are generally experienced at the background of the listener's attention, and may come to the forefront only when they denote danger (e.g. alarms) or when they are experienced anew after an extended period of auditory deprivation (e.g., as noted in section 2 with cochlear implant listeners). Furthermore, the widespread proliferation of high levels of generic background low frequency noise from various types of appliances and machinery (e.g., ventilation, highway traffic, loan mowers) often masks softer identifiable environmental sounds such as bird chirps or rustling leaves. Listeners may often disregard their inability to identify specific sound sources in their environment and dismiss potentially identifiable ones as general background noise (29). Thus, difficulties in environmental sound identification may be revealed only when explicitly tested with a large corpus in a quiet setting or when these sounds contribute to specific tasks (e.g., sonar operation, medical diagnosis).

Another little explored, but important topic in environmental sound testing relates to the effects of context on the perception of individual sounds. Few studies that have examined the effect of context to date have shown that perception of sound producing objects and their properties is affected by sounds that precede or follow it in time (72, 104). Ballas & Howard (104) reported an experiment in which the same metallic clang sound was perceived as a car crash when combined with a screechy valve turning sound or as a factory machine sound when combined with water drip and noise burst. Fowler (72) found that upon hearing the same sound of a steel ball rolling off a ramp listeners judged the steepness of the ramp differently depending on the duration of the following sound made by the ball when it continued to roll on a flat surface. However, context effects demonstrated in these studies may be restricted to the specific sounds used, and may be difficult to generalize. Contrary to intuitive expectations, "natural" or "typical" acoustic context may not have a facilitatory effect on the identification of an environmental sound, and in some cases, may result in inhibition (105). For instance, in a perhaps most comprehensive study of context effects to date, it was not found that a more typical context has a facilitatory effect on the identification of an environmental sounds compared with identification of these sounds in isolation (106). However, the authors did find that target sound identification in more typical context was better than in a random or an atypical one. In another study the identification of environmental sounds embedded in natural auditory scenes was actually better in inappropriate contexts (for example, a horse galloping in a restaurant) than in appropriate contexts (a dog barking in a playground)(105). Specific reasons for variability in the effects of context on environmental sound perception may not become clear until context itself is classified with more precision.

Difficulties in classifying and defining context are due to the fact that the same environmental sound may be typically heard in a variety of real life situations and settings, where it is not always clear what constitutes a "typical" acoustic context. Furthermore, there are a large number of highly familiar environmental sounds that the majority of listeners hear only as special effects in movies or radio shows. For instance, while most listeners are familiar with the sounds of crashing cars and gunfire, only a small group may be exposed to these sounds in outdoor settings on a regular basis. Similarly, few urban dwellers have a chance to hear cows moo or roosters crow (11, 13, 103), but have no difficulties identifying them correctly. Thus, the "typical" context of these sounds is more often defined by the imagination of sound engineers than the actual context in which these sounds are heard in real-life. In some cases, listeners may even judge synthesized analogues of environmental sounds as more realistic than accurate recordings of actual events (107).

Taking a broader view of environmental context, when environmental sound testing is conducted in the laboratory, it is not clear how the testing environment itself (which at the time of testing constitutes the overall environmental sound context) may affect listeners' perception. Clearly, personal significance of the sounds of 'gun fire' or 'lion roaring' would be quite different if those sounds are heard "live" on the street or in the jungle instead of headphones in the laboratory. Although it seems that the context and the setting in which sounds are presented does not interfere with listeners' ability to identify their sources, it is possible that differences in listeners' reaction may emerge at other cognitive and physiological levels.

Some of the methods of speech research (e.g., bandpass filtering and vocoder processing) have been used on environmental sounds with some success but it is not clear how far other methods used in speech research can be applied, since many of them rely on both molecular and large-scale structure of speech that may or may not be relevant to environmental sounds. With both speech and music, the low level units of analysis (phonemes and notes, respectively) are well-established (if not entirely uncontroversial), as are the grammar and syntax. Neither of those is known for environmental sounds, or even if they exist. This renders many of the common paradigms in speech and music studies (e.g., formant analysis or melodic transposition) problematic for environmental sound research.

Although many methodological and theoretical issues remain to be resolved, environmental sounds already play an important role in experimental research. As mentioned above, certain environmental sounds are already standard stimuli in EEG studies, and clinical applications of environmental sounds are increasing. Certainly investigators who need a particular type of sound to suit their research question (one of the more unique examples was in (96), who used a fingernail clicking against a tooth) should not hesitate to use it. However, to avoid reams of ungeneralizable results, communication with other people who have worked with environmental sounds is strongly advised. Researchers who are interested in using environmental sounds but are not sure where to get them or the legal issues involved (an important topic not covered here) are advised to consult Shafiro & Gygi (108) as a starting reference.

The cognitive dimensions of environmental sound perception have suffered the same lack of activity as other areas of environmental sound research. Since environmental sounds are complex stimuli that are learned, central factors, such as memory and attentional capacity are obviously to be considered. Many of the same issues that arise in learning of speech are applicable to environmental sounds, such as lexical density, attention to relevant dimensions and categorical perception.

There have been some attempts to examine how environmental sounds compare to speech sounds on various cognitive tasks, such as recognition memory, effects of priming on identification, and, interference caused by speech or cross-modal stimuli (12, 109-115): see Gygi (102), pg 23-25 for a review) which have yielded some promising results. In general, these more cognitively-oriented studies seem to indicate that environmental sounds are remembered differently and less well than speech. Whereas speech, and to a lesser extent music, can be abstracted away from the auditory stimulus, retaining largely the semantic content (perhaps because for both classes of sounds there exist a standardized notation system), it seems that memory for environmental sounds is more explicitly bound to the details of the waveform. However, as with other studies mentioned above, the use of different catalogs of environmental sounds and different methodologies make the findings difficult to compare.

6. A VISION OF THE FUTURE

The field of environmental sound research will continue to develop and expand into new directions opening numerous opportunities for practical and theoretical work. It may be too early to know specific ways in which the outstanding issues described in the previous section will be resolved. However, a speculative outline of the future of environmental sound research may help one to set the present course.

Although in principle the number of environmental sounds is virtually infinite, in practice listeners are exposed to and are familiar with only a subset of all sounds, and can accurately identify sound sources of an even smaller subset. Thus, one practical approach to constructing a representative environmental sound test is to establish ecological frequency, familiarity, and identifiability of specific sounds listeners are exposed to. These initial measurements can then constitute the basis for developing specific environmental sound tests that would be representative for specific populations of listeners depending on their age, cognitive, and linguistic abilities. The ground work for this approach has been already laid down by previous research (14, 30, 41) which has provided some initial normative measurements.

Because of inter-population differences in experience and familiarity with different sounds, it will likely not be possible to develop a single environmental sound test that will suit all research and clinical needs. Instead, a number of such tests will be developed and standardized to be used for a variety of purposes. In audiology, as described in Section 3, environmental sound tests have the potential of being used for estimating hearing abilities in young children as well as cognitively and linguistically impaired individuals (23, 41). Rehabilitative techniques can be developed for cochlear implant patients and hearing aid users that would increase their awareness of their environment and improve their auditory memory and cognition through better environmental sound training. Neurologists may be able to use environmental sound tests for differentiating auditory agnosia, a condition when the meaning of common sounds cannot be perceived, from aphasia, which is language impairment. One such test, the Sound Recognition Test, using thirteen environmental sounds and pictures rather than labels, was developed by Spreen and Benton (116). Research in auscultation (51) can indicate perceptually salient acoustic cues in specific bodily sounds that are perceived by experienced but not novice practitioners. Training programs can then be designed to emphasize specific acoustic parameters that need to be learned for accurate diagnosis.

Research into the relationship between the physical and perceptual aspects of environmental sounds will provide a basis for developing perceptually motivated synthesis models for production of existing environmental sounds in auralization, and for designing new sounds for representing complex information structures. Indeed, the process of mapping the relationships between the acoustic parameters of an artificially constructed sound and its significance can be substantially enhanced through the study of existing meaningful sounds. This knowledge can provide a basis for creating new sounds such as warnings, alarms and common electrical appliances. For instance, specific alarm sounds can be created for hearing impaired or cochlear implant users that take into account specific strengths and weakness of the listeners' auditory system. Cues in harmonic structure that may be difficult to perceive by listeners with poor frequency resolution can be supplemented by clearly defined temporal cues in the sounds' envelope. As an alternative to constructing new sounds, existing familiar environmental sounds can also be used as warnings for specific types of situations (117), or as auditory data display objects in which changes in an underlying variable are linked to some property of the sound source (118).

Our hopes for the future are several: in addition to exploring perceptual and acoustic properties of individual environmental sounds, more research attention will be paid to ensembles of environmental sounds that are more typical of everyday listening environments. The role of context on the perception of specific sounds, and the question of how individual sounds arranged in particular ways in the temporal and spectral domain affect the perception of the environment as a whole will be investigated. More systematic research will be carried out into positive psychological effects of acoustic environments comprised of specific sound inventories. This will provide a basis for constructing artificial sonic environments to enhance listener performance and well-being. On the other hand, more real-world acoustic environments will be used for testing performance of sensory aids for the hearing impaired and other audio equipment. Although real-world environments are less controllable that the artificially generated noises traditionally used for testing various hearing instruments, their use will add to the ecological validity of such assessments. Recent technological advances in sound recording, editing, and synthesis technologies have considerably simplified the process of making real-world recordings usable in the laboratory.

Another important aspect of environmental sound perception that will undoubtedly receive attention in the future is the study of active responses to sounds in one's environment, and the effects of listener activities on sound perception. Individuals dynamically interact with objects and events in the environment and modify their behavior based on what they perceive to be happening around them. Often specific sounds call for quite complex responses: moving to avoid collisions, running after an ice cream truck, or opening a door upon hearing a bell. Some data have suggested that responses to auditory stimuli by individuals who are actively engaged in some physical or mental task are likely to be different from those of an individual who is focusing solely on the acoustic information (119). One study found that reaction times for turning away from danger in a simulated driving task were shorter when a warning tone indicated the escape route rather than direction of danger (120). Advances in real time synthesis and computational speed will make this line of research approachable within controlled laboratory settings.

Defining formal relationships between the acoustic and perceptual structure of environmental sound will stimulate further development of sound recognition by machines. Machine listening applications will be geared toward the analysis of specific sounds such as use automatic classification of heart beats (121), respiratory sounds (122), or the sounds of automobiles (123). Certainly, devices which could perform reliable identification of environmental sounds could be very useful in security applications, noise monitoring and assisted living situations. As an example, (124) reported on an automatic system designed to recognize a type of pig cough that would indicate if a pig was sick. Specific environmental sounds have great salience in certain contexts, and research can uncover those acoustic features that enable identification (or perhaps separation from background noise).

Multi-modality studies using environmental sounds are another promising and largely untrodden area of research. Lawrence and colleagues performed a variety of experiments using comparisons between different modalities (vision, touch and hearing). They found that tactile recognition of common objects was superior to auditory recall for environmental sounds (125). Blind people were no different from sighted in this respect (126). Cross-modal priming between vision and audition showed no advantage for either modality; pictures primed with appropriate sounds were recognized as easily as sounds primed with appropriate pictures (127). Interactions of auditory and visual information have been studied for some specific types of environmental sounds. In a task involving perception of elasticity for a bouncing ball, the visual and auditory modalities were found to be equivalent in terms of extracting relevant information from the kinematics of the bounce (128). Some studies have shown that appropriate sounds can help resolve ambiguous visual information for a physical event. In a display in which two disks could be seen as either bouncing off each other or passing through each other, the addition of a transient increased the likelihood of a collision percept (129). Similarly, the sound of a ball rolling or hitting the ground influenced the visually perceived path of a 3-dimensionally modeled ball (130). Not surprisingly, visual cues have been found to aid listening in cocktail party situations (131). The use of combined audiovisual (and perhaps tactile) information is bound to play a larger role in future research, for in the world we live we seldom are forced to use only a single modality. In summary, we hope this article has demonstrated that environmental sounds offer numerous openings for new and original research in quite diverse areas that are still waiting to be explored.

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Footnotes: [1] Some additional testimonials can be found at http://www.healthyhearing.com/library/testimonials.asp, [2] This 6 DVD set can be ordered from 50 North Medical Dr. Room 3C120, Salt Lake City , UT 84132, [3] http://www.cochlearamericas.com/Support/169.asp, [4] In the past two or three decades more attention has been focused on ‘complex sounds,’ which can refer to, among other things, tonal sequences, sounds with complex spectra, such as profiles and rippled noises and sounds that change over time (e.g., co-modulated sounds). Although these are more similar to the kinds of auditory events experienced in day-to-day living than were sinusoids or clicks, the demands of psychophysics generally require that their spectral-temporal makeup be parametrically manipulable, and so they are still far simpler than most naturally-occurring sounds. [5] As discussed in Section 3, some electronically synthesized sounds are a quite new auditory experience, because they do not necessarily reflect physical sound sources and so are not bound by the acoustic laws we have learned. How this affects the rest of our everyday listening will likely not be clear for some time, although see Truax (29) for interesting speculations.

Key Words: Environmental sounds, Ecological Acoustics, Practical Applications, Sonification, Auralization, Review

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http://www.bioscience.org/current/vol12.htm