Auditory Distance Estimation in an Open Space

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1. Introduction

Auditory spatial perception is the ability to perceive relative locations of sound sources in the environment and the spatial character of the surrounding acoustic space. Any property of an auditory event causing a rise to spatial sensation is called a spatial cue. Specific types of judgments resulting from spatial cues are categorized and discussed in the psychoacoustic literature as horizontal localization, vertical localization, auditory distance estimation, and spaciousness assessment. While judgments of directions toward sound sources received considerable interest in psychoacoustic literature, the judgments of auditory distance, and especially the judgments of spaciousness, received much less attention.

Human horizontal and vertical localization judgments and formal and methodological issues related to directional localization of sound sources have been recently reviewed by Letowski and Letowski [1]. Comprehensive summaries of the issues related to auditory distance estimation have been published by several authors including Coleman [2], Blauert [3], and Zahorik et al. [4]. However, these summaries were based on auditory research conducted primarily in closed spaces and at relatively short distances up to about 25 m. Very few studies were reported to be conducted in an open space and they never involved distances exceeding 50 m.

The present chapter is intended to address the distance estimation issues for distant sound sources in an open space and discuss them in the context of our current knowledge of auditory distance estimation. The first part of the chapter provides a comprehensive review of concepts related to auditory distance judgments. It also includes an overview of environmental conditions that effect sound propagation in both closed and open spaces. The second part provides new distance estimation data for free field sound sources located at distances from 25 to 800 meters and uses these data as a basis for a discussion of the environmental variables affecting auditory distance estimation in an open space.

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2. Distance perception

Distance perception, sometimes referred to as ranging [5], is the human ability to determine the distance between oneself and a target in space or the distance between two targets in space. The distance to a target can be judged on the basis of its visual, olfactory, and/or auditory properties. Distance judgments may have a form of distance discrimination or distance estimation. Distance discrimination is a relative judgment of the distance in terms of further-closer, less-more, or same-different. Distance discrimination threshold is calculated as a fraction (percentage) of the distance change that is noticeable by the observer. Distance estimation is an absolute judgment about distance in terms of meters, feet, or time to travel; categorical judgment of distance in terms of near-far or predetermined categories; or a direct-action estimation of distance by reaching for the target or walking toward the target. The first two classes of judgments are *explicit estimations* while the third one is an *implicit estimation* (e.g., [6]). Perceived and physical distance seem to be in general monotonically related but can be quite different. In general, human estimation of distance is much less accurate than the determination of angular direction and observers normally underestimate the magnitude of distance.

There are three basic dichotomies that can be used in classifying distance judgments. The first dichotomy divides distance judgments into static (explicit, no-action) and dynamic (implicit, directed-action) behaviors of the judges (observers, listeners). In static (no-action) estimation the judge estimates the distance to a given target from his/her stationary location. These estimates are usually numerical but also can be comparative in relation to other objects in space. In implicit (directed-action) estimation the observer reaches for (e.g., infants) or walks toward (e.g., blindfolded) a target.

The second dichotomy refers to static (stationary) and dynamic (moving) behaviors of the targets. Although dynamic behaviors of judges and target are discussed in the theoretical part of this chapter, the main focus of the chapter is on human ability to assess the distance numerically from a stationary position (explicit estimation). In an open space and for long distances the directed-action (implicit) estimation is often impractical and in many cases unrealistic.

The third dichotomy divides distance judgments into egocentric judgments and exocentric judgments [7]. Egocentric judgments, or body-centered judgments, are the judgments where the point of reference is the observer's location in space. The specific subjective reference point that people use for egocentric visual judgments is the point that lies between the eyes of the observer. In the case of auditory judgments it is the midpoint of the interaural axis of the listener [8-9]. The estimation that the target is located at a certain distance from the observer is an egocentric judgment. In the case of auditory judgments the sound source can be perceived as located either in the head of the listener (such situation takes place in most headphone listening) or outside of the head. In the latter case, the sound source can be in front of, behind, to the left, to the right, above, or below the listener. Exocentric judgments, also called allocentric or geocentric judgments are based on the external frame of reference and are independent of the actual location of the observer. The location of one target in space is referenced to the location of another target (e.g., a landmark) or to the axes of the external frame of reference. Giving the response as *further north* rather than *further to the right* is an exocentric judgment. This chapter is limited to auditory egocentric judgments and exocentric judgments are not discussed.

3. Auditory distance estimation

Auditory distance estimation is an estimation of a distance to a sound source on the basis of perceived sound. Estimated distance is perceptual measure of a physical distance. The goal of auditory distance estimation is to determine the perceived location of a real or phantom sound source generating a specific auditory event. Such judgments can be made in real surrounding space in respect to natural and electroacoustic (loudspeakers) sound sources or in virtual reality space simulated either through loudspeakers or headphones.

The results of auditory distance judgments are dependent on the availability of several auditory distance cues. Depending on the state of motion of both the sound source and the listener the distance estimation cues are usually classified as static cues (stationary sound source and listener) and dynamic cues (moving sound source or listener) [10-11]. The five basic *static cue*s include: sound intensity, direct-to-reverberant energy ratio, sound spectrum, level of background noise, and auditory parallax (interaural differences). The *dynamic cues* include motion parallax and acoustic tau effect (estimated time-to-contact). Please note that static cues operate as well in both the static conditions and the dynamic situations when the either the listener or the sound source is moving. In this chapter only stationary sound source and stationary listener situations are considered.

Another important characteristic of the distance cue is the absolute or relative character of the cue. Absolute cues are those that do not require the listener's familiarity with the sound source and surrounding environment in making distance estimates. Relative cues are those that do. Sound intensity, sound spectrum, and background noise are relative cues and all others are absolute cues. In order to make an informed (relatively accurate) distance judgment using relative cues the listener must be familiar with the sound source (have *a prior* knowledge about sound emission level) and surrounding environment. A prime example of a relative cue is sound intensity. Sound intensity alone is insufficient for the listeners to determine the actual distances to an unfamiliar sound source since its original sound intensity is unknown to the listener [12]. However, with increasing familiarity with both the given sound and surrounding environment distance judgments based on sound intensity can become quite accurate [2, 13].

Other non-specific factors contributing to auditory distance estimates are the listener's expectations, past experience, and non-auditory cues (e.g., visible objects). For example, whispered speech (produced typically at a level of about 30 dB SPL at 1m) is expected by the listener to come from a nearby sound source whereas, normal (conversational) speech (65 dB SPL at 1 m) and a shout (90 dB SPL at 1 m) from much larger distances [14-15]. Therefore, it should be expected that the distance to artificially amplified whispered speech produced by a distant sound source will most likely be greatly underestimated by the listener because a whisper is expected to come from a relatively close distance. More in-depth discussion of acoustic cues and other general factors affecting distance estimation judgments may be found elsewhere (e.g., [4, 16]).

Auditory distance is a prothetic (ratio scale) perceptual continuum. It has the natural zero point (egocenter point) and a unit of measurement (e.g., meter) [17-18]. Each prothetic continuum (y) is exponentially related to the underlying physical dimension (x) by a psychophysical Power Law $y=kx^n$ (see Stevens Power Law [17-19]). In case of distance perception the Power Law has the form

$$PD = kd^{a} \tag{1}$$

where PD is the perceived distance, d is the physical distance, α is the sensitivity of the observer to the perceived distance, and k is a constant dependent on the unit of estimation. If $\alpha = 1$, then the changes in the physical or intended distance to the target are accurately perceived. If $k=1$ and $\alpha < 1$ the distance is underestimated and when $k=1$ and $\alpha > 1$ then the distance is overestimated.

In the case of vision, egocentric visual distance estimates are nearly linearly related to physical distances for short distances up to 15-20 m [20-25]. At larger distances observers begin to underestimate the physical distance with estimates converging at a certain asymptotic ceiling (visual horizon) [26-29]. In the case of audition the same general relationship exists but the degree of distance underestimation is greater and the auditory horizon [30] is achieved earlier. The distance to the horizon depends on the listener, available auditory cues, and the acoustic environment, thus it can vary from one situation to another. Zahorik [31] compared results of 10 studies (33 data sets) and reported that the average exponent of the exponential function as $\alpha = 0.59$ (SD=0.24) and the constant of proportionality as k=1.66 (SD=0.92). The exponents fitted to individual data ranged from 0.15 to 0.7 and varied much larger between the listeners than between the test conditions (environments). His own study conducted in virtual space (distances from 0.3 m to 14.0 m) resulted in $\alpha = 0.39$ (SD=0.13) and k = 1.32 (SD=0.56). In a later study, Zahorik et al. [4] expanded the analysis conducted by Zahorik [31] on the results of 21 studies (84 data sets) and reported the average exponent as $\alpha = 0.54$ and the constant of proportionality as k=1.3.

Several studies performed both in real and simulated (headphones) environments indicated that at short physical distances, the perceived distance increases almost linearly with the physical distance [30, 32] or the listeners slightly overestimate its value [4, 33-37]. The tangent of the initial slope of the performance function is close to unity and it can be said that for short distances the auditory distance is approximately a linear function of the physical distance. This range is limited to 1-3 m in both real and virtual environments and it varies depending on both the listening conditions and the listeners [4, 14, 30, 32].

At larger distances (3-48 m) listeners increasingly underestimate the actual distance to a sound source although the distance judgments are slightly more accurate with implicit (e.g., walking toward the source of sound) than explicit (numeric estimation of the distance when both sound source and the listener remain stationary) estimation (e.g., [37]). In both cases, however, the degree of the underestimation was critically dependent on the availability of specific auditory distance estimation cues, the listener's familiarity with the sound source, visibility of the environment, and the listener's expectations [4, 16, 38-39]. In general, the distance estimates were the most accurate in the case of live talkers [15, 30, 40]. It is also noteworthy that in the case of reproduced speech phrases listeners can make relatively accurate estimates to a source playing natural speech but fail when the speech is played backwards [38, 41].

Regrettably, despite an extensive knowledge accumulated to date about auditory distance perception to sound sources located at short and intermediate distances in enclosed spaces (both anechoic and reverberant) it is still unclear to what extent this knowledge may be applied to sound sources located in an open field at large distances (100 m and more) and operating under various atmospheric conditions. It is unknown what specific role auditory distance cues will have under such conditions and how the open field conditions may affect listener's expectations and perception. A short review of sound behavior under various propagation conditions is provided below.

4. Sound propagation in space

The egocentric auditory distance is the apparent distance from a listener to a sound source. This distance is dependent on the number of auditory cues resulting from the characteristics of the sound source, abilities of the listener, and factors related to sound wave propagation in the surrounding space. The basic sound source, environment, and listener properties that affect auditory distance estimation judgments are shown in Figure 1.

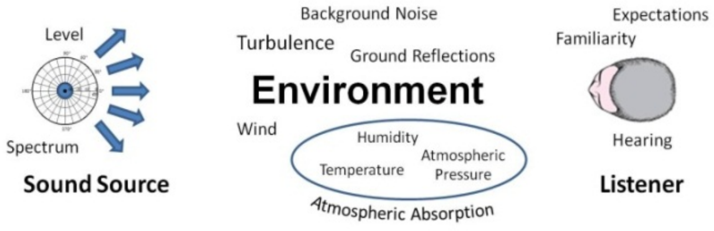

Figure 1. Basic variables that affect auditory distance judgments in an open environment. In a closed environment the additional variables are reflections from space boundaries (echoes and space reverberation) while some environmental variables not present.

4.1. Spherical wave propagation

For an ideal point source (acoustic monopole) radiating sound energy in an unbound sound field (free field), sound energy spreads in all directions (wave front spreading) and the sound intensity I at a given point in space is a function of distance r from the sound source

$$I = \frac{W}{4\pi r^2}, \tag{2}$$

where W is the power of the sound source [watts]. The equation (2) is commonly referred to as the *inverse-square law*. This law applies only to the ideal omnidirectional sound source operating in unlimited space and in the ideal medium, which does not attenuate sound energy. Based on equation (2), the sound intensity level i radiated by the sound source decreases at the rate of 6 dB for every doubling of the distance[1] from the point-like sound source (e.g., idling car) to the observer (listener) according to the formula

$$\Delta i = 10log\frac{I_2}{I_1} = 20log\frac{r_2}{r_1}, \tag{3}$$

where Δi is the difference in the sound intensity level between the sound source location and the observation point and I_1 and I_2 are the sound intensities at the sound source and at the observation point, respectively. Please note that the 6 dB rate of sound decay means that sound intensity decreases four times and sound pressure decreases twice per doubling of the distance. In calculating sound intensity level (dB IL) and sound pressure level (dB SPL) existing at a specific point in space, the common reference values are I_o=10^{-12} W/m^2 and $p_o = 10^{-6}$ Pa, respectively. The 6 dB decay per doubling of the distance only applies to free-sound field or anechoic conditions.. Typical sound decay outdoors over soft ground is about 4.5 dB per doubling the distance. In reverberant environments the decrease is even less, e.g. 4.25 dB in a normal room, due to sound reflections from space boundaries [43].

Assuming that sound intensity at the sound source location is always measured at the distance r_1=1 m, the equation (3) can be reduced to

$$\Delta i = 20\log(r_2). \tag{4}$$

Equations (3) and (4) are valid for an ideal sound source operating in a free sound field but would fail in the presence of reflective surfaces where the sound attenuation with doubling the distance can be expected to be no more than 4-5 dB (e.g., [43]).

Real sound sources, unlike the ideal point source, have finite dimensions and cannot be treated as point sources in their proximity. The sound waves produced by various parts of a real sound source interact in the space close to the source's surface creating; due to constructive and destructive interference of multiple waves originating from the sound source's surface; a complex pattern of spatial maxima and minima of sound intensity. In this region the sound intensity does not obey the inverse-square law and the particle velocity is not in phase with sound pressure. However, at some point in space these separate pressure waves combine together to form a relatively uniform front propagating away from the source. The distance from the sound source where the pattern of spatially distributed maxima and minima merges

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[1] . In the case of a line sound source, such as moving train or busy highway, producing cylindrical wave, doubling of distance from the sound source results only in a 3 dB reduction of sound intensity level.

in a uniform waveform front is approximately equal to the wavelength (λ) of the radiated sound [43]. The sound field where the sound source can be treated as a point source and the sound wave can be treated as a plane wave is called the *far field*. The area near the sound source where these conditions are not met is called the *near field*.

Most real sound sources are not omnidirectional as the point sound source and radiate most of their energy in certain specific directions. Such sound sources are called directional sources and can be further referred to as dipole, quadrupole, etc. The directionality of a sound source is captured by its *directivity factor Q* and it needs to be taken into account in calculating sound intensity existing at a given distance and direction. Factor Q depends on sound frequency and is equal to one (Q=1) at low frequencies when the wavelength of a sound wave is large in comparison to the dimensions of the sound source and the sound source is effectively omnidirectional. Factor Q can be as large as 10 or more for very directional sound sources. The logarithmic form of the factor Q

$$DI = 10 log Q, \tag{5}$$

is called *directivity index DI* and is expressed in dB.. For an omnidirectional sound source radiating into unlimited free space, DI=0. For the same sound source radiating energy over ideal reflective surface (hemispherical radiation), DI=3 dB [49]. To account for sound source directivity the equation (2) can be modified as

$$I = \frac{QW}{4\pi r^2}, \tag{6}$$

where Q is the directivity factor of the sound source. This equation is only valid for the observation point that is located on the main radiation axis of the sound source.

4.2. Atmospheric attenuation

In a real medium, such as air, sound energy propagating through the medium not only spreads in different directions but is also absorbed by the medium resulting in an exponentially decaying of energy described as the *inverse exponential power law* also called *Beer-Lambert law*. According to this law

$$I = I_o e^{-\alpha d}, \tag{7}$$

where I_o and I are sound intensities at the sound source and the observation point, respectively, d is the distance between these two points, and α is the absorption coefficient of the medium. Absorption of sound energy by a medium, called *atmospheric absorption*, is the result of internal friction within the medium that converts acoustic energy into heat. The basic mechanisms of atmospheric absorption are heat conduction, shear viscosity, and molecular relaxation processes [44]. The amount of energy loss caused by these mechanisms depends on sound frequency, temperature, and atmospheric (static) pressure within the medium and, in case of molecular relaxation processes, on the humidity of the medium (air). This means, that changes in meteorological conditions (weather) have a large effect on sound propagation. Note that although light rain, snow, and fog have relatively very small effects on sound propagation, their presence at larger quantities affects air humidity. The relations between the amount of sound energy absorbed at given frequencies by a medium and meteorological conditions (temperature, atmospheric pressure, and humidity) are complex and non-monotonic functions and the actual amount of resulting absorption depends on specific combinations of these conditions. For example, sound absorption at the temperature of 30 °C is greater for relative humidity of 10% than for 40% while the reverse is true for the temperature of 15 °C (e.g., [45]).

Combining equations (6) and (7) we can predict sound intensity in a real medium as

$$I = \frac{QW}{4\pi r^2} e^{-\alpha d}. \tag{8}$$

At intermediate distances, up to approximately 200-300 m, and at low frequencies the loss of sound energy due to atmospheric absorption by a laminar (not turbulent) medium is usually small (less than 1 dB) and can be neglected for practical purposes [46]. However, at large distances and high frequencies energy loss due to atmospheric absorption can be quite large and exceed the loss caused by a three-dimensional spread of energy. The effect of atmospheric absorption on sounds with high frequency energy above 10 kHz “can become distinctly audible at distances as short as 15 m” (3, p126).

The relationship between the coefficient of absorption (α), sound frequency, and temperature, atmospheric pressure, and relative humidity of the propagating medium can be calculated as

$$\alpha = 8.686 f^2 \sqrt{\tau} \times \left[\frac{1.84 \times 10^{-11}}{\rho} + \frac{(b_1 + b_2)}{\tau^3} \right], \tag{9}$$

where f is sound frequency in Hz, τ is relative temperature ($\tau = T/T_{20}$ in K; T_{20}=293.15 K), ρ is relative atmospheric pressure ($\rho = p/p_n$ in Pa; p_n=101,325 Pa), r_h is relative humidity in %, and b_1 and b_2 are complex coefficients dependent on relative humidity r_h in %, relative temperature τ, sound frequency f, and relaxation frequencies f_n and f_o of nitrogen and oxygen (see ISO 9613-1:1993(E) standard [47], Southerland and Daigle [44], or Salomons [48] for more detailed description of b_1 and b_2 coefficients, which are functions of some of the variables listed above). According to this formula, the coefficient of absorption is proportional to the square of the frequency and is a complex function of weather conditions. The formula is valid for pure tones and narrow-band noises. Its accuracy is estimated to be ± 10% for $153 < T < 323$ K, $0.05 < h$ (concentration of water in the atmosphere; $h = r_h (p/p_n)$) < 5%, $p > 200{,}000$ Pa, and $0.0004 < f/p < 10$ Hz/Pa [48, p111]. An example of the dependence of the absorption coefficient on frequency for a specific set of environmental conditions is shown in Table 1. Note, however, that equation (9) does not take into account the presence of wind and properties of the ground’s surface.

Spherical spread of sound energy (equation 2) and atmospheric absorption (equation 7) are two main sources of attenuation of energy of the propagating sound. However, there are also

f_c	25	50	100	200	400	800	1600	3150	6300
	31.5	63	125	250	500	1000	2000	4000	8000
	40	80	160	315	630	1250	2500	5000	10000
A	0.018	0.07	0.25	0.77	1.63	2.88	6.3	18.8	67.0
	0.028	0.11	0.37	1.02	1.96	3.57	8.8	29.0	105.0
	0.045	0.17	0.55	1.31	2.36	4.58	12.6	43.7	157.0

Table 1. Atmospheric absorption coefficient α (in dB/km) for the preferred 1/3-octave center frequencies f_c (in Hz) [T=283.15 K (10°C); r_h=80%; p=101,325 Pa (1 atm)].

several others. Sound waves propagating close to the ground surface are absorbed and reflected by the ground. This additional factor affecting sound propagation is called ground attenuation. Constructive interactions between direct and reflected sound waves may increase the sound level at the listener up to 6 dB. Destructive interaction may in the worst case completely cancel out the sound. In general, the softer the ground the greater ground attenuation in reference to an ideal reflective surface. The overall amount of ground attenuation depends on the type of ground (ground impedance), sound frequency, the distance over the ground, and the heights of both the sound source and the listener above the ground surface. In the case of a grassy field the ground absorption is most pronounced in 200-600 Hz range and extends toward higher frequencies [44, 49]. The closer the sound source is to the ground surface the greater amount of ground attenuation and greater attenuation of energy at higher frequencies. Fortunately, in many cases ground effects are of little consequence for transmission of sound at heights of more than 1.5 m above ground level [50].

The presence of wind and changes in air temperature with level above the ground surface are additional factors affecting sound propagation. Both these factors are discussed in the next section.

4.3. Wind and other open space effects

When sound travels through still air with uniform atmospheric conditions, it propagates in straight lines. However, wind conditions (velocity and direction), as well as temperature, changes in altitude (height above the ground) affect sound velicity and cause sound waves to propagate along curved lines. Under normal sunny conditions solar radiation heats the earth surface and at lower altitudes the atmosphere is warmer and sound velocity is higher causing a temperature gradient. In the evening, the earth surface cools down and the temperature gradient reverses itself. These two respective temperature conditions are called temperature lapse and temperature inversion. Similarly, wind conditions depend on the height above the ground due to the slowing of the wind at the ground surface due to surface friction. This causes additional wind gradients. When sound velocity decreases with height (upwind sound propagation; daytime sunny warming of the ground) it causes an upward bend of the sound wave (upward refraction). Conversely, when sounds velocity increases with height (downwind sound propagation; evening temperature conversion chilling the ground) it causes a downward bend of sound waves (downward refraction). Upward (downward) refraction of sound caused by the wind can decrease (increase) the expected sound level at the listener location compared to no wind condition by as much as 10 dB depending on the wind strength and change the region of the audibility of sound from smaller or larger.

Atmospheric turbulence, i.e., existence of regions of inhomogeneity in air velocity; caused by local variations in temperature and wind velocity; also affects sound propagation by scattering and focusing sound energy. The changes in sound level caused by atmospheric turbulence can be as large as 15-20 dB, are time dependent, and are characterized by increased sound level in acoustic shadow zones. In addition, all solid objects, such as berms, barriers and towers that are in the path of the propagating sound, disrupt natural propagation of sound energy causing frequency-dependent diffraction and reflection of sound energy. In the case of trees and forests their sound attenuation effect is usually negligible and should only be taken into account at high frequencies (5 dB per 30 m at 4000 Hz [52]). For frequencies above 2 kHz sound attenuation caused by dense forest made of large trees (e.g., jungle) can be estimated as [53]

$$\Delta I\, d = 8.5 + 0.12D, \tag{10}$$

where D is the depth of an infinitely wide belt of forest[2] (m). This estimation is somewhat higher but not much higher than estimation of sound wave attenuation for grassy areas. All these phenomena and mechanisms affect propagation of sound energy in the open space and ultimately affect sound source distance estimations.

4.4. Closed space effects

In closed spaces reflections from space boundaries distort the smooth decrease of sound intensity with the increasing distance from the sound source. Early sound reflections may cause local reinforcement or decrease in sound energy in various locations in the space while the late and multi-boundary reflections fuse together, forming a characteristic delayed trace of sound called reverberation. Reverberant energy is roughly independent[3] of the distance from the sound source and can even dominate overall sound energy at large distance from the sound source. According to the *Hopkins-Stryker Equation* [55] sound intensity at a given point in a closed space is equal to

$$I = W\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right), \tag{11}$$

where the first element is sound intensity of a direct sound and the second element is sound intensity of the reverberant field caused by space reflections. R is the room constant (in m^2) dependent on total absorption of the space boundaries.

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[2] This is an empirical formula predicting the amount of sound attenuation (in dB) caused by a certain thickness of a belt of trees. Sound attenuation (in dB) of octave band noises due to sound propagation through dense foliage is given in ISO 9613-2:1966 standard [51].

[3] This cannot be said about early reflections, which depend on the position of the sound source in the space.

$$R = \frac{aS}{1 - a}, \tag{12}$$

where S is the total area of room boundaries (m^2) and a is the average sound absorption coefficient of room surfaces. The further from the sound source the smaller contribution of direct sound energy and greater contribution of reverberant energy to the overall acoustic energy in the space. At some distance from the sound source the contributions of direct and reverberant (reflected) acoustic energies are equal and this distance is called *critical distance* $d_{c,}$ which can be calculated from the equation (11) as

$$d_c = 0.141\sqrt{QR}, \tag{13}$$

where V is space volume (m^3), Q is directivity of sound source (dimensionless), and R is room constant expressed in m^2. The relative amounts of direct and reflected energy heard in the room affect listener's perception of the distance to a sound source. Note that in the case of a directional sound source the direct-to-reverberant ratio of sound energy at a given location in the room is also dependent on the orientation of the sound source in respect to room boundaries and the listener's position causing additional dependence of distance judgments on the relative relation of the listener's location to the acoustical axis of the sound source.

5. Distance estimation in an open field

The difficulty of making auditory judgments of distance to a sound source in an open space has been recognized for many years even in relation to relatively short distances [2, 39]. This difficulty dramatically increases in larger spaces and for greater distances. From all the auditory cues discussed above only sound intensity, sound spectrum, and the level of background noise can be used by the listener in a large open field. The only sound reflections available to the listener in an open space are the ground reflections, which are dependent on the form and type of terrain. However, these reflections create a confusing pattern of interferences rather than providing a helpful distance cue to the listener. Still, such an open space is an easier environment for making accurate distance judgments than an urban setting, which is very confusing due to multiple strong reflections coming from unrelated surfaces (e.g., urban canyon).

Meaningful distance estimation to a sound source in a large open space requires the listener to know something about the signal at the source and the types of degradations affecting the signal propagation through the space. This means that the listener needs to be familiar with capabilities of the sound source and be able to predict specific sound source output under given circumstances. In respect to sound propagation through space the sound is degraded by overall attenuation, frequency-dependent attenuation (coloration), reverberation (in woods), and fluctuations in level. In general, it is possible to measure (quantify) each of these kinds of signal changes and even develop a single composite measure of these effects [56] but their effects on auditory distance judgments would be still unknown due to missing field data.

In order to address the existing gap in knowledge regarding auditory distance estimation in an open space we conducted a field study collecting auditory distance estimation data at distances from 25 m to 800 m. To our knowledge this is the first study of this kind and therefore with very limited guidance from literature we had to make several arbitrary decisions regarding the extent of the study and selection of experimental conditions. For example, the study was limited to stationary conditions of both the sound source and the listener, was conducted under relatively stable weather conditions, and only included sound sources located in front of the listener. These specific limitations of the study's design will be evident in the description of the study detailed below. We refer to this study as the *Spesutie Island Study*, in reference to the place where the experimental data were collected.

5.1. Spesutie island study: Method

The Spesutie Island Study was conducted at Spesutie Island, MD on the outdoor test area known as EM Range. The EM Range is an open field approximately 900 m long and 200 m wide. The area is flat, covered with grass, and includes a sand/gravel track encircling the area. Three sides of the area are surrounding by young trees and bushes and the fourth side is separated by additional 50 m of grassy area separating the EM "Range" from a local road. The general view of the area is shown in Figure 2.

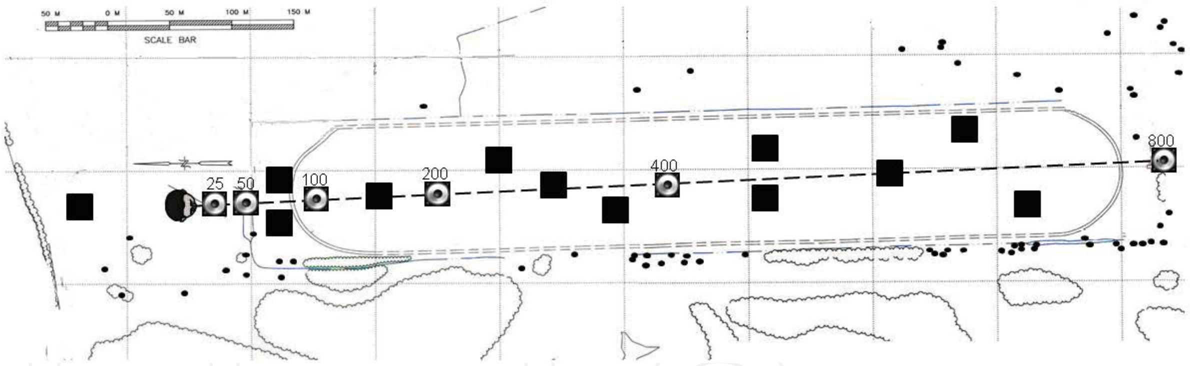

Figure 2. Outdoor test area on Spesutie Island where the study was conducted. The human head represents the listening station, squares with numbers next to them represent active loudspeakers and respective distances from the listener, and black squares without numbers represent dummy loudspeakers. Some elements of the figure are not to scale.

Eighteen boxes were scattered along the field within ±15° of the main listening axis of the listener (see Figure 2). The boxes were made of wood with a removable front panel covered with acoustically transparent cloth. Six of the loudspeaker boxes housed test loudspeakers and other boxes served as decoys. The boxes that contained the test loudspeakers were located at 25, 50, 100, 200, 400, and 800 meters away from the listening station (see Figure 2). The loudspeakers were Electro-Voice Sx500+ stage monitors capable of delivering approximately 120 dB peak SPL at 1 meter distance from the loudspeaker that were fed from Crown 2400 power amplifiers.

The listening station consisted of a table, chair, monitor, keyboard, and a mouse. The station was situated on a concrete slab, protected from sun and bugs by a (2.1m tall) canvas canopy with the walls made of bug netting. The station was also equipped with a Brüel & Kjær 4133 microphone and a Davis Monitor II weather station. The microphone, mounted in an upright position, 1 foot to the left of the listener was used to record actual background noise and test signals during each sound presentation. A weather station, positioned 2 meters to the left of the listener was used to monitor temperature, humidity, wind strength, and wind direction. The data were automatically recorded in the listener file and were used to assess the effects of meteorological variables on sound propagation.

The study was run using a PC desktop computer, TDT System II Signal Processing System, Sony T77 DAT recorder, and supporting hardware and wiring. All equipment not used at the listening station was located in a trailer located at the north end of the range; 50 m to the left of the listening station (not shown in Figure 2). Proprietary software was used to control the experiments and collect listener responses.

A group of 24 listeners between the ages of 18 and 25 participated in the study (M = 21.4; SD = 3.6). All listeners had pure-tone hearing thresholds better than or equal to 20 dB hearing level (HL) at audiometric frequencies from 250 through 8000 Hz (ANSI S3.6-2010 [56]) and no history of otologic pathology. The difference between pure-tone thresholds in both ears was no greater than 10 dB at any test frequency. The listeners had no previous experience in participating in psychophysical studies and were not previously involved in any regular activity requiring distance judgment (e.g., archery, hunting).

Eight natural test sounds were used in the study. Each sound had an overall duration of less than 1s. All sounds, with an exception of generator and rifle shot sounds, which were recorded during another study, were recorded by the authors. The recordings were made with an ACO 7012 microphone and a Sony T77 DAT tape recorder. The respective A-weighted sound pressure levels of the recorded sounds were measured during sound recording. These levels were recalculated for a 1m distance from the sound source and are listed in Table 2. The same sound levels measured at a 1 m distance in front of a loudspeaker were used in the study. The only exception was the *rifle* sound which had a sound pressure level that was too high at a 1m distance to be reproduced and was scaled down by 30 dB to 94 dB A. Spectral and temporal characteristics of all the sounds are shown in Figure 3.

During the study the listener was seated at the listening station and was asked to listen to incoming sounds and respond using a computer keyboard and mouse. An individual test trial consisted of an (1) a warning period indicating the beginning of a new test trial, (2) an observation period and (3) a response period. A yellow-red-green status system light was built into the graphical user interface located on the monitor in front of the listener. The light was used to indicate the warning period (yellow light, 1s), the observation period (red light, 10s), and the response period (green light) when listeners recorded their responses. The length of the response period was not predetermined and listeners could use this time to take short breaks. Listeners were also asked to wait prior to starting the next trial in the presence of occasional extraneous sounds such as an airplane flying over or a car passing by that could interfere with the performed task. To start the next trial, the listener selected the "GO" button on the monitor with the mouse and activated the yellow light which indicated the beginning of the new observation period.

Test Sound	Sound Description	Sound Level
Boltclick	Rifle bolt closure sound	83
Carhorn	Car horn sound	95
Dogbark	Dog bark	88
Generator	Generator sound	74
Joe	Male whisper ("Joe")	72
Rifle	Rifle shot sound	124
Splash	Water splash sound	73
Throat	Throat clearing sound	74

Table 2. List of test sounds and their production levels (in dB A) at 1 meter distance from the sound source.

During each observation period a single test sound or no sound at all was presented. The sound lasted less than 1s and could appear at any time during the observation period. The time when the sound appeared within the observation period was randomized. During the response period the listener was asked (1) to indicate if a sound was present, (2) to identify the presented sound using a 12-item closed-set list of alternatives (which included all the sounds presented in Table 2, plus bird, car engine, airplane, and other), and (3) to determine the distance to the sound source in either meters or yards. No response feedback was given to the listeners but the listeners were told that some sounds may appear very often while others may appear occasionally or not at all. Instructions regarding individual responses and the templates for response input were provided on the computer screen. Prior to the experiment the specific sounds used in the study plus several others listed on the list of alternatives were demonstrated to the listener from a nearby loudspeaker and a short training session was conducted.

One listening block included all seven sounds presented from all six loudspeakers with four repetitions each. In addition 48 blank (no sound) trials were randomly presented in each block resulting in 216 test trials per block. The responses made during the blank trials are not included in the presented data analysis. The order of sounds in each listening block was randomized. Four listening blocks were presented to each listener during a single listening session. The duration of the listening session depended on the duration of the rest periods taken by the listener but was typically 3.0 to 3.5 hours. Large amounts of data were collected during the study but only the auditory distance estimation data collected when the listener correctly recognized the sound are discussed in this chapter. The requirement of correct sound recognition for making distance estimate a valid distance estimation judgment was made to minimize the effects of occasional environmental sounds (birds, cars, remote military sounds, airplanes, etc.) that could have been confused with the test stimuli on listeners' responses.

The study was conducted during a two week period in the month of August. At this time the weather in Maryland is typical of that of the Mid-Atlantic United States. Historically, weather conditions in August in Aberdeen, MD (Spesutie Island area; sea level altitude) are relatively stable with 71% average relative humidity varying from high 50s% (morning) to high 80s% (afternoon); mean temperature during the day in 22-26 ˚C range (mean 24.1°C) and are characterized by the lowest average wind velocity throughout the year (about 5-6 km/h) [57-58].

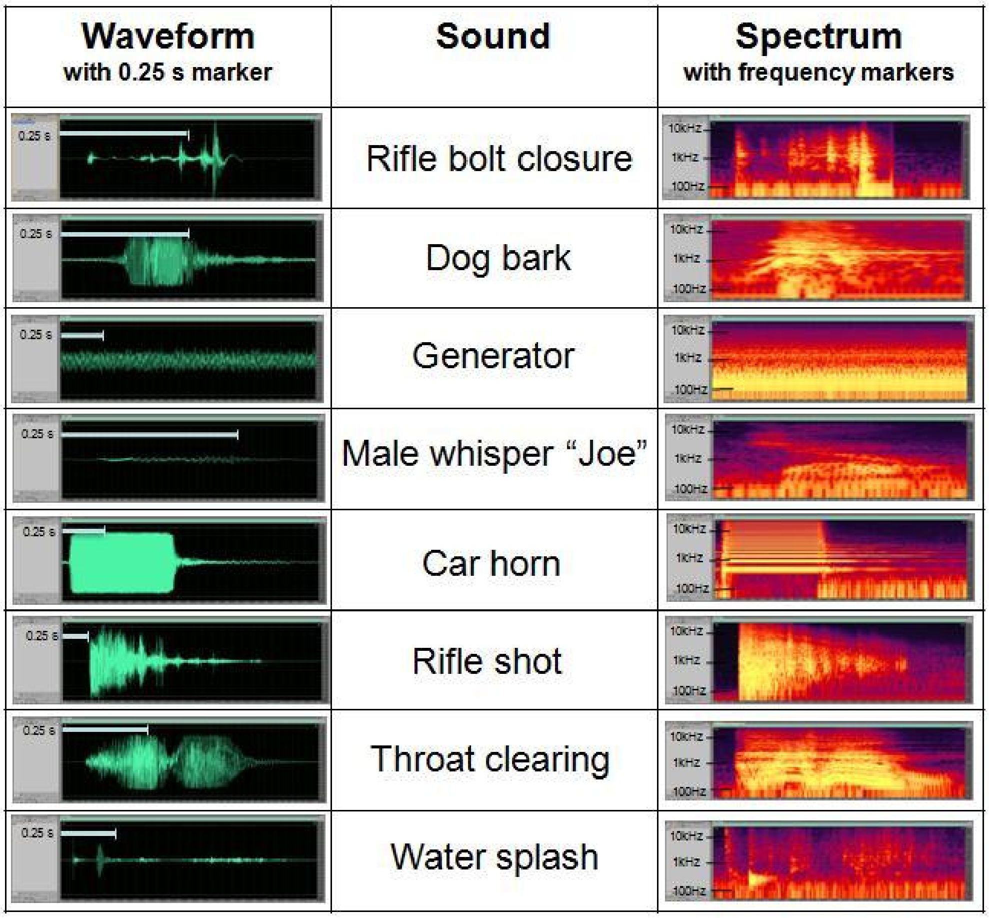

Figure 3. Spectral and temporal characteristics of the sounds used in the study.

The Maryland Department of Natural Resources [59] reports that there are over 400 species of birds and an untold number of insects inhabiting the area surrounding the test site. Sounds made by many of these species created the ambient noise floor that served as a backdrop for our study. The time and temperature of the day also contributed to the acoustic behaviors of some of the wildlife. Many of the insects that contributed to our background sounds were crickets, katydids, cicada, bees, beetles, and grasshoppers. The average weather and noise conditions observed during the study are listed in Table 3. The averages are mean values of the average conditions for individual listening sessions. The overall weather conditions were a bit warmer and drier than average for the area resulting in an average heat index of 31˚C.

Parameter	Mean	>Median	Standard Deviation	Unit
Temperature	28.5	29.0	2.3	°C
Relative Humidity	67.6	68.0	0.2	%
Atmospheric Pressure	1.005	1.006	0.018	Atm
Wind Velocity	5.3	4.6	2.3	km/h
Wind Direction	150.0	159.0	37.6	°
Noise Level	50.7	53.0	5.2	dB

Table 3. Mean, median, and standard deviation values of the weather and noise conditions during data collection.

Stronger winds generally came from the South and South-East directions while with many periods of weak wind came from the other directions. The background noise varied between 35-60dB A-weighted depending on the time of the day and weather conditions with a large number of insects producing sounds in the range of 4-8 kHz.

5.2. Spesutie island study: Data

One of the main arbitrary decisions that had to be made in designing the study was the decision about production levels of the loudspeaker-simulated sound sources used in the study. Since the goal of the study was to simulate as much as possible natural sound sources and to learn some basics about the expected distance to an emitting sound source emitting sound in an open space, all recorded sounds were reproduced at their natural recorded levels (except for the rifle shot). This means that each sound was produced at only a single level (see Table 2) by all loudspeakers regardless of the distance of the loudspeaker from the listener. As a consequence, not all the sounds were heard and properly recognized by all listeners when emitted from the distant loudspeakers. The variable audibility of sounds was also exuberated by changes in weather conditions across the study. This was the expected constraint of the implemented study design focused on natural production levels. Obviously, the selected sound events and their levels were selected arbitrarily, but they were representative of specific sound sources and the selected design focused on sound production (as opposed to presentation) level. This design was considered important in an initial study of the effects of sound propagation in an open field on perceived distance to a sound source.

The numbers of valid responses, that is, distance estimations made for correctly detected and recognized sound sources, made by listeners for specific sound source-distance combinations are shown in Table 4. The listeners made close to 100% valid distance estimations for distances up to 100 m and more than 50% valid estimations for distances up to 400 m for all the sounds except for *Joe* and *Throat*. They also made at least 50% valid estimations for *Carhorn* and *Rifle* sounds presented at 800 m distance. The *Joe* and *Throat* sounds were practically inaudible to most listeners beyond 100 m distance. Therefore, in order to avoid making conclusions on the basis of a very limited number of responses for some sound-distance combinations, only the combinations for which more than 50% of responses were collected were generally considered in data analysis. The few exceptions are noted in the text.

Test Sound	Distance (m)					
	25	50	100	200	400	800
Boltclick	■	■	■	▒	▒	□
Carhorn	■	■	■	▒	▒	▒
Dogbark	■	■	■	▒	▒	□
Generator	■	■	■	▒	▒	□
Joe	■	■	▒	□	□	□
Rifle	■	■	■	▒	▒	▒
Splash	■	■	■	▒	▒	□
Throat	■	■	▒	□	□	□

Table 4. Number of valid responses (detected and recognized sounds) made by the listeners. Black cells: 24-22 responses; gray cells: 18-12 responses; white cells: 10 or fewer responses.

5.2.1. Effects of distance

Distance was the main variable investigated in the study. In order to assess the general effect of distance on auditory distance estimation, estimates made by the listeners for all eight sounds were averaged together for each of the six distances. Two specific cases were considered one, where only distance-sound combinations providing at least 50% of valid responses were considered and two, where all valid responses were averaged together regardless of the actual numbers of responses for specific sound-distance combinations. Both mean and median results of both types of averaging are shown in Figure 4. The standard deviations of the data are not shown since the data are characterized by high variability and standard deviations are in the order of the range of the distance being estimated. Such large variability of the auditory estimation data is normal and is commonly reported (e.g., [4, 12, 60]).

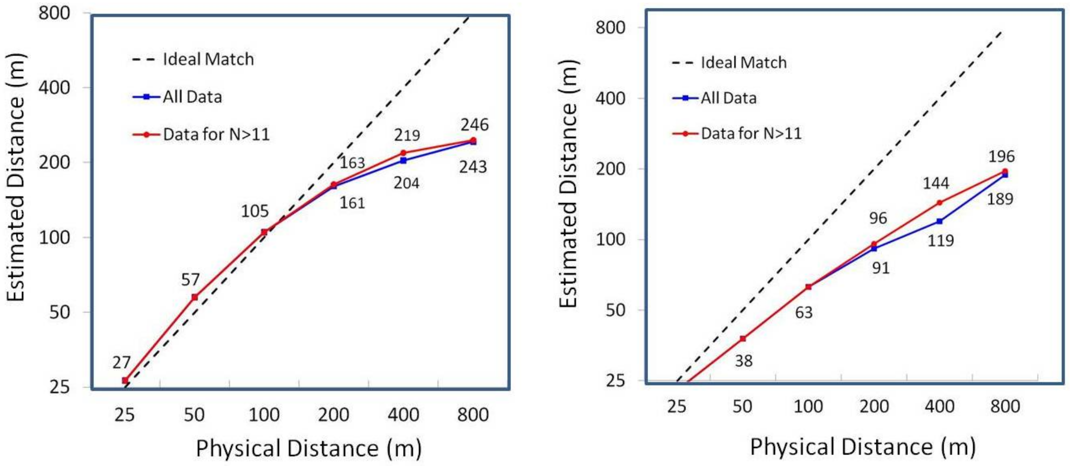

Figure 4. Auditory distance estimation. Mean (left panel) and median (right panel) estimated distance as a function of physical distance for all collected data and for cases where the number of listeners making valid responses was larger or equal to 12. The numbers in the graph are the actual average estimated distances for six physical distances used in the study.

The two curves shown in both panels of Figure 4 are very close to each other despite the quite different number of listeners' responses for 200-800 m data. This supports the general validity of the data collected for sound-distance combinations resulting in 50% or more valid responses. The reported mean curves seem to reach their plateau of about 300 m at the distance of 1000-2000 m that can be hypothesized to be the *auditory horizon* (see [30, 32]) for the listeners in an open grassy field. The shape of the curves agrees with typical curves published in similar studies conducted at close distances and in enclosed environments. They can be approximated by power functions (see equation 1) $PD=12d^{0.41}$ (data for $n \geq 12$; $R^2>0.9$) and $PD=12d^{0.46}$ (all data; $R^2>0.9$). The power exponents of both functions are relatively close to the average values reported for shorter distances by Zahorik [31] and Zahorik et al. [4].

The most notable property of the mean curves shown in Figure 4 is that the listeners were either very accurate in their judgments or slightly overestimated the actual distance for distances up to 100 m. Recall that in almost all previous studies conducted in closed spaces such accurate or overestimating judgments were typical for distances not exceeding 1-3 m [32, 34, 61-62, 63]; the last study was conducted in an open space]. Brungart [64] investigated auditory distance estimates over headphones to talkers recorded in open field at distances ranging from 0.25 m to 64 m and reported underestimation of distances larger than 1 m. Visual estimates made in open field at distances at 10 m and beyond are also reported as being underestimated by observers (e.g., [65-66]). These data agree with the general trend in distance estimation judgments described in Section 3. The low intensity sounds coming from larger distances make the differentiation between distances more difficult for listeners. Additionally, listeners tend to expect distant sound sources to be closer than they are in reality due to the typical lack of experience with such judgments and missing cues.

A completely different character of the collected data emerges from the analysis of median values. As shown in Figure 4 (right panel) all distances from 25 m to 800 m have been heavily underestimated by most of the listeners. The observed difference between the mean and median data results from the large variability of the listener responses. The majority of the listeners underestimated all judged distances but several cases of overestimation greatly affected the mean values. Inspection of the data indicated that some listeners had a tendency to overestimate the actual distance to the sound source regardless of the distance and the type of sound source. The latter agrees qualitatively with data reported by Cochran et al. [40] who presented listeners (n=20) with both live and recorded speech stimuli in an outdoor environment at distances from 1 to 29 m. Listeners estimated the distances using magnitude estimation judgment relative to a standard distance and underestimated the longest distance by as much as 30% when the standard distance was close to the listener.

One possible explanation is the fact that some listeners had a tendency to overestimate distances to sound sources across all distances, which may be a sensory influence caused on some listeners by a large visible space and a large number of potential sound source located at large distances. They could expect a greater number of sounds coming from further distances and could react accordingly. Calcagno et al. [67] studied auditory and audio-visual distance estimation in a closed space for distances from 1 m to 6 m and reported that while auditory distance estimates for distances over 2 m underestimated the distance, adding visual cues led to more accurate judgments or even overestimation of distance in the whole range of distances up to 6 m. They hypothesized that auditory distance estimation is affected by visual awareness of the environment, which hypothesis seems to be supported by the estimates made by some of our listeners.

5.2.2. Effects of sound type

The distance estimation functions for the individual simulated sound sources used in the study are shown in Figure 5.

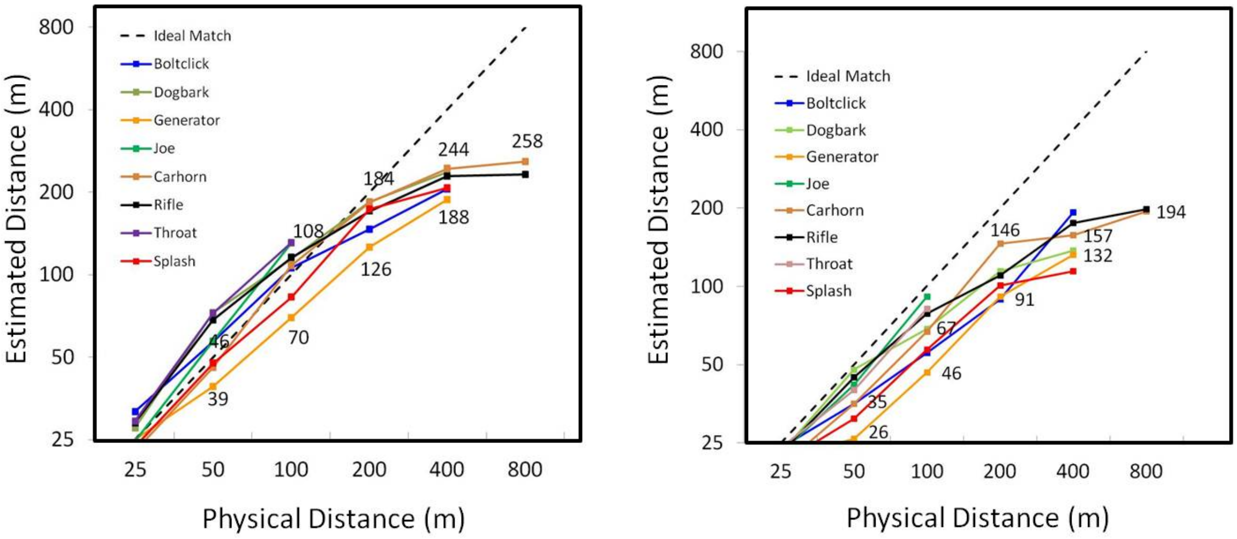

Figure 5. Auditory distance estimation. Mean (left panel) and median (right panel) estimated distance as a function of physical distance for individual sounds and distances where the number of listeners making valid responses was larger or equal 12. The numbers on the graph are the average estimated distances for *carhorn* (top numbers) and *generator* (bottom numbers) sounds.

Inspection of Figure 5 shows that distances to some of the sound sources (*splash*, *generator*) were underestimated regardless of the actual distance. This can be seen in both mean (Figure 5, left panel) and median (Figure 5, right panel) data representations. In contrast, the distances to sound sources producing relatively low output (*joe*, *throat*) that could only be heard at short distances were judged accurately (medians) or overestimated by some listeners more than the distances to other sound sources (means). These differences among sound sources may be due to the spectro-temporal properties of emitted sounds, listeners' expectations, or – in the latter case - to a relatively narrow range of effective distances at which these sound were heard. Interestingly, both the *joe* and *throat* sounds differed very much in their both temporal and spectral properties (see Figure 3). Considering this, it seems unlikely that their spectro-temporal properties themselves could be the only or the main factors causing the observed mean overestimation of distances to both of these sound sources. In addition, both sounds are vocal sounds which are familiar to general listeners and should result in fairly accurate judgments. However, due to the requirements of the experimental deign of the study both selected exemplars of sounds were relatively loud for their classes of sounds (whispered *joe* was a voiced whisper). Therefore, it is quite possible that some listeners facing a large open space and hearing louder than expected familiar sounds overestimated the actual distances trying "to use" the whole visually available space. This hypothesis could be verified in the future by conducting a similar study with both sounds presented with different intensities for blindfolded listeners. It may be expected that lack of a visual cue in a form of a large open space could lead to more accurate judgments of both sounds by all the listeners.

The data collected for *boltclick*, *dogbark*, *rifle*, and *carhorn* sounds show similar tendency and they mostly influenced the average data discussed in Section 5.2.1. Surprisingly, scaling down the rifle sound by 30 dB was not reflected in distance estimation estimates made by the listeners. This may be attributed to the fact that the actual distance to the "real" rifle location was much beyond the auditory horizon of the listeners. It may also be considered as a finding supporting the theory that the size of visible environment affects (limits, in this case) the range of available distance estimation options (alternatives).

Overall greater underestimation of distances to the *splash* and *generator* sounds was most likely due to expectations and previous life experience of the listeners. The *generator* sound was originally produced by a field generator that could be confused with residential outdoor power equipment, such as a lawn mower, which produces spectrally very similar noise but is typically heard from closer distances. The *splash* sound had the intensity and character typical for this class of sounds but such sounds are seldom heard without close visual effect of splash. A mental image of a visually close event could potentially affected listeners' judgments.

5.2.3. Effects of temperature, humidity, and atmospheric pressure

The two main weather parameters investigated in this study were temperature and relative humidity. Temperature is the measure of the average amount of kinetic energy in the body or environment expressed on a normalized scale. Relative humidity is the ratio of the amount of moisture in the air to the total amount of moisture that can be held at a given temperature, that is, the degree of saturation of air with moisture.

In order to assess the effects of temperature and humidity on auditory distance estimation the data collected during the times of highest and lowest values of both parameters have been analyzed separately. The four extreme weather conditions labeled hot, cool, dry, and humid weather and their temperature and humidity ranges are listed in Table 5. Obviously, they are the extreme conditions in relation to the average weather conditions experienced during the study. Note that temperature and humidity of air are interdependent variables and they could not be absolutely separated for analysis purposes in our study.

Analysis of distance estimation data obtained under the weather conditions listed in Table 6 has been conducted by comparing data collected during pairs of each opposite conditions: hot (5 listeners) and cool (5 listeners) and dry (4 listeners) and humid (4 listeners).

Hot-Cool: The five listeners exposed to the *hot weather* condition performed on the same level as the rest of the listeners. However, the listeners exposed to the *cool weather* condition

Type of Weather	Temperature Range	Relative Humidity Range	Average Temperature	Average Relative Humidity
Hot Weather	29 - 34°C	55 - 75%	31°C	64%
Cool Weather	24 - 27°C	65 - 88%	25°C	78%
Dry Weather	24 - 33°C	50 - 62%	28°C	61%
Humid Weather	24 - 27°C	77 - 98%	26°C	80%

Table 5. Extreme (relative) weather conditions (temperature and relative humidity) recorded during the study.

underestimated the distances for all sound sources more than the rest of the listeners. The mean distance estimations of the *cool weather* group were frequently as much as twice smaller than those of the rest of the group. The behaviors of both groups were very uniform across distances from 25 m to 100 m and they become somewhat random at larger distances where the numbers of responses became quite sparse (all listeners' responses have been included in calculations).

Dry-Humid: For distances from 25 m to 100 m both the *dry weather* and *humid weather* conditions listeners responses differed from the mean values for the whole group. The *dry weather* group provided slightly larger and the *humid weather* group considerably smaller distance estimates than the rest of the group. The behaviors of both groups were the same for all sound sources with one exception. The dry weather condition did not affect the judgments for the *dogbark* sound. For distances above 100 m the effect of the *dry weather* conditions seemed to disappear and above 200 m the effect of the humid weather condition becomes less clear.

Obviously, the above observations need to be treated with caution since they are based on relatively small samples of both the listeners and weather conditions. Since the changes in weather conditions also affect insects' behavior, the weather-related changes in the distance estimates may be affected, and to some degree explained, by the simultaneous changes in the background noise level. These changes are discussed in the forthcoming Section 5.2.5 and additional comments about joint temperature, humidity, and noise conditions are made in that section. In addition, the listeners exposed to the "extreme" weather conditions had their own expectations and experience that could be different from those of others and affected their responses in a unique way.

No effect of atmospheric (barometric) pressure has been noted in the study. Atmospheric pressure is the hydrostatic pressure caused by the weight of air molecules above the measurement point on the Earth's surface. Low atmospheric pressure means that the air is rising and high barometric pressure means that the air is sinking. Atmospheric pressure observed during the study was quite high and relatively stable averaging 1.005 atm and varying from 1.001 atm to 1.009 atm across all listening sessions. Such pressure is typical for very warm weather and was slightly higher than the historically average pressure for the month of August in Maryland. Thus, due to relatively stable pressure conditions during the study no specific effects of atmospheric pressure on distance estimation data were observed.

5.2.4. Effects of wind

Wind is one of the major factors affecting sound wave propagation in the environment. Wind effects are quite complex, fast changing (e.g., wind gusts), and confounded by other weather conditions and, as a result, it is hard to assess various wind effects in studies like the current one. Therefore, it was important for the study that all data collection was limited to a relatively stable and weak wind conditions. The average wind speed throughout the study was 5.3km/h (median = 4.6 km/h), with an average direction of 150° (SSE direction). On the Beaufort wind force scale most wind conditions recorded in the study ranged between 0 (calm, less than 1km/h) and 1 (light air, between 1-5.5km/h). There were several (9) sessions with stronger winds ranging from 5.8 km/h to 9.8 km/h but in all cases except one (side wind; no strong perceptual effects) the wind blew downwards (toward the listener). This limited the potential analysis of the wind effects to the comparison between data collected during strong downwind conditions (8 cases) and data collected during no-wind and low-strength-wind conditions (15 cases; 0 to 5.15 km/h; various wind directions) referred later as no wind condition. The results of this analysis are shown in Figure 6.

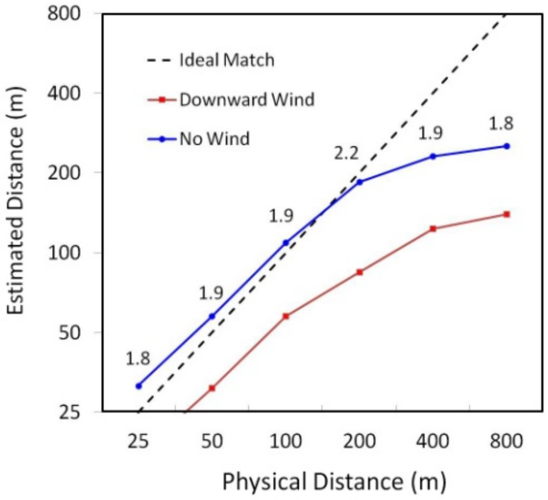

Figure 6. Comparison of auditory distance estimation data for no wind and downwind conditions. The numbers in the graph are the ratios of distance estimates for no wind and downwind conditions.

Under both no wind and downwind conditions the listeners generally underestimated distances to all sound sources. The distance estimates made by the listeners making judgments under no wind condition (M=3.9 km/h; SD=1.0 km/h) were about twice as large as those made by the listeners exposed to strong downwind condition (M=8.2 km/h; SD=1.2 km/h). The results were somewhat dependent on the type of sound with *rifle* (~2.4 ratio) and *carhorn* (~1.7 ratio) sounds being affected the most and the least, respectively. Both of these sounds were the most intense sounds but they greatly differed in spectro-temporal properties. The *rifle* sound was shorter and had lower high frequency content than the *carhorn* sound (see Figure 3). Therefore, it seems that the downward wind enhanced audibility of the *rifle* sound and helped to preserve its less intense high frequency content but such enhancement did not change the perceptual impressions of the listeners in the case of the *carhorn* sound. Recall also that the rifle sound was scaled down by 30 dB during its reproduction.

5.2.5. Effect of background noise

The background noise that affected the audibility of sounds produced by loudspeaker-simulated sound sources was for the most part noise produced by ever-present insects. Occasional sounds produced by birds, animals, distant cars, and overflying airplanes were relatively rare, quite distinct, and usually quite short. They could affect one or two of the specific judgments, resulting usually in invalid response, but they did not contribute significantly to the continuous noise present in the field. The average noise level across the study was about 51 dB A and was dependent on the weather conditions and time of the day. Typically, as the day became warmer insect activity decreased making the afternoons quieter than the mornings. As a result most sounds were less audible during cooler mornings than hotter afternoons. The relationship between the noise level and the temperature of air recorded throughout the study is shown in Figure 7.

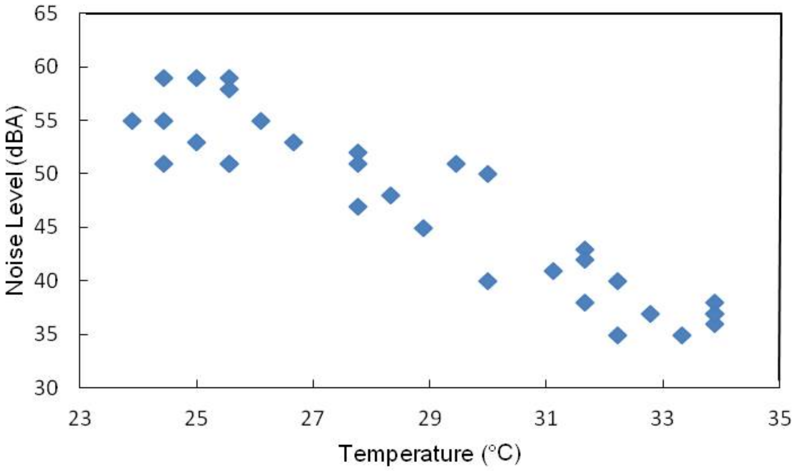

Figure 7. Relationship between background noise level (insects' calls) and temperature of air measured during the study. Not all the points on the graph correspond to actual listening sessions.

The spectral properties of the background noise are shown in Figure 8. The insects' calls were most intense in the frequency band from about 4 kHz to 8 kHz and the noise level resulting from a number of insects' calls decreased by 3-5 dB in the frequency range from ~0.5 kHz to 10 kHz when temperature increased from 28 °C to 32 °C.

As discussed in Section 5.2.3 in general cooler and more humid weather conditions resulted in greater underestimation of the distances to all sound sources. The participants that listened during these weather conditions usually gave closer distance estimates despite the fact that the background noise level under these conditions was higher. However, the negative effect on the audibility of sounds in an open field caused by higher background noise levels made by insects at low temperatures was apparently compensated by the decreasing amount of air

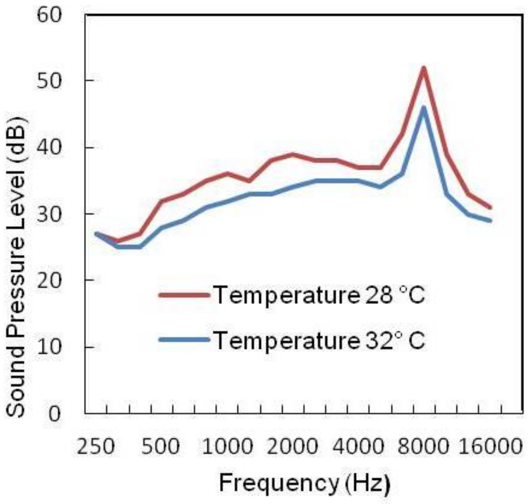

Figure 8. Examples of background noise levels in the morning (28 °C) and in the afternoon (32 °C) of the same day.

absorption (see Section 4.2) caused by increasing humidity and decreasing temperature or by some other factors. Thus, two explanations for the observed effects are possible. First, that the effect of changes in air absorption had stronger impact on the judgments of the listeners than potentially counteracting simultaneous changes in noise level. Second, that poorer audibility of sounds due to higher background noise level was perceptually associated with closer distances to sound sources. The greater the background noise level and the lower signal-to-noise ratio the stronger the listeners' impression that the sound source was relatively near but was masked by background noise. Listeners informally reported that at higher noise levels they "heard" the space as being smaller. Such explanations of the noise effect also agrees with the results of previous research studies conducted in closed spaces regarding the role of *background noise cue*, where higher noise level masked environmental (reverberated) sounds masking the impression that the space was smaller. The discussed effects might also result from specific experience and predispositions of the small number of listeners who were exposed to the "extreme" listening conditions analyzed in our study. Further studies are needed to explain these relationships and answer the related questions.

5.2.6. Individual differences

Distance perception data obtained in the current study are marred by lack of consistency due to listeners' potential lack of ability to use distance estimation cues in open space and large individual differences among the listeners. Typical standard deviations of the group's judgments were close to the size of the physical distance being estimated and quite independent of the type of sound source. The large individual differences and disparities in judgments also have been encountered in closed spaces by other researchers. Recently, Wisniewski at al. [41] used open field recordings reproduced in a closed space and reported substantial individual differences among the listeners in judging auditory distance. The differences ranged from 51% to 77%. However, the listeners made the same general pattern of errors; a finding that is not supported by the results of the present study. Similar, widely varying results

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of distance estimation have been reported in visual distance estimation studies conducted in open fields. The results of all these perceptual studies indicate that regardless of sensory input we have not yet found a common relationship between physical and perceived space that is consistent with distance judgments in outdoor contexts [68-69].

6. Summary

The purpose of this chapter was to summarize the state of the art knowledge about the mechanism of auditory distance perception and to report the results of the distance estimation study conducted in an open field for distances in the 25-800 m range. Since this study seems to be the first study of this kind, it actually poses more questions than provides definite answers. A range of listeners' behaviors has been identified but the exploratory nature of this study and the relatively limited number of samples of both the listening conditions and participants advise caution in generalizing the reported data. In addition, interdependence of temperature, humidity, and environmental noise makes some observations tentative that require more rigorous confirmation.

In summary, within the constraints of the reported study, the following conclusions can be made on the basis of collected data:

- Auditory distance estimation judgments in the open field differ greatly among listeners; however, for most listeners the perceived distance and the physical distance are monotonically related.
- The auditory distance judgments in an open field at distances of 25 m and beyond are commonly underestimated compared to the actual distances to sound sources regardless of the distance.
- Some of the listeners participating in the study generally overestimated all distances to the sound sources[4]; this behavior can be explained by either the expectations caused by a large visible space or by lack of an internal concept of auditory distance resulting in the same numeric estimate across a range of physical distances.
- The type of sound source had an effect on the distance judgments; however, some of the observed environmental effects on the perceived sounds were not always clear.
- The effects of temperature, humidity, and environmental noise are interrelated and difficult to separate analytically; however, both higher humidity and lower temperature increased distance underestimation by the listeners in the current study.
- Increased level of environmental noise at lower temperatures affected the audibility of projected sounds but did not seem to affect in a clear way distance estimation judgements.

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[4] Individual data reported in some previous studies conducted in closed spaces and at shorter distances also indicate that some listeners had a tendency to overestimate most distances.

- Downward wind greatly increased the degree of distance underestimation across all sound sources and distances (upward wind has not been studied).

The authors hope that the results of this study will increase the listeners' awareness of the complex influences affecting listeners' behaviors in an open field under changing weather conditions. However, further studies are needed to expand our knowledge about the nature of auditory distance estimations made under such environmental conditions and to confirm or correct reported findings.

The future studies should include distance judgments in various types of listening environments (such as the in a desert or in the extreme cold), sounds coming from different directions (the back or sides) and a repeated version of the current study with blindfolded participants.

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References

[1] Letowski, T, & Letowski, S. Auditory spatial perception: Auditory localization. ARL Technical Report ARL-TR-6016. APG (MD): U.S. Army Research Laboratory; (2012).

[2] Coleman, P. D. An analysis of cues to auditory depth perception in free space. Psychological Bulletin (1963). , 60(3), 302-315.

[3] Blauert, J. Spatial Hearing. Cambridge (MA): MIT Press; (2001).

[4] Zahorik, P, Brungart, D, & Bronkhorst, A. W. Auditory distance perception in humans: A summary of past and present research. Acta Acustica (2005). , 91(3), 409-420.

[5] Howard, I. P. Auditory distance perception. In: Howard IP (ed.) Perceiving in Depth, New York: Oxford University Press; (2012). , 3, 277-308.

[6] Servos, P. Distance estimation in the visual and visuomotor systems. Experimental Brain Research (2000). , 130(1), 35-47.

[7] Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In: Freksa C, Habel C, Wender KF (eds.) Spatial Cognition- An Interdisciplinary Approach to Representing and Processing Spatial Knowledge. Berlin: Springer-Verlag; 1998. , 1-17.

[8] Cox, P. H. An initial investigation of the auditory egocenter: Evidence for a "cyclopean ear". PhD thesis. North Carolina State University Rayleigh; (1999).

[9] Neelon, F. N, Brungart, D. S, & Simpson, D. (2004). The isoazimuthal perception of sounds across distance: A preliminary investigation into the location of the audio egocenter. Journal of Neuroscience 2004; , 24(35), 7640-7647.

[10] Devallez, D. Auditory perspective: perception, rendering, and applications. PhD thesis. University of Verona Verona; (2009).

[11] Lu, Y-C. h, Cooke, M, & Christensen, H. Active binaural distance estimation for dynamic sources. Proceeding of the InterSpeech-August 2007, Antwerp, Belgium. International Speech Communication Association; (2007). , 2007, 27-31.

[12] Nielsen, S. H. Auditory distance perception in different rooms. Journal of the Audio Engineering Society (1993).

[13] Haustein, B. G. (1969). Hypothesen über die einhorige Entferungswahrnehmung des menschlichen Gehörs (Hypothesis about the perception of distance in human hearing with one ear). Hochfrequensthechnick und Electroakustik 1969; 78 45-57 (in German).

[14] Brungart, D. S. Preliminary model of auditory distance perception for nearby sound sources. In: Greenberg S, Slaney M (eds.) Computational Models of Auditory Function Amsterdam: IOS Press. (2001). , 83-96.

[15] Gardner, M. B. Distance estimation at 0° or apparent 0°-oriented speech signals in anechoic space. Journal of the Acoustical Society of America (1969). , 45(1), 47-53.

[16] Zahorik, P. Auditory display of sound source distance. Proceedings of the 2002 International Conference on Auditory Displays, July 2005, Kyoto, Japan. ICAD; (2002). , 2-5.

[17] Stevens, S. S. The measurement of loudness. Journal of the Acoustical Society of America (1955). , 27(5), 815-829.

[18] Stevens, S. S. On psychophysical law. Psychological Review (1957). , 64(3), 153-181.

[19] Stevens, S. S, & Galanter, E. H. (1957). Ratio scales and category scales for a dozen perceptual continua. Journal of Experimental Psychology 1957;*54*(6), 377-411.

[20] Fukusima, S. S, & Loomis, J. M. Da Silva JA. Visual perception of egocentric distance as assessed by triangulation. Journal of Experimental Psychology: Human Perception and Performance (1997). , 23(1), 86-100.

[21] Gibson, E. J, Bergman, R, & Purdy, J. The effect of prior training with a scale of distance on absolute and relative judgments of distance over the ground. Journal of Experimental Psychology (1955). , 50(2), 97-105.

[22] Loomis, J. M. Da Silva JA, Fujita N, Fukusima SS. Visual space perception and visually directed action. Journal of Experimental Psychology: Human Perception and Performance (1992).

[23] Rand, K. M, Tarampi, M. R, Creem-regehr, S. H, & Thompson, W. B. (2011). The importance of a visual horizon for distance judgments under severely degraded vision. Perception 2011; , 40(2), 142-154.

[24] Sedgwick, H. Space perception. In: Boff KR, Kaufman L,Thomas JP. (eds.) Handbook of Perception and Human Performance, New York: Wiley and Sons; (1986). , 1, 21.

[25] Gogel, W. C. The analysis of perceived space. In: Masin SC (ed.) Foundations of Perceptual Theory. Amsterdam; Elsevier; (1993). , 113-182.

[26] Loomis, J. M, & Philbeck, J. W. Is the anisotropy of perceived 3-D shape invariant across scale? Perception & Psychophysics (1999). , 61(3), 397-402.

[27] Proffitt, D. R. Distance perception. Current Directions in Psychological Science (2006). , 15(3), 131-135.

[28] Sedgwick, H. Environment-centered representation of spatial layout: Available visual information from texture and perspective. In: Beck J, Hope B, Rosenfeld A. (eds.) Human and Machine Vision. New York: Academic Press; (1983). , 425-458.

[29] 30] Békésy G vonThe moon illusion and similar auditory phenomena. American Journal of Psychology (1949). , 62(4), 540-552.

[30] Zahorik, P. Assessing auditory distance perception using virtual acoustic. Journal of the Acoustical Society of America (2002). , 111(4), 1832-1846.

[31] Bronkhorst, A. W, & Houtgast, T. Auditory distance perception in rooms. Nature (1999). http://www.nature.com/nature/journal/n6719/abs/397517a0.htmlaccessed 16 August 2012).

[32] Ashmead, D. H, Davis, D. L, & Northington, A. Contribution of listeners' approaching motion to auditory distance perception. Journal of Experimental Psychology: Human Perception and Performance (1995). *21*(2), 239-256.

[33] Brungart, D. S, & Scott, K. R. The effects of production and presentation level on the auditory distance perception of speech. Journal of the Acoustical Society of America (2001). , 110(1), 425-440.

[34] Kopco, N, & Shinn-cunningham, B. Effect of stimulus spectrum on distance perception for nearby sources. Journal of the Acoustical Society of America (2011). , 130(3), 1530-1541.

[35] Loomis, J. M. Da Silva JA, Philbeck JW, Fukusima S.S. Perception of location and distance. Current Directions in Psychological Science (1996). , 5(3), 72-77.

[36] Loomis, J. M, Klatzky, R. L, Philbeck, J. W, & Golledge, R. G. Assessing auditory distance

[37] perception using perceptually directed actionPerception & Psychophysics (1998). , 60(6), 966-980.

[38] Mcgregor, P. K, Horn, A. G, & Todd, M. A. Are familiar sounds ranged more accurately? Perceptual and Motor Skills (1985). Pt2) 1082.

[39] Coleman, P. D. Failure to localize the sound distance of an unfamiliar sound. Journal of the Acoustical Society of America (1962). , 34(3), 345-346.

[40] Cochran, P, Throop, J, & Simpson, W. Estimation of distance of a sound source. American Journal of Psychology (1968). , 81(2), 198-206.

[41] Wisniewski, M. G, Mercado, E, Gramann, K, & Makeig, S. Familiarity with speech affects cortical processing in auditory distance cues and increases acuity. PLoS One (2012). http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0041025accessed 30 September 2012)., 7(7), 1-8.

[42] Zahorik, P, & Wightman, F. L. Loudness constancy with varying sound source distance. Nature Neuroscience (2001).

[43] Morse, P. M, & Ingård, K. U. Theoretical Acoustics. New York: McGraw-Hill; (1968).

[44] Sutherland, L. C, & Daigle, G. A. Atmospheric sound propagation. In: Crocker MJ. (ed.) Encyclopedia of Acoustics. New York: Wiley and Sons; (1997). , 341-365.

[45] Harris, C. Absorption of sound in air versus humidity and temperature. Journal of the Acoustical Society of America (1966). *40*(1), 148-159.

[46] Albert, D. G. Past research on sound propagation through forest. Report ERDC/CRREL-TR-Hannover (NH): U.S. Army Corps of Engineers; (2004). , 04-18.

[47] International Standards OrganisationAcoustics- Attenuation of sound during propagation outdoors- Part 1: Calculation of the absorption of sound by the atmosphere. ISO Geneva: ISO; (1993). , 9613-1.

[48] Salomons, E. M. Computational Atmospheric Acoustics. Boston: Kluwer Publishers; (2001).

[49] Lamancusa, J. S. Outdoor sound propagation. Noise Control. ME 458: Engineering Noise Control. State College (PA): Penn State University. (2000). http://www.mne.psu.edu/lamancusa/me458/10_osp.pdfaccessed on 9 September 2012)., 10.

[50] Naguib, M, & Wiley, R. H. Estimating the distance to a source of sound: Mechanisms and adaptations for long-range communication. Animal Behavior (2001). , 62(5), 825-837.

[51] International Standards OrganisationAcoustics- Attenuation of sound during propagation outdoors- Part 2: General method of calculation. ISO Geneva: ISO; (1996). , 9613-2.

[52] Aylor, D. Noise reduction by vegetation and ground. Journal of the Acoustical Society of America (1972). , 51(1), 197-205.

[53] Bullen, R, & Fricke, F. Sound-propagation through vegetation. Journal of Sound and Vibration (1982). , 80(1), 11-23.

[54] Hopkins, H. F, & Stryker, N. R. A proposed loudness-efficient rating for loudspeakers and the determination of system power requirements for enclosures. Proceedings of the Institute of Radio Engineers (1948). , 36(3), 315-355.

[55] Brown, T. J, & Handford, P. Sound design for vocalizations: Quality in the woods, consistency in the fields. Condor (2000). , 102-81.

[56] American National Standards Institute ((2010). Specifications for audiometers (ANSI S3.6-2010). New York: ANSI; 2010.

[57] Current ResultsMonthly humidity averages for Maryland. http://www.currentresults.com/Weather/Maryland/humidity-by-month.phpaccessed on 14 September (2012).

[58] Current ResultsAverage temperatures for Maryland in August. http://www.currentresults.com/Weather/Maryland/temperature-august.phpaccessed on 14 September (2012).

[59] Maryland Department of Natural ResourcesMaryland plants and wildlife. http://www.dnr.state.md.us/wildlife/Plabts_Wildlife/index.aspaccessed on 14 September (2012).

[60] Mershon, D. H, & King, L. E. Intensity and reverberation as factors in auditory perception of egocentric distance. Perception & Psychophysics (1975). , 18(6), 409-415.

[61] Kim, H-Y. Relation between sound pressure level and auditory distance perception in anechoic room. *Journal of the Korean Academia-Industrial Cooperation Society*, (2009). in Korean).

[62] Mcmurtry, P. L, & Mershon, D. H. Auditory distance judgments in noise, with and without hearing protection. Proceedings of the 29th Human Factory and Ergonomics Society Annual Meeting, September- 3 October (1985). Baltimore, USA. HFES; 1985, 811-813.

[63] Speigle, J, & Loomis, J. M. Auditory distance perception by translating observers. Proceeding of the IEEE Symposium on Research Frontiers in Virtual Reality, October 1993, Washington (DC), USA. IEEE; (1993). , 92-99.

[64] Brungart, D. S. Speech-based distance cueing in virtual auditory displays. Proceedings of the 44th Human Factors and Ergonomics Society Annual Meeting, 29 July- 4 August (2000). San Diego, USA. Proceedings HFES 2000; , 44(22), 714-717.

[65] Andre, J, & Rogers, S. Using verbal and blind-walking estimates to investigate the two visual system hypotheses. Perception & Psychophysics (2006). , 68(3), 353-361.

[66] Strauss, M, & Carnahan, J. Distance estimation error in roadway setting. The Police Journal (2009). , 82(3), 247-264.

[67] Calcagno, E. R, Abregú, E. L, Eguia, M. C, & Vergara, R. The role of vision in auditory distance perception. Perception, (2012). , 41(2), 175-192.

[68] Jackson, R. E. Individual differences in distance perception. Proceedings of the Royal Society: Biology (2009). , 1665-1669.

[69] Norman, J. F, Crabtree, C. E, Clayton, A. M, & Norman, H. F. The perception of distance and spatial relationships in natural outdoor environments. Perception (2005). , 34(11), 1315-1324.