Springer Handbook of Auditory Research

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Loudness

with 75 Illustrations

Springer

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In Memoriam and Honor

Søren Buus
(January 29, 1951–April 29, 2004)

(Søren Buus's obituary was published by Scharf, B. and Florentine, M. in the Journal of the Acoustical Society of America, 2005, 117, p. 1685.)

Series Preface

Springer Handbook of Auditory Research

The *Springer Handbook of Auditory Research* presents a series of comprehensive and synthetic reviews of the fundamental topics in modern auditory research. The volumes are aimed at all individuals with interests in hearing research including advanced graduate students, postdoctoral researchers, and clinical investigators. The volumes are intended to introduce new investigators to important aspects of hearing science and to help established investigators to better understand the fundamental theories and data in fields of hearing that they may not normally follow closely.

Each volume presents a particular topic comprehensively, and each serves as a synthetic overview and guide to the literature. As such, the chapters present neither exhaustive data reviews nor original research that has not yet appeared in peer-reviewed journals. The volumes focus on topics that have developed a solid data and conceptual foundation, rather than on those for which a literature is only beginning to develop. New research areas will be covered on a timely basis in the series as they begin to mature.

Each volume in the series consists of a few substantial chapters on a particular topic. In some cases, the topics will be ones of traditional interest for which there is a substantial body of data and theory, such as auditory neuroanatomy (Vol. 1) and neurophysiology (Vol. 2). Other volumes in the series deal with topics that have begun to mature more recently, such as development, plasticity, and computational models of neural processing. In many cases, the series editors are joined by a coeditor having special expertise in the topic of the volume.

Richard R. Fay, Chicago, IL
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Volume Preface

The topic of loudness is of considerable concern, both in and outside of research laboratories. Most people have developed an opinion about some aspect of loudness, and many complain about the loudness of background sounds in their daily environments and their impacts on quality of life. Moreover, such sounds interfere with the ability to hear useful sounds, and such masking can be especially problematic for people with hearing losses, children, older adults, and nonnative speakers of a language.

At the same time, not all loud sounds are undesirable. Some loud sounds are important for human well-being, such as warning signals, whereas other loud sounds, such as music, can be pleasurable. In fact, loudness is essential for enjoying the dynamics of music. Thus, loudness is a pervasive and complex issue, and one that needs to be examined from a wide range of perspectives, and that is the purpose of this volume.

Research in loudness has been performed in many countries, and this volume is an international endeavor with authors from Europe, Japan, and the United States, making the volume an attempt to provide a global network of information about loudness. The editors are very pleased to be able to bring together information on many aspects of loudness in this one volume, as well as to highlight approaches from many different perspectives.

The overall stage for understanding the issues of loudness is set up in Chapter 1 by Florentine, who defines loudness and provides an overview of the many factors that influence loudness, Chapter 1 also addresses how language and culture may influence loudness, and concludes with a summary of current knowledge of the physiological mechanisms involved in loudness. Chapters 2 and 3 cover issues related to the measurement of loudness. Marks and Florentine, in Chapter 2, discuss the theoretical, empirical, and practical constraints on loudness measurement. The chapter starts with a brief history of loudness measurement in the nineteenth and twentieth centuries, and ends with contemporary methods of measurements. Of course, measures of loudness are also influenced by the context in which sounds are heard. In Chapter 3, Arieh and Marks discuss the ways in which context affects loudness and loudness judgments. In Chapter 4, Epstein reviews two issues related to responses to loudness: physiological effects of loud sounds, and perceptual and physiological data that correlate with loudness. Loudness in the laboratory is discussed in Chapters 5 and 6 using a traditional, but artificial, classification to divide the subject matter. Jesteadt and Leibold address the loudness of steady-state sounds in Chapter 5. Kuwano and Namba examine the loudness of nonsteady-state (time-varying) sounds in Chapter 6.

The bridge between loudness in the laboratory and daily environments begins in Chapter 7 and is expanded upon in Chapter 8. In Chapter 7, Sivonen and Ellermeir review studies on binaural loudness that have used different modes of stimulus presentation: headphones and free, diffuse, and directional sound fields. They show how mode of presentation affects the measurement of binaural loudness. In Chapter 8, Fastl and Florentine cover how loudness is related to annoyance, music, multisensory (audio-visual and audio-tactile) interactions, and the environmental context in which sounds are heard. They also discuss issues related to setting sound levels to optimal loudness for large groups of people. The topic of loudness is especially important for the one out of ten people who have a hearing loss and for those doing work with some aspect of aural rehabilitation. Knowledge of loudness in hearing loss is also important for anyone trying to understand normal hearing, because it puts constraints on theories of loudness. In Chapter 9, Smeds and Leijon summarize current thinking on the formation of loudness as it relates to different types of hearing loss and they describe strategies used to compensate for altered loudness. The volume ends in Chapter 10 with an introduction to models of loudness by Marozeau.

As with most volumes in the *Springer Handbook of Auditory Research*, chapters often build upon material discussed in earlier volumes. In particular, generally related material can be found in Volumes 3 (*Human Psychophysics*), 6 (*Auditory Computation*), 18 (*Speech Processing in the Auditory System*), and 29 (*Auditory Perception of Sound Sources*).

The editors express their appreciation to a number of colleagues and friends, including the authors of the chapters, who assisted in review of one or more of the chapters. We are grateful to William J. Cavanaugh, Leo Beranek, Brian Fligor, Julia B. Florentine, Michael G. Heinz, Sharon Kujawa, Andrzej Miśkiewicz, Brian C. J. Moore, Andrew Oxenham, Torben Poulsen, Bertram Scharf, and the students of the 2009 Loudness Seminar at Northeastern University.

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Chapter 1
Loudness

Mary Florentine

1.1 Why Learn About Loudness?

The topic of loudness is no longer something esoteric, discussed only in research laboratories and psychoacoustics lectures. It is mainstream in social conversation, and most people have developed an opinion about some aspect of loudness. Our daily environments are too loud and people are taking notice. In their book, *One Square Inch of Silence*, Hempton and Grossmann (2009) document the lack of quiet places. The fact that a book about this topic can be published by Free Press, a division of Simon and Schuster, and appear on bookshelves – from Barnes and Noble to WalMart and Sam's Club – indicates that problems associated with loud sounds strike a resonant chord with a large segment of the population. Loud sounds intrude on our enjoyment of life and affect our performance; loud background sounds interfere with our ability to hear sounds we want to hear and can create communication problems for everyone, especially those with hearing losses (Chap. 9), children (Nelson et al. 2002), older adults (Kim et al. 2006), and non-native speakers of a language (e.g., Mayo et al. 1997; Lecumberri and Cooke 2006; Van Engen and Bradlow 2007). These combined groups add up to be a significant portion of the overall population.

News reports and media broadcasts in many countries have alerted the general population to the potential risk of hearing loss caused by exposure to high levels of sound, especially music. Many parents are especially concerned about the music-listening behaviors of their children. In fact, recommendations to prevent noise-induced hearing loss are often not heeded, although they are simple to understand (Florentine 1990). Research compiled during the past two decades is not unambiguous regarding the limits of toxic exposure levels. For example, sound exposures for musicians in symphony orchestras show that in many cases the sound exposure exceeds an 8-h limit of 85 dBA (Royster et al. 1991), but measurements of hearing

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thresholds in sound-exposed musicians do not indicate much change – although they often have tinnitus and may have more difficulty with complex auditory processing. Likewise, Axelsson et al. (1995) found surprisingly little change in the hearing thresholds of rock musicians tested in the beginning of their careers and tested after 20 years of performing. Hearing thresholds, however, may be a poor way to assess damage to hearing because they are quite insensitive to neural degeneration (Kujawa and Liberman 2009). Effective hearing in daily life, such as the ability to hear speech in background noise, requires more physiological processing than is needed to simply detect the presence of a sound.

It is noteworthy that the sound exposure limit of 85 dBA is based primarily on data collected from white adult males, who were exposed to industrial noise (ISO 1999 1990); recommendations for children exposed to music are estimations. Some data suggest that previous exposure to high-level noise has a deleterious effect on the progression of age-related hearing loss (Gates et al. 2000; Kujawa and Liberman 2006). In other words, ears with noise damage may age differently from those without noise damage. Although there is evidence that some people may be more susceptible to noise-induced hearing loss than others, there are currently no standardized tests that can identify those who may be at greater risk. Therefore, it is best to use caution around loud sounds (for iPod recommendations and other information, see Chap. 8).

Although there is some debate on the limits of toxic noise exposure, there is clear consensus among scientists that very high-level sounds can cause hearing loss and impact our general physical and psychological wellness (see Chap. 4). Some loud sounds have more physical and psychological impact than others, and the magnitude of noxious sounds in our daily environments are too loud in many locations. The background sounds of our daily lives – the soundscapes – have changed (Schafer 1977). Although there have always been loud sounds in nature such as waterfalls and thunder, people could choose not to live close to waterfalls; thunder was not a daily experience. Humans designed bullhorns for use as warning signals and long-distance communication devices. Although people experienced loud sounds, most people agree that the soundscapes of our daily environments are much louder and more intrusive today than in the past. Soundscapes in entire areas of countries can change rather quickly. For example, soundscapes took on a dramatic change in loudness in early twentieth century America with the onset of modern technology (Thompson 2002).

Loudness correlates highly with the degree of annoyance of community noises (Berglund et al. 1976). The problem of intrusively loud soundscapes is not confined to any one country; it is a global issue. It is not confined to spaces outside dwelling places. Sounds inside homes are often too loud. In fact, at the time of this writing the Commercial Advertisement Loudness Mitigation (CALM) Act is being discussed in the U.S. House of Representatives. The CALM Act addresses widespread consumer complaints regarding the abrupt loudness of television advertisements. The Act would enable the Federal Communications Commission (FCC) to monitor the levels of advertisements in television programming to ensure that the loudness levels of commercial breaks are consistent with those of the programming that it brackets. National standards on the loudness of commercials have already been adopted in Australia, Brazil, France, Israel, Russia, and the United Kingdom.

Most loud sounds are unnecessary and avoidable. Modern technology exists that can reduce the level of sounds. There are a number of ways to quiet loud sounds that are not difficult to implement, but they require awareness, effort, some financial resources, and in some cases political action. Even when regulations to control unreasonably loud sounds are enforced, technological knowledge has been used to get around the regulations. For example, a loudness maximizer has been developed to increase loudness of media broadcasts and commercials to grab the attention of potential customers, while staying within legal sound-level limits (see Chap. 8). This device was developed with knowledge of how we perceive loudness; this same knowledge can be used to set more effective sound-emission limits and is found within the chapters of this book.

Although many loud sounds should be eliminated, some loud sounds are important, useful, and even desirable. Warning signals are essential for our safety. Some loud sounds allow us to experience the dynamics of music and speech. To eliminate loud, unwanted sounds and keep desired sounds optimally loud requires an understanding of the many factors that influence the perception of loudness.

Another important reason to learn about loudness is to aid in the rehabilitation of people with hearing losses. According to the National Institutes of Deafness and Communication Disorders, one out of ten people have a hearing loss, and many people will develop a hearing loss as they age. The most common treatment for hearing loss is hearing aids. Kochkin's survey (2005) of 1,500 hearing-aid users indicates that only 60% of them reported being satisfied when asked about comfort with loud sounds.

This chapter provides an overview of the many factors that influence loudness and they are described in greater detail in subsequent chapters. It also includes topics that have not been covered elsewhere in this book. Section 1.2 includes the definition and the meaning of loudness, and gives an overview of the complex nature of loudness. It also specifies correct terminology and cautions about the use of incorrect and misleading terminology. The third section addresses how language and culture influence judgments of loudness. It describes how the connotative meaning of a percept, such as loudness, can be obtained and how it can differ among languages, even though the dictionary definitions indicate the same meaning. It also describes some early international collaboration undertaken to understand loudness and other aspects of perception that are related to it. The fourth section describes the current state of knowledge regarding loudness and points toward new areas of investigation.

1.2 Definition and Meaning of Loudness

Loudness has been defined as the perceptual strength of a sound that ranges from very soft (or quiet) to very loud. Scharf (1978) suggested that loudness may be defined "as the attribute of a sound that changes most readily when sound intensity is varied," but preferred to define it as the subjective intensity of a sound. The term "subjective" assigns the evaluation of intensity to be within the listener. Accordingly, no “right” and “wrong” answers exist in loudness judgments. Because there is no objective measure of loudness, measurements of loudness should employ methods of converging evidence. For example, a matrix design can be used in which sounds are matched in loudness to themselves and to each of the other signals (e.g., Florentine et al. 1978). The resulting data can be easily examined for symmetry and transitivity (see Chap. 2). Most definitions of loudness are somewhat vague, but most people behave in a consistent manner when judging loudness.

The scale of loudness not only allows ordering sounds from soft to loud, but also has a magnitude associated with it. A commonly used unit of loudness is the sone. One sone is defined as the loudness of a 1-kHz tone at 40-dB SPL heard binaurally in a free field from a source in the listener’s frontal plane. A sound with a loudness of 2.0 sones is twice as loud as a 40-dB SPL, 1-kHz tone, and a sound with a loudness of 0.5 sones is half as loud. In many instances, however, loudness judgments entail comparisons between two sounds and the loudness is expressed in terms of SPL of an equally loud comparison sound. If the comparison sound is a 1-kHz tone heard binaurally in a free field, its SPL gives the loudness level, which is measured in a unit called a phon. For example, a 60-Hz tone at 60-dB SPL is on the average about as loud as a 1-kHz tone at 40-dB SPL. Accordingly, the loudness level of the 60-Hz tone is 40 phons. (For more information on sones and phons, see Chap. 5. Encyclopedia entries that give a brief summary of loudness can be found in Scharf (1997), Florentine and Heinz (2009), and Epstein and Marozeau (2010).)

The study of loudness is a subarea of psychoacoustics, which is the study of the relationship between physical properties of sound and perceptual responses to them. Loudness is the primary perceptual correlate of the level of a sound. The adjective “primary” is important because loudness also changes with other physical properties of sound (e.g., frequency, bandwidth, duration, spectral complexity of a sound, the presence of other sounds, etc.). There is no simple one-to-one correspondence between loudness and any physical property of a sound, including level. A review of how loudness changes with physical properties of sound can be found in Jesteadt and Leibold (Chap. 5) for steady state sounds, and Kuwano and Namba (Chap. 6) for nonsteady-state sounds. In addition to stimulus factors, loudness changes with memory, multisensory interactions, the manner sounds are presented and how it is measured, cognitive factors, psychological and physical state of the listener, and cross-cultural differences.

Sounds are perceived in a context. Context changes in various ways, including the physical environment and methods used to measure loudness. Using the taxonomy of Buus (2002), methods include the procedures (mode of stimulus presentation, listener’s task, measurement strategy, and datum definition). A review of contemporary methods by Marks and Florentine is provided in Chap. 2. Arieh and Marks (Chap. 3) review the numerous ways in which loudness judgments depend on sequential presentations of relatively short sounds.

Whenever a sound is heard in daily life, it is heard in a multisensory context and in the context of other competing sounds. Experiments have shown that sounds presented simultaneously with a target sound can reduce its loudness; this is known as partial masking of loudness (Scharf 1964). Partial masking of loudness is a common experience in daily life; loudness changes depending on the background soundscape. For example, a friend's voice will sound softer on the street near a noisy construction site than in a quieter area. This phenomenon is referred to as partial masking of loudness, because the loudness of a sound attended to (i.e., a friend's voice) is partially masked by the background sounds. Some sounds are experienced as partially masked, whereas others are not. For example, when successive sounds are heard in daily environments – such as sounds produced by playing successive notes on a piano – the sounds partially overlap one another, but the sounds are heard as separate and loudness does not appear to change (see Chap. 6). Experiments that have been designed to bridge the gap between traditional laboratory experiments and daily experience in natural environments have demonstrated the influence of environmental contexts (see Chaps. 3 and 8). For example, on average a red sports car will be judged to be slightly louder than a green sports car when both are heard with the same automotive sounds (see Chap. 8). Therefore, the percept of loudness at the time of an event will be altered by both sensory and cognitive factors.

Although loudness is a one-dimensional concept in theory and research, it is a multidimensional concept as it is used in daily life. When sound is described as "loud" in daily life, it is the remembrance of the loudness that is being judged, not the same judgment of loudness at the time the sound was heard. This is important because research indicates that our memory of loudness can be altered over time (Ward 1987). There is some evidence that one or more very loud sounds in a soundscape may take precedence in memory over other sounds. For example, Kuwano and Namba (1985) compared two loudness judgment tasks: overall loudness ratings and instantaneous loudness ratings. In overall loudness ratings, listeners were asked to listen to a reasonably long-duration soundscape (e.g., 10 min) and judge the loudness of it at the end of the sound. In instantaneous loudness ratings, listeners were presented the same sound and were asked to track their perceived loudness continuously by varying line length (at various time intervals) while the sound was being heard. Results showed that the overall loudness judgments were larger than the average of instantaneous judgments for the same sounds. This is consistent with the contention that loud sounds in a soundscape may take precedence in memory and alter judgments of loudness over time (see Chap. 6).

In addition to the perceptual phenomenon already reviewed, another fascinating empirical phenomenon is how loudness depends on the manner in which sounds are presented and the listening environment. In general, loudness changes with distance from the sound source, but not always. Loudness can remain constant in the presence of substantial changes in the physical stimulus caused by varying sound distance. For example, the loudness of conversational speech can remain constant even when the distance between the talker and listener changes (Zahorik and Wightman 2001). This phenomenon is referred to as loudness constancy. Loudness also depends on whether sounds are presented monaurally or binaurally and whether sounds are presented via earphones or loudspeakers. Binaural loudness summation refers to the finding that a sound presented binaurally is louder than the same sound presented monaurally. Recent research indicates that the amount of binaural loudness summation is less for speech from a visually present talker than for recorded speech or tones, and the amount of binaural loudness summation is less when sounds are presented in a room than when sounds are presented via earphones (Epstein and Florentine 2009). This lack of binaural loudness advantage in rooms is called binaural loudness constancy, because of its relation to loudness constancy. (For a review of binaural loudness, see Chap. 7.)

It is well known that overexposure to high-level sounds can cause hearing loss. Loudness, as well as threshold, may change after a person is exposed to high-level sounds. Loudness changes can be short term, taking anywhere from a few minutes to several days to return to normal. This condition is called fatigue, or temporary loudness shift (see Chap. 4). With exposure to high level sounds over a prolonged time, or even a very short time with sufficient intensity, changes in loudness can be permanent. Loudness also changes with hearing loss in different ways depending on the type of hearing loss (see Chap. 9).

Not everyone experiences loudness in the same way, as is clearly evident in people with hearing losses. The same physical stimulus can elicit different perceptions of loudness depending on the etiology of the hearing loss and other factors (see Chap. 9). It is noteworthy that people with hearing loss may not use the terms describing loudness in the same manner as people with normal hearing. For example, an individual with a hearing loss may use "very soft" to describe the softest audible sound, whereas a person with normal hearing may describe the same sound as "moderately soft." Further, whispered speech that is amplified may still be identified as "soft" even though the presentation level is high and the sound is perceived as "loud." Because loudness is a subjective experience, it is impossible to know exactly how a person is using descriptive terms.

Although most people with normal hearing have a clear concept of the percept of loudness, terminology used to describe loudness is often incorrect and misleading. For example, many people use the term "volume" to describe the loudness of a sound when they should simply use the term "loudness." The term "volume" is incorrect because it is used to describe a percept that is different from loudness; volume refers to the subjective size of a sound, not its perceptual strength. In fact, we know that loudness is separate from volume by employing the principle of independent invariance; you can hold the percept of loudness constant and vary the volume of a sound (Stevens 1934). Therefore, "volume" should not be used to connote loudness; they are different subjective attributes.

Another common error is use of the term "intensity" to connote loudness. Loudness is a subjective attribute of sound, whereas intensity is a physical attribute of sound. The term "intensity" refers to a physical property of a sound, which is related to its level. Sound can be measured in units of intensity or pressure. Level is usually measured in units of SPL in decibels, or dB SPL, which is a logarithmic ratio of the sound pressure relative to a standard reference sound pressure.

Use of correct terminology is not trivial because it limits our ability to communicate concepts that lead to a better understanding of loudness. Understanding what people mean when they use a term related to a physical continuum is not difficult, because it can be quantified and compared with physical evidence. It is much more difficult to understand what people mean when they use a term related to a psychological continuum, because there is no way to directly measure a person's perception. All measurements of loudness are indirect and scientists are required to use converging lines of evidence to indirectly measure loudness. Although indirectly measuring loudness is challenging, it is possible. Marks and Florentine in Chap. 2 describe methods, problems, and pitfalls of measuring loudness.

1.3 Loudness, Language, and Culture

There are problems with using the correct terms associated with the concept of loudness in different languages. Because loudness research has been performed in different languages in laboratories around the world, it is especially important to understand exactly what is meant by loudness-related terms in those languages. Some languages have different terms for loudness that are used by people in daily language and other terms used by scientists. For example, the term "volume" is commonly used interchangeably with "loudness" in daily conversations in American English.

To determine what a person means when he or she uses a word related to loudness, translations by native speakers of the language are needed. One group of native speakers translates words from one language to another, and another group of native speakers translates back to the original language. The purpose of this cross-translation is to ensure accuracy of the translation. Even if the translation is as close as possible, it may not have the exact same meaning and/or may have other meanings associated with it. For example, the English word "soft" can be used to characterize an acoustic event, as in a soft sound. Soft can be translated into German as "leise" to also mean a soft sound. Other meanings that are associated with "soft" and "leise" are different. In German, "ein leiser Mensch" connotes an introverted and reserved person, whereas in English "soft" has an informal meaning for older people of foolish or silly, as in "He is soft in the head." and an informal meaning for young people of not being strong enough, as in "Don't be so soft; you are a pushover." Language usage changes over time and terms related to loudness are unlikely to be an exception to this rule. Schick and Höge (1996) point out the problem of the equivalence of words in different languages and they proposed an investigation of the amount of overlap in meaning and the development of a Meaning-Overlap-Atlas. It is unfortunate that this has not been realized; it would provide a valuable resource.

The connotative meaning of a percept, such as loudness, can be obtained using the method of semantic differential (Osgood et al. 1957) in which participants rate their impressions on adjective scales to obtain information about the meaning of a percept. Florentine et al. (1986) used this method to gain insight into the meaning of four words: loudness, noise, noisiness, and annoyance. Data from participants in three different countries were compared. In general, participants from England responded in a similar manner to those in the United States, but different from the Japanese participants. Whereas the responses of Japanese participants indicated that the word for loudness was a rather neutral concept, the participants in England

and the United States somewhat negatively polarized it. The opposite was true of the precept of noise; it was a somewhat neutral concept as indicated by the participants in England and the United States, but negatively polarized by the participants in Japan. For noisiness and annoyance, participants in all three countries negatively polarized the percepts. The results of this investigation suggest that the connotative meaning of the word "loudness" may be different between English and Japanese, although the meaning of the word in the dictionary seems to be the same. The same is true of the word "noise." A subsequent study (Kuwano et al. 1991) indicated that the word "loud" has neutral connotations in China, Japan, and Sweden, but negative connotations in Germany and the United States.

An international understanding of loudness is required to address issues related to loudness around the globe. Judgments of what is too loud depend on the cultural background of the listener. What is an acceptably loud sound in one culture may be unwanted noise in another (Namba et al. 1986, 1991). Merchants in street markets loudly announcing what they are selling are accepted and are considered part of the life of the city in some parts of the world. In other parts of the world, the same sound would be considered too loud and annoying. Acceptable levels of loudness are likely to depend on the culture and the meaning of the sound.

The International Organization for Standardization initiated a comprehensive international collaboration to understand the loudness of impulsive noise in the 1970s. A study group was formed and members of The Acoustics Laboratory, Technical University of Denmark, including O. Juhl Pedersen, Poul Erik Lyregaard, and Torben Poulsen, coordinated work and analyzed the data. A total of 22 laboratories from 12 countries around the world agreed to participate in the determination of the loudness level of a number of impulsive noises. The loudness level was determined by means of test subjects who evaluated the loudness of carefully calibrated noise and reference signals. About 500 test subjects participated. The project was dubbed "The Round Robin Test on Evaluation of Loudness Level of Impulsive Noise" with reference to Robin Hood and his gang, who encircled their signatures to indicate solidarity when petitioning the Sheriff of Nottingham (Petersen et al. 1977). Stimuli were made at the Acoustics Laboratory in Denmark and consisted of 21 sounds: nine impulsive noise signals (1 s), five single impulses, six tone pulses, and a 1-kHz pure tone for calibration purposes. The reference signal was a 1/3-octave noise band centered on a 1-kHz tone for the nine noises and a 1-kHz tone pulse for the other signals. The stimuli were recorded on audiotape and a set of tapes was sent to each laboratory with general instructions. The instructions did not specify a specific transducer type (headphones or loudspeakers) or measuring methods, although suggestions were made. It was believed that the psychophysical method for measuring loudness level (not loudness) was of minor importance for the results. Therefore, the participants were instructed to simply report the method used.

When the measurements were returned to the Acoustics Laboratory in Denmark, the investigators were amazed at the "variability" in the data. The stimuli – which were the same in all laboratories – were judged differently in different laboratories. As in many important investigations, the Round Robin experiment raised many more questions than it answered. It was an important turning point in the knowledge of loudness; it made scientists question what they thought they knew. In hindsight, it is clear that a number of factors could have significantly influenced their measurements of loudness, including transducer type (Chap. 7) and measuring methods (Chap. 2).

In the 1980s, another international study group was formed to study cross-cultural factors in the subjective impressions of environmental sounds, as well as social factors related to community noise problems. Scientists from Osaka University in Japan – Seiichiro Namba and Sonoko Kuwano – played a major role in initiating and coordinating the work. Participants included scientists from China, England, Germany, Japan, Korea, Sweden, Turkey, and the United States. Although the overall purpose of the series of studies was to examine the overall impressions of environmental sounds, important insights were gained regarding loudness. Results of this collaboration revealed that there are some differences in the connotative meaning of terms related to loudness among the different languages, although the dictionary definitions appear to be the same (Kuwano et al. 1991). Results also revealed that music creates a unique response in listeners from very different cultures in a similar manner; music can be loud, but not annoying unlike many other sounds (Kuwano et al. 1992; for details and data, see Chap. 8). International collaborations have been fruitful in increasing our understanding of loudness and the social and cultural issues related to community noise problems (Namba et al. 1991).

1.4 Current State of Knowledge Regarding Loudness

Much of what is known about loudness is summarized in the chapters that follow in this book. Our understanding of loudness is still unfolding and there is no comprehensive theory that explains all phenomena related to the perception of loudness. A general overview of the current state of knowledge can be found in loudness models. Loudness models can be divided into two types: models that describe and predict the relationship between the stimulus and the perception of loudness (i.e., psychoacoustical models) and models that attempt to make correlations between changes in the level of a stimulus and the physiological response to these changes (i.e., physiological models).

Psychoacoustical models have been used successfully to take into account many phenomena related to loudness. Although they do not account for all aspects of loudness, they have been effective in leading to a better understanding of loudness. An introduction to psychoacoustical models can be found in Marozeau (Chap. 10 and the references therein; Appell et al. 2001; Fastl and Zwicker 2007).

Despite scientific progress in the general understanding of the physiology of hearing (Pickles 2008), current understanding of the physiology of loudness does not warrant a separate chapter on physiological models of loudness. It is not surprising that physiological models of loudness are much less developed than psychoacoustic models, given the limited amount of data in the area of the physiology of loudness. Physiological data have been related to responses that are correlates of loudness, but not to loudness, per se (for correlates of loudness, see Chap. 4).

In addition, loudness is often discussed in conjunction with the topics of level detection (a.k.a. absolute threshold) and level discrimination (a.k.a. intensity discrimination). This is a debatable practice because the subjective attributes of changes in level may not be perceived as differences in loudness; they may be perceived as changes in pitch or other subjective attributes of sound – especially in individuals with hearing losses (for some discussion, see Buus et al. 1997; Oxenham and Buus 2000).

Substantial physiological data have been obtained on aspects of the neural coding of sound intensity (Plack and Carlyon 1995; Plack 2005; Pickles 2008). Neural coding measurements have been correlated with psychoacoustical measurements of level discrimination. In fact, psychoacoustical modeling of level discrimination across frequency (i.e., Florentine and Buus 1981) was used to develop and test the first quantitative model of auditory perception in a nonhuman species (the starling), tying together a wide variety of physiological and behavioral data for that species (Buus et al. 1995). The integration of information across frequency bands has been used by other authors in the development of physiologically based models of perception, but not applied directly to loudness. The psychoacoustical models of loudness indicate that although major contributions to the loudness of tones stem from excitation in auditory channels tuned to the tone's frequency (Moore et al. 1985), contributions from the other channels are also apparent (Florentine et al. 1997). Thus, it appears that loudness can be formed as a sum of activity from frequency-selective auditory channels and physiological models will need to take this into account.

Data from noise-exposed cats (May et al. 2009) appear roughly consistent with psychoacoustical data from humans with noise-induced hearing losses. For example, the bandwidth of vowels appears qualitatively consistent with loudness summation data from a group of humans with noise-induced hearing losses (Florentine and Zwicker 1979; Florentine et al. 1980). Unfortunately, much of the other data in the literature obtained from human listeners with sensorineural hearing losses of primarily cochlear origin are averaged and not separated by etiology, nor are individual data routinely reported. It is now sufficiently clear that there are substantial individual differences in how loudness grows with increasing level in people with sensorineural hearing losses. These individual differences are highly likely to reveal important mechanisms that contribute to loudness. For example, Marozeau and Florentine (2007) reviewed data from five experiments using different methods to obtain individual loudness functions of hearing-impaired listeners. Results suggest that: (1) when the level of a sound is increased there are considerable individual differences in loudness growth among hearing-impaired listeners and (2) averaging the results across hearing-impaired listeners will mask these differences.

Physiological studies of loudness in animals have been constrained by a lack of psychoacoustic measures of loudness. Common methods used to study loudness in humans, such as equal loudness matching and magnitude estimation, are not applicable for animal studies. Some studies have used a reaction–time paradigm – the louder the sound the faster the reaction time – that correlates with loudness (for review of reaction–time measures in humans, see Wagner et al. 2004 and Chap. 4).

The relationship between sound level and reaction time has been measured for nonhuman primates (Stebbins and Miller 1964; Pfingst et al. 1975) and the domestic cat (May et al. 2009). Attempts have been made to relate equal loudness contours from humans to equal latency contours from reaction times in both species (Stebbins 1966; Pfingst et al. 1975; May et al. 2009). Results show similarities between human and animal data, but also differences such as a compressed range of latencies at the highest frequencies. Pitch and annoyance-type subjective cues are potential confounds and it is not currently feasible to know the subjective experience of nonhumans. Further, attempts have been made to study the influence of noise-induced hearing loss on loudness. Reaction time latencies have been measured in sound-exposed monkeys and cats and compared with the data from humans (e.g., see Pfingst et al. 1975; May et al. 2009).

Only some aspects of the physiology of loudness appear to be explained. For example, the increase in loudness with increasing level is consistent with the basilar-membrane response function; there is a good correlation between the loudness-growth function and physiological data (see Chap. 4). How the loudness of a sound increases with level is not well understood at the auditory nerve, although attempts have been made to relate the psychoacoustical phenomena to knowledge of the auditory-nerve response (see e.g., Goldstein 1974; Pickles 1983; Relkin and Doucet 1997; Heinz and Young 2004; Heinz et al. 2005). Some features of psychoacoustical data are readily apparent in the auditory nerve data, but others are not. In particular, it appears to be an inescapable conclusion that any frequency-selective channel carries information about the stimulus level over dynamic range of about 120 dB, but how this information is used is unclear. Because most neurons tend to saturate within a dynamic range of only 30–60 dB, the encoding of stimulus level within a channel is not straightforward and requires careful consideration of the available evidence. For example, as the level of a tone increases, the firing rate of neurons in the auditory nerve also increases, but at some point increases in level cause no further increase in the firing rate. Although some benefit is obtained from a small number of auditory neurons with higher thresholds, this does not appear to be enough to account for the fact that loudness increases over a level range of about 120 dB. This is known as the dynamic range problem (see Chap. 4 and Delgutte 1996 for review of early physiological data correlated with sound level).

Two hypotheses to explain the dynamic range problem have received much attention. They are not mutually exclusive. One states that loudness is related to the total amount of neural activity. As a tone increases in level, it excites neurons with primary sensitivity at the characteristic frequency and also excites an increasing number of neurons with adjacent characteristic frequencies. This is known as the “spread of excitation” – a term taken from psychoacoustical modeling. It is unlikely, however, that a simple sum of the spike activity in the auditory nerve is a physiological correlate of loudness (Relkin and Doucet 1997). The other hypothesis is that loudness is related to temporal properties of neural activity. It is well known that neurons fire at precise times correlated with temporal properties of sound. In other words, they tend to phase lock to certain frequencies. As a tone increases in level, more neurons phase lock to it and the overall synchrony across the population of auditory nerve fibers increases. However, the ability of the auditory nerve fibers to phase lock decreases at high frequencies, which is inconsistent with this hypothesis.

Therefore, the connection between physiological responses and our perception of loudness remains unclear. Although qualitative data indicate possibilities, there have not been encouraging quantitative assessments. Much of what is known about the physiology of the perception of sound levels comes from correlating psychoacoustic measurements with the physiological responses to level differences. For example, it has been shown that information from a single neuron in the auditory nerve is enough to account for our ability to discriminate two sounds that differ in level. Just because information is available, however, does not mean that it is used by the auditory system. More research is needed to understand loudness encoding.

The past quarter-century has been especially fruitful in the area of loudness research. Four trends in psychophysics and their interconnections have led the way: (1) investigations between temporal and spectral integration of loudness and the loudness function itself, (2) investigations of individual differences in loudness functions among normal listeners and listeners with different types of hearing losses, (3) investigations of how the many aspects of context affect loudness, and (4) investigations of binaural loudness in and out of traditional laboratory settings. Some examples can be found in Florentine (2009). These trends were aided by technological developments that permitted large amounts of data to be modeled. Old theoretical frameworks have been challenged. Some concepts have been upheld; others have been reformulated. For example, it had been assumed that loudness at threshold was zero. This assumption influenced models of loudness for people with normal hearing and hearing losses. When measurements were actually made of loudness at threshold, the data showed a low, but positive value of loudness at threshold (Buus et al. 1998). A new standard (ANSI S3.4-2007) has been revised in light of these new data. The collapse of this assumption opened other assumptions to scrutiny. If loudness at threshold has a positive value, could it be that loudness at threshold is different for different listeners? Many studies have assumed that loudness at threshold is the same for all listeners whether they have normal hearing or hearing losses. In fact, there is considerable evidence that loudness at threshold may be different for different individuals. Could loudness at threshold be different at different frequencies in the same listener? If so, this could have implications for hearing loss rehabilitation. These new discoveries – together with old discoveries – are introduced in the ensuing chapters.

Although significant progress has been made in understanding loudness, there are areas that are primed for new discoveries. It is highly likely that over the next quarter-century (1) there will be an understanding of the physiological basis of loudness, (2) individual differences in loudness of listeners with normal hearing and hearing losses will be understood, resulting in better rehabilitation of people with hearing losses, (3) loudness context effects will be widely acknowledged – the gap between loudness in the laboratory and in daily environments will be better understood, and (4) new models will be developed that can predict individual differences in loudness among normal hearing-listeners and listeners with hearing losses, as well as predict the average perception of loudness for large groups of listeners in various daily environments. Prospects for the future of understanding loudness are quite hopeful as knowledge from different areas of study and psychoacoustics merge.

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Chapter 2
Measurement of Loudness, Part I: Methods, Problems, and Pitfalls

Lawrence E. Marks and Mary Florentine

2.1 Introduction

It is a matter of everyday experience that sounds vary in their perceived strength, from the barely perceptible whisper coming from across the room to the overwhelming roar of a jet engine coming from the end of an airport runway. Loudness is a salient feature of auditory experience, closely associated with measures of acoustical level (energy, power, or pressure) but not identical to any of them. It is a relatively straightforward matter for a person to note whether one sound is louder or softer than another, or to rank order a set of sounds with regard to their loudness. To measure loudness, however, in the typical sense of "measuring," requires more than just ranking the experiences from softest to loudest. It entails quantifying how much louder (e.g., determining whether the ratio or difference in the loudness of sounds A and B is greater or smaller than the ratio or difference in loudness of sounds C and D).

The quantitative measurement of loudness in this sense is important both to basic research and to its applications – important to scientists seeking to understand neural mechanisms and behavioral processes involved in hearing and to scientists, engineers, and architects concerned with the perception of noise in factories and other industrial settings, in the streets of urban centers, and in residences located along flight paths and near airports. As Laird et al. (1932) wrote more than three-quarters of a century ago, in an article describing one of the earliest attempts to quantify the perception of loudness,

> When a considerable amount of money is to be appropriated for making a work place quieter, for instance, the engineer can say that after acoustical material is added the noise level will be reduced by five or ten decibels. "But how much quieter will that make the office," is likely to be the inquiry. "A great deal" is not only an unsatisfactory but an unscientific answer. (p. 393)

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