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Arthur N. Popper *Editors*

The Frequency-Following Response

A Window into Human Communication

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With 66 Illustrations

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Chapter 1
The Frequency-Following Response: A Window into Human Communication

Nina Kraus, Samira Anderson, and Travis White-Schwoch

Abstract The frequency-following response (FFR) is a measure of synchronous sound-evoked neural activity that reveals the integrity of sound processing in the brain. Studies of the FFR are organized around two intertwining themes: learning and everyday communication. These studies tie into a conceptual framework wherein making sense of sound is fundamental to everyday life and is at the intersection of cognitive, sensorimotor, and reward networks. Understanding how well an individual listener processes sound provides a snapshot of auditory function and its impact on everyday communication skills. This chapter provides an overview of FFR research and contends that the FFR is a measure that reflects an individual's past and potential in sound. Despite diverse terminology in the field, it is argued that FFR provides a good umbrella term for these biological approaches. A brief historical perspective illustrates how FFR has a longstanding history in auditory neuroscience and has addressed many basic and clinical questions in hearing. The FFR is on its way to becoming a mainstream tool in neuroscience. Perhaps most exciting is the potential for use in brain screening to assess hearing in newborns to evaluate risk for communication impairments, setting the stage for early interventions that offset a life spent struggling to learn and communicate.

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1.1 Introduction

Making sense of sound is fundamental to everyday life. Sound is an invisible but powerful force that provides a critical medium for learning about the world. Much of this learning is tangible, such as a child's prodigious ability to soak up speech and, eventually, learn to talk. But sound also provides a channel for phenomena that are less concrete, such as making friends, building relationships, and learning how to navigate the social world.

The ability to make sense of sound relies on the remarkable spectrotemporal precision in the auditory system. Listeners can detect auditory events that are shorter in duration than an action potential, and neurons in the auditory system can respond to sound more than 1,000 times more quickly than photoreceptors in the visual system. This temporal precocity is intimately tied to everyday communication. Thus, enriched auditory milieus that facilitate the coordination of cognitive, sensorimotor, and reward systems also enhance the integrity with which the brain processes sound with concomitant gains in communication skills. In contrast, disruptions to any chain in this system cascade to communication impairments that are coupled to poor auditory coding (Kraus and White-Schwoch 2015).

The frequency-following response (FFR) is a measure of synchronous sound-evoked brain activity that reveals the integrity of sound processing in the brain and reflects auditory-neurophysiological processes with granularity and precision rarely offered by other tools in human neuroscience. FFR provides a snapshot of the hearing brain and reflects the confluence of cognitive, sensorimotor, and reward systems on auditory processing, reliably showing individual differences that align with everyday communication skills.

1.2 Why Measure Sound Processing in the Brain?

A longstanding goal in auditory neuroscience has been to understand the relationship between hearing and everyday life and to elucidate the biological mechanisms underlying this link in humans. This goal has translational consequences because understanding how sound processing and communication are disrupted can pave a way toward strategies to evaluate and manage communication impairments, spanning listening, language, and literacy.

A first step in achieving this overarching goal is to understand the biological mechanisms that underlie auditory processing and its impairments. This theme pervades the chapters in this volume and shows how measuring neurophysiological responses to complex sounds illuminates the role of auditory processing in communication, language development, literacy, and other important functions of everyday life. Additionally, this approach documents the disruption of auditory processing in clinical populations. Yet this processing is not static; rather, it is sculpted by a life in sound. Thus, auditory neurophysiology reveals the imprint of learning. As reviewed throughout this book, the same neurophysiological markers implicated in communication impairments are amenable to explicit training, motivating the use of targeted interventions to boost communication skills and their underlying biological mechanisms. The FFR reveals biological hearing health in individual humans with unprecedented granularity.

1.3 What Is the Frequency-Following Response?

The FFR is a reflection of sound-evoked synchronous neural activity that is distinguished from other evoked potentials by its *transparency*. Whereas other potentials are abstract representations of sound that are identified by "neural waves," the FFR reflects phase-locked activity that codes sound; thus, it physically resembles the eliciting stimulus, as illustrated in Fig. 1.1.

What distinguishes the FFR from other types of sound-evoked neuroelectric responses is that an individual's FFR offers a wealth of information about sound processing in the brain—a biological mosaic that goes far beyond the timing and amplitude measures gleaned from most types of sound-evoked electrical activity. Because the FFR reconstructs most properties of the eliciting stimulus (Fig. 1.1), the response is as complex as the sound that elicits it. Thus, the integrity of an individual's neural coding of discrete cues, such as those that convey a speech

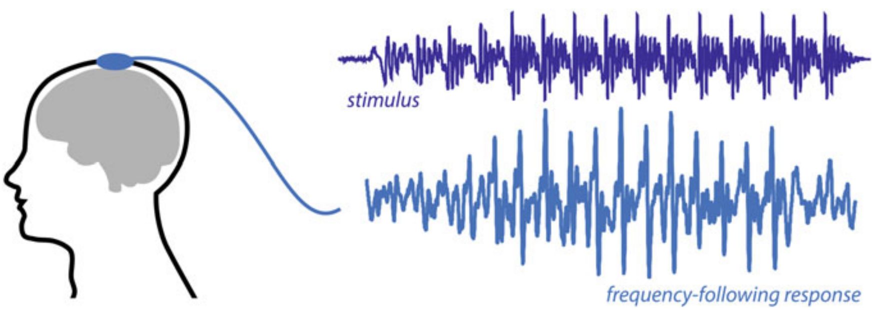

Fig. 1.1 The FFR is a scalp-recorded auditory evoked potential. Unlike most measures of biological activity that provide abstract measures, the FFR is transparent—it recreates many physical features of the evoking sound. As may be seen, the stimulus and response are similar with respect to duration, periodicity, rise, and more. Thus, the FFR is an avenue to evaluate the neural coding of multiple features in sound

sound's identity, may be teased apart. The diversity of FFR-derived measures is reflected in the diverse chapters in this book. What will become clear when thinking about these chapters as a whole is that each FFR component is somewhat independent from the others: a large response is not necessarily a stable response, and a stable response is not necessarily a large response.

The chapters presented in this book cover a vast territory, but all of them review work focused on the FFR. Together, these chapters illustrate how the FFR meets two high-reaching goals. For one, FFR studies encapsulate how making sense of sound is coupled to communication and shed light on basic principles of sound processing in the brain, its malleability, and its stability. Unlike other approaches, though, the FFR reliably reveals *individual differences*. A single FFR can reflect the past (White-Schwoch et al. 2013) and predict the future (White-Schwoch et al. 2015). Thus, the second goal: the FFR is an approach that may be applied clinically to understand communication disorders. The FFR, therefore, is a candidate clinical tool because it moves beyond asking *whether* an individual makes sense of sound to shed light on *how well* an individual makes sense of sound and *which* of the biological processes that are important for making sense of sound are enhanced or diminished.

1.4 The FFR: Nothing New

The last decade has borne a surge of interest in the FFR. As shown in Fig. 1.2, a Google Scholar search shows over 700 references to "frequency-following response" between 2010 and 2016, compared to 436 references between 2000 and 2010. It is, however, interesting to trace the early history of the FFR because it illustrates how the FFR has always played a role in auditory neuroscience and neurophysiology in general. For over 50 years, the FFR has been used by scientists interested in hearing assessment, pitch perception, diagnostics, cochlear transduction, and attention.

The first FFR-like recordings even predate Lord Adrian, often considered one of the founding fathers of neurophysiology, who would win the Noble prize for (among many other discoveries) conducting some of the first single neuron

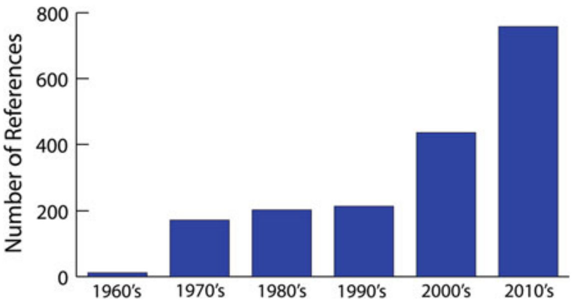

Fig. 1.2 A Google Scholar search (May 2016) revealed the surge in papers referencing the "frequency-following response" in the past two decades, but also illustrated its long history

recordings and establishing the all-or-none principle of action potentials (Adrian 1926). But almost two decades earlier, Buytendijk (1910) recorded sound-evoked electric activity in guinea pigs, rabbits, and frogs (although he refered to similar, unpublished observations made in 1904). While his recordings were likely dominated by eighth nerve activity, he did record an FFR-like dipole in the rabbit with an active electrode near the internal auditory meatus and a reference electrode "on an indifferent spot of the hindmost skull-cavity." He also noted differences in response properties between anesthetized and deceased animals, portending discovery of active cochlear mechanics by more than a half century (for review see Dallos 1992).

Derbyshire and Davis (1935) conducted one of the first comprehensive studies of sound-evoked electrical activity and, like neurophysiologists to follow, were struck by the similarity between periodicities in the stimulus and the response. Like many FFR scientists to come, they were interested in the neural basis of pitch perception, a topic that was to recur periodically through the FFR's history. As early as 1965, the FFR was used to arbitrate between place and volley theories of pitch perception (Boudreau 1965). This was to become a focus of FFR research in the 1970s and 1980s (Hall 1979; Greenberg et al. 1987). It was clear that the FFR lent itself to experiments aiming to understand pitch processing in humans (e.g., Galbraith 1994). This remains a topic of intense scrutiny (Gockel et al. 2011), especially given new evidence that pitch coding, vis-à-vis the FFR, is subject to experience (Krishnan and Gandour, Chap. 3; Carcagno and Plack, Chap. 4; White-Schwoch and Kraus, Chap. 6).

During the 1970s much attention turned to the origins and basic properties of the FFR in an effort to develop it as an objective measure of hearing thresholds. Worden, Marsh, and their colleagues made the first FFR recordings in humans and dedicated energy to understanding its origins (Worden and Marsh 1968; Marsh et al. 1970). Complementary studies in animal models worked to distinguish the FFR from the cochlear microphonic and to rule out stimulus artifact—a challenge for the FFR researcher that remains to this day (Faingold and Caspary 1979; Snyder and Schreiner 1984). It was perhaps fate that pioneering scientists in the field of auditory neuroplasticity, such as Michael Merzenich (Gardi et al. 1979) and Norman M. Weinberger (Weinberger et al. 1970), briefly forayed into this biological approach that has now become a powerful approach to study auditory learning in humans (Sect. 1.6).

Eventually, FFR researchers felt adventuresome. Rather than just measuring responses to pure tones, they sought to test the limits of just how much an FFR could resemble the stimulus. It soon became apparent that the rich spectrotemporal details contained in natural sounds, such as speech and music, were beautifully recreated by the FFR (Fig. 1.1). In fact, if a computer was tricked into playing an FFR, listeners could identify the evoking stimulus (Galbraith et al. 1995). Soon, stimuli combining transient and sustained features (e.g., consonant-vowel syllables) and complex listening situations (e.g., speech in background noise) were getting closer and closer to approximating everyday listening environments, revealing biological bottlenecks in everyday sound processing (Cunningham et al. 2001). Parallel experiments in an animal model elucidated the specific biological mechanisms underlying these phenomena (Cunningham et al. 2002). This crucial discovery opened a door to the use of complex stimuli to understand complex auditory phenomena, which is the focus of this volume. Additionally, this approach showed that a single FFR offered a wealth of information about discrete aspects of sound processing in the brain, which has motivated FFR work since, and allows for a more thorough evaluation of sound processing than periodicity tracking or response amplitude (Anderson et al. 2012). FFR technology has now advanced to the point where it is no longer constrained to the laboratory, facilitating clinical and community-based studies of auditory processing and learning (Kraus et al. 2014a, b).

1.5 Call It "FFR"

Following the resurgence in interest, the FFR has entered the throes of a terminology identity crisis. At times it seems there are as many terms to refer to the FFR as there are papers using it! While this might be seen as a point of consternation, the editors hold that it is a sign of maturity: the FFR is on its way to becoming a mainstream approach in neuroscience. "FFR" provides an excellent umbrella term that ties together diverse approaches, populations, and questions. The FFR has come a long way and accomplished a lot and, like other approaches to evaluating sound processing, it can encompass many offshoots. FFR can be thought of as a suite of methods that can be tailored to the population and stimuli of interest.

Common terms, aside from FFR, include: cABR, auditory brainstem response to complex sounds (Skoe and Kraus 2010); EFR, envelope-following response (Dolphin and Mountain 1992; Aiken and Picton 2008); AMFR, amplitude-modulation following response (Kuwada et al. 2002); sABR, speech-evoked auditory brainstem response (Russo et al. 2004); and SSSR, subcortical steady-state response (Bharadwaj and Shinn-Cunningham 2014). Weinberger et al. (1970) poetically termed it the "auditory neurophonic," a term that caught on for a brief period to distinguish it from the cochlear microphonic; however this name also was used to refer to auditory nerve activity (Snyder and Schreiner 1984). Sometimes the FFR is simply called an "auditory brainstem response" (ABR)—woe to the reader imagining hearing thresholds! In addition, a single evoked potential is sometimes dichotomized into its "ABR" and "FFR" portions (Cunningham et al. 2001). Even more confusing is that all of these terms are often hybridized, such as "speech-evoked-envelope-following response" (Easwar et al. 2015), even though it is unlikely there is a one-to-one mapping between *acoustic envelope* and temporal fine structure and *neural envelope* and temporal fine structure (Shamma and Lorenzi 2013). In other words, the FFR envelope may not solely reflect coding the stimulus envelope, and the FFR fine structure may not solely reflect coding the stimulus fine structure.

The advantage of the term "ABR" and its derivatives is that it provides a good technical description. FFRs are similar to ABRs in many ways, including with respect to technique, such as the collection parameters (electrode montage, filtering, averaging, and more). Additionally, ABRs are classically thought of as responses to transients and when FFRs are elicited to complex sounds, they contain these rich transient cues, such as those found in consonants (Fig. 1.1). Unfortunately, the term ABR undermines the rich biological information offered by the FFR because only latencies and amplitudes are classically analyzed in ABRs. Moreover, the term "brainstem" is something of a misnomer. First, the FFR is thought to have a strong contribution from the inferior colliculus of the auditory midbrain, or at least from synchronized inputs to the midbrain (for review see Chandrasekaran and Kraus 2010). Second, an emerging view characterizes the auditory system as a distributed, but integrated, experience-dependent network, and it has been argued that the FFR reflects this interactivity (Kraus and White-Schwoch 2015, 2016).

In fact, recent evidence from Zatorre and colleagues suggests a cortical contribution to the FFR (Coffey et al. 2016), and recent work from Shinn-Cunningham and colleagues suggests a contribution from eighth nerve fibers (Shinn-Cunningham, Varhgese, Wang, and Bharadwaj, Chap. 7). Thus, terminology that implies anatomic generators can be misleading, especially "ABR." In fact, the editors of this volume and their colleagues introduced the term "cABR" (Skoe and Kraus 2010; Anderson et al. 2013) but in retrospect regret the localization implied. "Brainstem" may be especially problematic by implying low-level afferent processes when, in fact, the activity revealed by the FFR is exquisitely tuned and retuned by the convergence of afferent and efferent influences. Moreover, in many cases, click-evoked ABRs appear normal in listeners with an abnormal FFR that reveals a communication disorder (King et al. 2002; Banai et al. 2009).

The advantage of the term "FFR" is that the response does just that—it follows the frequencies of the stimulus, thus offering its wonderful transparency and richness as an evoked potential. Unfortunately, this term is not without its problems either. Traditionally the FFR referred solely to phase-locked activity to pure tones, intended to measure low-frequency hearing sensitivity (see Sect. 1.4). For many in the field, then, it does not imply the rich information across frequencies offered by the FFR to a complex sound. In addition, real-world sounds, such as speech, contain transients. Although these are technically brief, broadband bursts of acoustic information, they are rarely thought of on a frequency-specific basis and are instead thought of in terms of timing. Thus, "FFR" risks eliding important aspects of the technique.

Although no term is perfect, it is the view of this volume's editors that "FFR" is the best compromise. FFR can be thought of as an umbrella term that encapsulates all of the others. FFR stimuli and recording parameters can be tailored to the specific population and question of interest.

1.6 A Window into Human Communication

This volume is organized around two themes: the neurobiology of (1) learning and (2) everyday communication. What should be clear upon reading any chapter—and especially when considering the book as a whole—is that these themes are connected and interactive. That is, the ability to communicate is shaped by experience, and experience is shaped by everyday communication.

Fuh-Cherng Jeng (Chap. 2) reviews how auditory experience early in life shapes brain development. This is intertwined with a discussion of theories of early speech and language development and how language experience during the first year of life shapes auditory neurophysiology. He then reviews FFR studies during infancy and early childhood that illustrate both the rapid developmental plasticity incumbent in young children and how this maturational course intersects with everyday linguistic experience. FFR studies during infancy and early childhood have translational implications. As reviewed later in this volume, in older children and adults FFR measures indicate communication impairments. Jeng makes a convincing case that the FFR is a robust and reliable measure during infancy, opening up an avenue for early identification of communication disorders to facilitate early interventions.

Ananthanarayan Krishnan and Jackson Gandour (Chap. 3) discuss how everyday linguistic experience shapes auditory processing, with an emphasis on the neural coding of pitch-bearing information. Different linguistic systems employ distinct acoustic cues to convey lexical information. Tone languages, such as Mandarin, use pitch contours to convey meaning, and Krishnan and Gandour highlight their seminal work using the FFR to examine how this experience shapes automatic auditory response properties. They couch this in a discussion of models of language and pitch processing through the auditory system. In addition to revealing the profound influence of everyday experience on the auditory system, Krishnan and Gandour show how elegant FFR experiments shed light on the biological legacy of experience, the organization of pitch processing in the auditory system, and the fundamental link between language and hearing.

Samuele Carcagno and Christopher Plack (Chap. 4) provide a comprehensive review of FFR studies of short-term training and perceptual learning. Auditory abilities are not static, and short courses of intensive auditory training shape perceptual skills. The FFR is increasingly used as an outcome measure in these experiments. Following a brief review of perceptual learning and some of the major questions facing the field, Carcagno and Plack lucidly cover each FFR training experiment, including those in children, young adults, and older adults, with a critical assessment of each experiment's strengths and weaknesses. They connect the dots to the broader literature on auditory neuroplasticity, pulling on work in animal models to evaluate several frameworks for learning that have been posited in light of these FFR experiments. While auditory training is often recommended for listeners with communication impairments, Carcagno and Plack lay out what must be accomplished in future work to strengthen this clinical potential.

Carles Escera (Chap. 5) considers a different form of auditory plasticity—the ability to rapidly adapt to a sensory environment "online". Listeners must navigate constantly changing auditory worlds, and sensory systems need to be dynamic enough to accommodate this diversity. Escera considers experiments in humans and animal models of context-dependent adaptation observed throughout the auditory system. This leads to a discussion of work in humans that examines how FFR response properties are shaped by stimulus context, which is couched in a discussion of context-dependent modulation in the auditory midbrain. As Escera argues, this work provides insights into the fundamental organization of the auditory system, and he rejects the view that context-dependent modulation is a strictly cortical phenomenon in favor of a more integrated model for auditory processing.

Travis White-Schwoch and Nina Kraus (Chap. 6) complete the section on learning and provide a bridge to the section on everyday communication. They review principles of auditory learning, emphasizing the enduring biological legacy that everyday experiences impart. A central argument is that experiences—good or bad—shape automatic processing, and they argue that both may do so through congruous pathways. Thus, the auditory brain's default state is in a constant push-and-pull between stability and plasticity. After reviewing FFR studies of communication abilities and disabilities, they juxtapose lifelong music training (a case of enrichment) to growing up in poverty (a case of deprivation). Against the backdrop of understanding how different FFR measures indicate communication impairments, they argue that enrichment activities, such as music training, language experience, and auditory training, can be targeted to strengthen the neurobiological bottlenecks endemic to specific populations.

Barbara Shinn-Cunningham, Leonard Varghese, Le Wang, and Hari Bharadwaj (Chap. 7) open the section on everyday communication by reviewing cutting-edge work that unravels biological processes that facilitate and constrain sound-directed attention. The work they review illustrates how the auditory system operates as a distributed but integrated circuit, highlighting complex interactions between the integrity of the auditory periphery, fine-grained temporal coding, and guided attention. Shinn-Cunningham and colleagues review the challenges and opportunities offered by the FFR in the study of these individual differences. Next, they highlight one candidate mechanism for individual differences, namely, a noise-induced deafferentation of synapses at the inner hair cells. While they emphasize what the FFR has contributed to the study of everyday listening skills and individual differences in those abilities, they clearly outline its limitations, identifying important avenues for future experiments and highlighting how everyday communication skills rely on many interactive auditory and non-auditory processes.

Gavin Bidelman (Chap. 8) discusses two insidious constraints on everyday communication: noise and reverberation. Few everyday listening situations are pristine, and for too long the field imagined that auditory performance in the sound booth was a good predictor of listening skills in a restaurant. Bidelman cogently discusses how both noise and reverberation constrain the intelligibility of a signal and how these constraints can be seen in the FFR. Next, he discusses several experiments that show links between the integrity of the FFR in adverse listening conditions and a listener's auditory performance. He ties this back to the question of auditory experience and shows how different experiences shape the contingency between the FFR and listening skills. One of the fundamental questions for auditory neuroscience is how listeners manage to understand speech in noisy, everyday environments such as the cocktail party. Bidelman emphasizes just how much the field has learned through FFR experiments.

Eliane Schochat, Caroline Nunes Rocha-Muniz, and Renata Filippini (Chap. 9) tackle auditory processing disorder—poor auditory function despite a normal audiogram—a clinical condition that continues to vex audiologists and scientists. They emphasize the importance of objective biological approaches in evaluating listening skills, especially in children with related cognitive and language impairments, and how the FFR has contributed in the context of auditory neurophysiology. What Schochat et al.'s summary highlights is that the FFR is that rare tool in translational science that both teaches basic lessons about the mechanisms underlying communication skills and offers clinicians a strategy to improve diagnosis and management of their patients. In short, the FFR inherently is a biological index of auditory processing and its disorders.

Rachel Reetzke, Zilong Xie, and Bharath Chandrasekaran (Chap. 10) review the extensive literature using the FFR to study reading impairments such as dyslexia. If it is at first surprising that a book on the auditory system includes a discussion of reading and dyslexia, Reetzke et al. quickly make clear that auditory processing is fundamental to literacy development, and they highlight the contributions from the FFR in this lesson. As they review, literacy is coupled to listening, and many children with poor reading skills have poor neural coding reflected in the FFR. Research in dyslexia and reading remains fraught with controversy; the FFR provides a stabilizing view. Thus, from a pragmatic standpoint, Reetzke et al. make a convincing case that FFR work dovetails with several models of reading impairment and that irrespective of the underlying causes of poor reading, one can still appreciate the FFR's contributions as an experimental—and potentially clinical—tool.

Samira Anderson (Chap. 11) closes the volume with a discussion of clinical translation in the context of aging and hearing loss. The communication problems that older adults face are of strong interest in the hearing sciences and audiology, and they are exacerbated by age-related hearing loss. Anderson reviews studies that show the FFR reveals distinct bottlenecks in sound processing associated with aging and hearing loss. Next, she discusses how the FFR serves as a research tool in studies of auditory training, and how it is beginning to emerge as a technique in the study of amplification. Finally, she lays out the directions necessary to translate the FFR from the lab to the clinic.

Together, these chapters illustrate the diversity of research applying the FFR. The core theme that emerges is that human communication is intimately tied to experience with sound. These experiences range from in-the-moment adaptation to lifelong experience with language or music. These communicative skills extend into everyday life, including listening in noise, spatial hearing, and literacy. Interest in capitalizing in the communication-experience link motivates an eventual goal of using the FFR in clinical settings to evaluate listening skills, predict future listening challenges, and reveal outcomes from interventions.

1.7 Next Steps: A Mainstream Role for the FFR in Neuroscience

A few broad conclusions can be drawn from these chapters; these highlight some of the future directions for this field. From a technical standpoint, the FFR has reached a reasonable level of sophistication. Although ongoing work is dedicated to refining its collection and analysis, how to go about measuring and interpreting an FFR is now basically understood (Skoe and Kraus 2010). This opens the door to applying the FFR to new and diverse areas in the study of communication, listening, and experience. Particularly exciting is the potential for the systematic study of individual differences in the FFR, including in clinical populations. This can eventually lead to a better understanding of how listening skills can be disrupted. If the FFR continues to pattern in distinct ways in different clinical populations, it may prove to be a sensitive and specific biological marker for communication impairments.

At the same time, there are areas in need of technical refinement. A persistent challenge to FFR work is the signal-to-noise problem: an FFR needs to be the averaged response of many repetitions of sound. As techniques develop to reduce collection time and, perhaps, make sense of the response to just a few stimuli, the FFR can provide a stronger measure of real-time listening and adaptation. Additionally, use of the FFR will become more practical, especially in difficult-to-test clinical populations.

Tracing the FFR's history (Sect. 1.4) shows that it was first predominantly applied to animal models. The past few decades, however, have seen it turn almost exclusively to a technique used in humans. While it is a robust marker of auditory processing in humans, several authors in this volume and elsewhere outline questions that are best answered in animal models. An exciting new avenue is to study humans and animal models in conjunction to understand the neural mechanisms underlying auditory phenomena and their consequences for every day, real-world listening (Warrier et al. 2011; White-Schwoch et al. 2016). It is clear that the midbrain is subject to experience-dependent modulation (Gao and Suga 2000; Bajo et al. 2010); using the FFR can provide a deeper understanding of the mechanisms underlying experience-dependent plasticity.

The FFR has proven its worth in studying groups of listeners. However, as many authors here note, it is unusual among evoked potentials in its reliability and interpretability in an individual. Systematically studying individual differences with the FFR represents a new frontier for auditory neuroscience, which can take the field to a point where it considers how auditory function is shaped by an individual's life in sound. The evidence reviewed here, particularly in the second half of this volume, shows how individual differences in the FFR reveal an individual's strengths and weaknesses in sound processing. These individual differences are stable across stimuli and test sessions, motivating longitudinal studies employing the FFR. It remains to be seen whether this information can be harnessed to be clinically useful, but early evidence is promising.

FFR studies span a wide scope. This volume focuses on learning and communication and emphasizes the more longstanding spheres of FFR research. However, new domains are rapidly being applied to the FFR, including mental health (Tarasenko et al. 2014), amplification/auditory prostheses (Easwar et al. 2015; Anderson, Chap. 11), attention deficit/hyperactivity disorder (Jafari et al. 2015), amusia (Lehmann et al. 2015), concussion (Kraus et al. 2016), and more. Perhaps it is not a surprise that the FFR has so many future avenues: it evaluates the incredibly fast and challenging auditory brain computations that are hypothesized to be easily disrupted by acute and long-lasting insults (Kraus and White-Schwoch 2015).

With increasing knowledge of how FFR signatures distinguish listeners and indicate an individual's strengths and weaknesses in making sense of sound, the FFR can inform medicine, education, and social policy. Early studies show that the FFR is an effective field-based technique for conducting neurophysiological studies outside of the traditional laboratory (Kraus et al. 2014a, b). As FFR technology continues to be refined, the FFR can be placed in schools and clinics to provide an adjunct for the evaluation of listening skills. Finally, an exciting potential for the FFR is to predict future communication skills (e.g., White-Schwoch et al. 2015). The FFR is a robust measure of auditory-neurophysiological processing in infants (Anderson et al. 2015; Jeng, Chap. 2), suggesting that it could be used as a measure to screen for communication disorders in newborns and, given the plasticity of these neurophysiological processes, identify approaches for early intervention (Carcagno and Plack, Chap. 4; White-Schwoch and Kraus, Chap. 6). One of hearing science's largest contributions to public health has been the introduction of universal newborn hearing screening. Research in the FFR, as reviewed in this book's diverse chapters, has the potential to make a second such contribution by screening the newborn brain, opening a door to early interventions that prevent a life spent struggling to make sense of sound.

1.8 Summary

This volume spans diverse work employing the FFR, revolving around intertwining themes of learning and everyday communication. The editors are grateful to each of the authors for contributing to this volume, and would like to emphasize the following points in closing:

- The FFR is a biological snapshot of the integrity of sound processing in the brain. This sound processing is shaped by experience, predicts the future, and reflects the integration of cognitive, sensorimotor, and reward networks.
- "FFR" provides the best terminology to refer to this biological approach and should be adopted as a standard.
- FFR has always had a place in auditory neuroscience. As it becomes a more mainstream technique, FFR has the potential to inform basic and applied questions in learning and communication.

- Perhaps one of the most exciting clinical outlets for the FFR is to screen the newborn brain. This could expedite early and targeted interventions for a myriad of communication disorders.

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