15 Auditory Neurophysiology of Reading Impairment: Theory and Management

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Summary

Why does literacy develop smoothly for some children, whereas others struggle? Up to 17% of children struggle are diagnosed with a reading impairment such as dyslexia. Reading impairments constrain opportunities for education, economic success, and emotional well-being. Converging evidence shows that auditory processing is disrupted in many struggling readers. This evidence aligns with several major hypotheses about the causes of reading impairment and suggests that measures of auditory function could indicate a child's risk for reading struggles. We review evidence that auditory processing is tied to literacy development and present three clinical protocols for the audiologic evaluation of literacy. These protocols use the frequency-following response, a scalp-recorded auditory evoked potential that relies on coordinated and precise neural synchrony. Multiple studies show that these protocols effectively evaluate auditory processes tied to literacy, that they forecast the development of future reading impairment, and that they can document individual benefits from interventions.

Keywords

literacy, dyslexia, auditory processing, language development, frequency-following response, audiology, subcortical, phonological processing, temporal processing, language impairment

Key Points

- Auditory processing is disrupted in many struggling readers, meaning that measures of auditory function can indicate whether a child is at risk for poor literacy. This idea aligns with multiple theories of reading impairment.
- It is crucial to identify children at risk for reading impairment as early as possible to provide interventions.
- Audiologists can play a key role in identifying and managing reading impairment by conducting objective neurophysiologic evaluations in children.

15.1 Early Literacy and Early Intervention

Why does literacy develop smoothly for some children and not for others? Up to 17% of children suffer difficulties learning to read, which devastates opportunities for education, economic success, and emotional well-being. Converging evidence shows that auditory processing is disrupted in many struggling readers. This evidence aligns with several major hypotheses about the causes of reading impairment and suggests that measures of auditory function indicate a child's risk for poor reading skills.

Here we review evidence that auditory processing is tied to literacy development and outline three clinical protocols for the audiological evaluation of literacy. These protocols use the frequency-following response (FFR; also called the auditory brainstem response to complex sounds, or cABR), which is a scalp-recorded auditory evoked potential that relies on coordinated and precise neural activity along the auditory pathway.

Multiple studies show that these protocols effectively *evaluate* auditory processes tied to literacy, that they *forecast* the development of future reading impairment, and that they *document* individual benefits from interventions. Thus, audiologists can play an important role in identifying and managing reading impairment by conducting objective neurophysiologic evaluations.

Early auditory experiences provide children with input (auditory information) that bootstraps language development. Within the first 6 months after birth, an infant's recognition of speech sounds narrows to match those in his/her native environment.[1] This early sensory input is critical to build a robust knowledge of the sound structure of spoken language—a skill called *phonological awareness*.

A child's phonological inventory will provide the chief ingredients for oral language. For example, the child will gain an implicit knowledge of what speech sounds go together (e.g., /d/ and /a/ can go together to form "da," but /d/ and /x/ cannot go together to form "dx") and how to build them into words. Eventually, when explicit reading instruction begins, children need to map knowledge of speech sounds onto letters. This sound-to-letter mapping begins years after children learn to talk, often around ages 5 to 6, and the process of moving from letters to words to text can take an additional 2 to 3 years. Once children learn to read, they need to become *fluent* readers so that they can learn new material from text.[2]

15.1.1 Reading Impairment

Some children struggle in this learning process. *Developmental dyslexia* is a specific learning disability characterized by poor reading that cannot be explained by a lack of motivation, low intelligence, poor instruction, or a sensory impairment such as blindness.[3] Estimates of the prevalence of dyslexia vary from 5 to 17% of the population,[3] and the consequences go beyond reading itself. Individuals with dyslexia exhibit higher rates of depression, suicide, and incarceration,[4] and it is estimated that the added cost to families raising a child with a disability is at least $22,000.[5]

There are additional children who struggle to read but may not be diagnosed with dyslexia proper. For example, children with specific language impairment (SLI) often exhibit poor reading in addition to broader language problems (such as poor spoken language comprehension).[6] Moreover, children from impoverished socioeconomic backgrounds often experience greater difficulty in developing good language and literacy skills.[7] We will use the term *reading impairment* (RI) to refer broadly to children who face a particular struggle in literacy development despite normal intelligence, motivation, and instruction.

15.1.2 Identification and Intervention

A major challenge is to identify which children are at risk for RI—meaning they are candidates for intervention—as early as possible. The current approach to RI diagnosis relies on a wait-to-fail model. In other words, children have to exhibit prolonged difficulties in reading before they qualify for school-based support. This "dyslexia paradox" can set back the opportunity for intervention by years.[8] In turn, children's broader learning is circumscribed because they cannot learn effectively from text in other coursework.

Converging evidence suggests that measures of auditory function effectively predict which children will struggle in literacy development. While it may be surprising that a chapter on literacy appears in an audiology textbook, it should soon become clear that audiologists can play a key role in identifying children at risk for RI and in encouraging early and focused interventions.

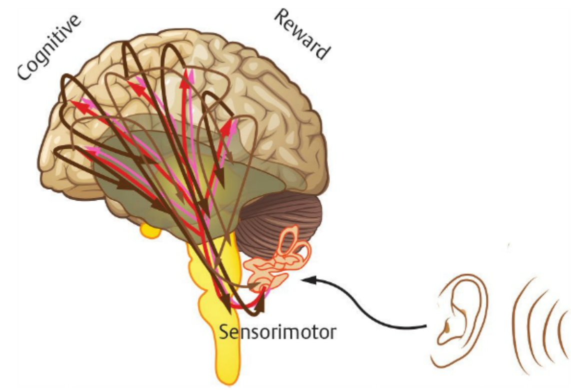

Fig. 15.1 The cognitive-sensorimotor-reward framework for auditory processing. Listening is not isolated in the auditory system. Instead, auditory processing happens at the nexus of cognitive, sensorimotor, and reward systems. These neural circuits provide input throughout the auditory system that reshapes its response properties. The entire network is modified by ear-to-brain pathways and by brain-to-ear pathways, meaning auditory processing shapes skills important for reading, and skills important for reading shape auditory processing.

Pearl

Excellent interventions are available to boost literacy, but *early* intervention is key. For example, Bishop and Adams followed a cohort of children with SLI and showed that if their oral language problems resolve by 5.5 years old, literacy development proceeds smoothly—but if not, literacy problems can be anticipated.[9] Classroom intervention studies show that simple remediation strategies are shockingly effective: a few extra hours of weekly phonics instruction in kindergarten and first grade can bring up to 92% of struggling readers in line with their peers.[10]

15.2 The Interactive Auditory System

Reading relies on the tight integration of sensory information, prior knowledge, cognition, and language. A new conceptual framework positions auditory processing at the nexus of cognitive, sensorimotor, and reward systems[11] and provides a helpful biologic anchor for thinking about RI (**Fig. 15.1**).

Traditional models of auditory processing emphasize the stepwise progression of signals through the cochlea and along the auditory neuraxis. While this model is important, we fear that there is sometimes a tendency to compartmentalize each processing station along this chain, ignoring how those stations work together. Instead, we think about the auditory system as a ***distributed, but integrated, whole***.[11] At the heart of this framework is the intersection of cognitive, sensorimotor, and reward circuits that optimize auditory function by catalyzing activity throughout a network of highly interactive afferent (ear-to-brain) and efferent (brain-to-ear) pathways (**Fig. 15.2**).

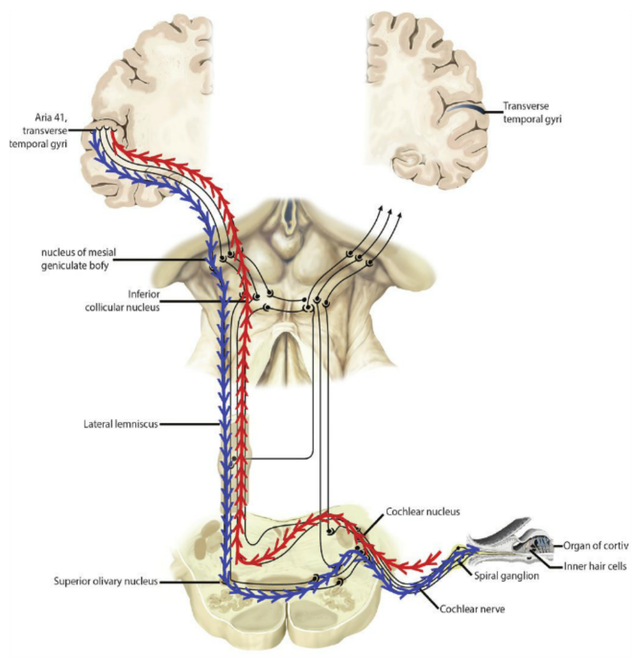

Fig. 15.2 The auditory pathway is interactive. Traditional models of auditory processing focus on how each station along the system specializes for a specific function. We encourage thinking about the interactivity between these stations. This interactivity happens because the auditory pathway is suffused with ear-to-brain (afferent) and brain-to-ear (efferent) modulatory connections. (Adapted from Schuenke M, Schulte E, Schumacher U. Thieme Atlas of Anatomy. Vol. 3, Head, Neck and Neuroanatomy, 2nd ed. New York, NY: Thieme; 2017:474.)

Because this framework recognizes that auditory processing is shaped by nonauditory systems, certain predispositions that may not originate in the auditory system are nevertheless revealed by objective indices of auditory processing. Broadly, this idea intersects with the notion that sensory circuits are shaped—for better or worse—by experience, including experiences with language and literacy.[12]

Pitfall

When thinking about auditory processing, remember that the whole system is more than the sum of its parts. RI and auditory processing problems in general are too complicated to attribute to a lesion at one station in the auditory highway system. Auditory processing happens in the context of cognitive, sensorimotor, and reward systems.

15.2.1 Auditory Processing and Literacy

The role that auditory processing plays in reading and RI has been debated for decades. It is now generally agreed that auditory processing deficits are often observed in individuals with RI, but that these deficits may not be a direct cause of RI.[13] Following our model of an interactive auditory-cognitive system, it makes sense both that poor cognitive input and linguistic knowledge could create a coarser infrastructure for processing sound and that imprecise auditory processing could lead to a poor construction of a phonological inventory. Indeed, the process of learning to read itself reshapes sensory[14] and cognitive[15] functions important for reading. This experience interacts with genetic predispositions; both auditory processing and literacy are highly heritable.[16,17]

15.3 Reading, Auditory Processing, and Genetics

RI has a strong genetic component. Up to 50% of children with a familial risk of dyslexia (parent or sibling) will eventually receive a dyslexia diagnosis.[16] Several genes have been identified as candidates that increase risk for RI,[18] and research on the roles these genes play developmentally corroborates impaired auditory processing as a key component of the RI phenotype. For example, it is possible to “knock down” expression of these genes in animal models such as rats or mice. These animals exhibit behavioral deficits in the processing of speech sounds and show smaller, more sluggish, and more variable neural responses to speech in auditory cortex[19,20]—deficits that parallel those observed in humans.[12] These risk genes have also been directly linked to impaired auditory processing in humans.[21]

15.4 Theories of Reading Impairment

Here we review several prominent hypotheses about the cause of RI. Our goal is not to arbitrate between these theories; rather, it is to highlight how auditory processing is implicated in these theories, and how measures of auditory processing could objectively evaluate and predict RI (see **Box 15.1** for a distinction between hearing and auditory processing with respect to reading). Although these models provide theoretical grounding in *why* auditory processing is implicated in RI, one may be agnostic to the core deficit(s) in RI and still appreciate how measures of auditory processing can provide meaningful and objective information.

Box 15.1 Deafness and Reading

A contrast must be drawn between *hearing* and *auditory processing*. No theory of RI and the auditory system attributes reading problems to *deafness*. Put simply, these hypotheses attribute RI to differences in the integrity of sound processing in the brain—not whether or not sound gets into the system in the first place. (See **Chapter 1** for more information about hearing loss and auditory brain development.)

15.4.1 Phonological Deficit

Perhaps the most prominent hypothesis is that RI is caused by a phonological processing deficit.[22,23] Phonological processing refers to knowledge of, and the ability to manipulate in one’s mind, the sound structure of spoken language. (For example, if you remove the sound /k/ from the word “fixed,” what word do you get?) This explains why individuals with RI can struggle to align letters with sounds, and why they can struggle to recognize subtle speech features. If phonological systems in the cortex are imprecise or sluggish, they may fail to feed back to refine auditory circuitry and fail to feed forward to integrate with other literacy skills.[24]

The phonological deficit hypothesis aligns with evidence that RI individuals do not accurately process speech sounds. Several studies, for example, have shown that brain responses do not accurately distinguish between acoustically similar, but phonologically distinct, speech sounds.[25,26] However, there is also evidence that individuals with RI struggle to process the basic acoustic ingredients of speech, including nonlinguistic tasks.[27] This may indicate a basic auditory processing deficit that causes a phonological deficit.

15.4.2 Auditory-Temporal Processing Hypothesis

Tallal and colleagues suggest that individuals with RI struggle to process fast stimuli.[28,29] They have shown that individuals with RI perform poorly on verbal and nonverbal auditory tasks that require fast temporal judgments, but they perform similarly to control subjects on tasks requiring only slow temporal judgments. In other words, individuals with RI struggle in tasks where it is critical to perceive a brief or rapid event. This could explain an eventual phonological processing problem, because consonant-vowel transitions occur quickly in natural speech, meaning that subtle, rapid cues distinguish sounds such as /ba/ from /da/.[30]

This hypothesis is supported by evidence that fast neural timing is disrupted in individuals with RI, including in the context of speech.[31] Additionally, Tallal and colleagues have shown that training children with RI to recognize fast acoustic events better boosts language and literacy skills.[32,33] Moreover, Benasich and colleagues have shown that rapid auditory processing in infancy predicts future language and literacy skills.[34]

Others have challenged this hypothesis, however, suggesting that this phenomenon is due to more general cognitive or perceptual abnormalities in RI.[35] It has also been shown that computerized training on rapid auditory processing is equally effective as traditional speech-language therapy for children with language impairment, suggesting there is not something "special" about temporal processing.[36] Perhaps it is best said that abnormal rapid auditory processing is often observed in individuals with RI, but it remains under debate whether these deficits *cause* RI.

15.4.3 Magnocellular Hypothesis

Stein[37] argues that the magnocellular visual system, which is responsible for coding object location and motion, is sluggish in individuals with RI, causing reading and attention problems. Some of the most compelling evidence for the magnocellular hypothesis is the presence of anatomic abnormalities in magnocellular cells of individuals with RI on autopsy.[38] There is also some evidence that training this system boosts reading skills.[39]

However, the visual system undergoes substantial reorganization as individuals learn to read,[14] which could mean the anatomic abnormalities in individuals with RI are a consequence of their reading struggles, not a cause. Additionally, much of the evidence for visual training boosting literacy comes from studies of Italian readers. Italian has a much more consistent sound-to-letter mapping than other languages, suggesting visual attention training would not be as useful in a language such as English. This does raise the interesting possibility, however, that sources of RI may be partially language dependent.

While the magnocellular hypothesis might seem at odds with the auditory-temporal processing hypothesis, one view is that in RI there is a general deficit processing fast information.[38] In fact, Tallal and Piercy showed that children with language impairment perform poorly on parallel auditory and visual tasks that require fast processing.[29]

15.4.4 Temporal Sampling Framework

Goswami proposes that RI originates in the right auditory cortex, where neural ensembles do not efficiently align the oscillations with slow amplitude modulations in sound. This causes an abnormal parsing of auditory input and leads to problems hierarchically sorting incoming speech. In turn, there is an abnormal feed-forward to phonological networks and feedback to incoming auditory information.

This hypothesis is supported by evidence for anatomical abnormalities in auditory cortex of cadavers of individuals with RI[40] and evidence that right auditory cortex abnormalities precede RI in young children.[41] Moreover, children with RI struggle to recognize these slow amplitude envelope cues in speech and in temporal sequences such as rhythms;[42] they also show poor right auditory cortex entrainment to speech envelope.[43]

It can, however, be difficult to reconcile this hypothesis with the aforementioned evidence for the auditory-temporal processing and magnocellular hypotheses. Fast and slow auditory processing may depend on orthogonal underlying mechanisms,[44] which would suggest these are complementary causes of RI that manifest in different individuals.

15.4.5 Noise Exclusion Deficit

This hypothesis posits that individuals with RI struggle to distinguish signals from noise across modalities.[45] Proponents point to evidence that auditory and visual processing in quiet conditions are usually intact in individuals with RI but that performance differences emerge in "noise" (such as background talkers or visual masks over stimuli). There is also evidence that individuals with RI struggle to recognize tones[27] and sentences[46] in noise. Moreover, individuals with RI often have poor neural processing of speech in noise.[47]

There is, however, evidence that if signal perception is taxed in other ways, individuals with RI struggle, as in Tallal's aforementioned auditory-temporal processing hypothesis. Additionally, boosting the clarity of speech sounds in noise normalizes sentence perception in children with RI.[48] Thus, the noise exclusion evidence may have more to do with noise taxing perception and cognition, making tasks more difficult (and consequently pulling out differences between children with RI and controls), as opposed to the noise per se.

15.4.6 Sensory Blurring Hypothesis

This hypothesis suggests that RI is caused by a lack of neural synchrony in sensory pathways.[49] To form stable neural representations of auditory and visual objects, neurons need to coordinate their firing with each other.[50] If neural timing is imprecise, then a network of neurons responsible for coding an incoming sensory stimulus cannot robustly fire. This *timing jitter* could end up reducing population response timing and amplitude[51] and may be due to a reduction in neural connectivity and/or misbalance of excitatory and inhibitory neurotransmission—both of which have been observed in children with RI.[52,53] If the units within a neural network are coding different chunks of information with different timings, then the representation of that network's information as a whole could become "blurry" (**Fig. 15.3**). If children grow up with these blurry phonological representations, they may struggle to map them onto letters and words.

Support for this hypothesis comes from animal models of RI that show variable neural firing in single neurons[54] and cell populations[19] (see the section on Reading, Auditory Processing, and Genetics earlier in this chapter). Additionally, children with RI exhibit variable auditory evoked potentials,[55] but when neural firing is stabilized, literacy improves.[56] Coordinated neural timing is also important for linking perception to action;[57] a reduction in this basic multisensory integration could hamper letter-to-sound mapping and explain some of the auditory-motor integration deficits observed in individuals with RI.[42]

However, it remains to be seen whether this "blurring" uniquely causes RI or whether it represents a more general developmental liability that puts children at risk for any number of language or communication disorders.[49,58]

Pearl

A current trend in reading research is to turn to *multiple-deficit models*,[59,60] which argue that no single factor accounts for all cases of RI. These models instead posit that several factors—including those just discussed—can result in the RI phenotype. This view makes good sense from an evolutionary standpoint. Humans have been reading and writing for only about 5,000 years, which means these functions have had to piggyback on preexisting neural circuitry for cognition and language.[2] Reading, therefore, hinges upon an integrated and efficient constellation of sensory, cognitive, and linguistic functions. Like any finely tuned system, this creates many opportunities for disruption. Because auditory processing ties into each of the hypotheses previously discussed, one could imagine that tests of auditory processing could provide an avenue to screen for multiple potential deficits within an individual.

Fig. 15.3 Sensory blurring. If sensory systems encode information variably in time (jittered), then the system cannot form a crisp representation of an incoming stimulus. Imagine that each color represents a single neuron encoding information. On the left, these neurons fire with slightly different timing; when the message is averaged across those neurons, it becomes blurred. In contrast, the right panel shows a system where each neuron's firing is coordinated. When the message is averaged, there is a clean representation of the stimulus.

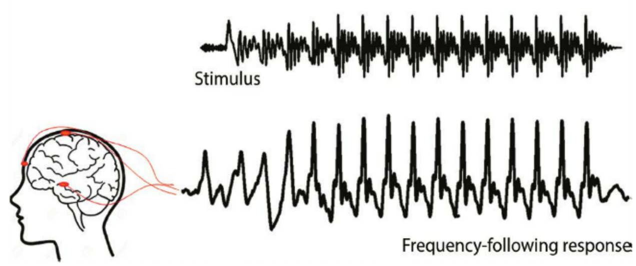

Fig. 15.4 The frequency-following response (FFR). The FFR is a transparent and granular measure of auditory processing because it physically resembles the evoking stimulus. At the top of the figure is the stimulus "da," and on the bottom is a representative FFR, measured with three scalp electrodes. The periodic spikes occurring in the FFR match those in the stimulus, and the activity in between the spikes reflects coding of the harmonics of the stimulus.

15.5 Clinical Protocols for Audiological Evaluation of Literacy

Here we present three protocols to evaluate auditory-neurophysiologic processes tied to early literacy. We encourage thinking about these protocols with respect to the several models of RI just discussed, which provide important theoretical context for these approaches. These protocols use the FFR (**Fig. 15.4**) and are in different stages of development and validation. Stimulus and recording parameters are summarized in **Table 15.1**.[31,61,62]

15.5.1 Measuring Sound Processing in the Brain: The Frequency-Following Response

The FFR is an auditory-evoked potential that relies on coordinated and precise neural processing along the auditory pathway. The FFR is a sensitive and individualized measure of brain function that provides a biological snapshot of auditory processing. As illustrated in **Fig. 15.4**, the FFR physically resembles the stimulus, providing a tremendous transparency and granularity

Table 15.1 Collection parameters for three FFR protocols that can be used to evaluate literacy skills

	Protocol 1	Protocol 2	Protocol 3
Stimulus	170-ms /da/	Two of /ba/, /da/, or /ga/	40-ms /d/
Intensity	80 dB SPL		
Presentation Rate	0.854 Hz		10.9 Hz
Background sound	6-talker babble track (/da/ presented at +10 dB SNR)	None	
Filters 2nd-order Butterworth bandpass	70–2,000 Hz		100–2,000 Hz
Time Window re stimulus onset	−40–210 ms		−15.8–69.45 ms
Number of Repetitions	4,000 artifact-free trials		6,000 artifact-free trials
Analyses	Timing, harmonics, response stability	Timing or phase difference between responses	Timing, harmonics, response stability
Norms available?	**Partially:** Normal-hearing children aged 3–5 years	**No**	**Yes:** Normal-hearing listeners aged 0–73 years
Example paper	White-Schwoch et al[61]	Neef et al[62]	Banai et al[31]
Bottom line	This protocol **predicts future literacy** achievement.	This protocol **classifies children as RI or controls**.	This protocol **is a standardized test of auditory processing**.

All stimuli and analysis routines are available for download at http://www.brainvolts.northwestern.edu.

to the study of brain health. After all, sound, like vision, contains multiple ingredients. In vision, these ingredients include color, texture, edge, and shape—cues that are coded by distinct neural computations. In sound, these ingredients include pitch, timbre, and timing.

The FFR provides an approach to evaluate how an individual's brain processes these cues. Importantly, the FFR requires no behavioral response from the patient, meaning it sidesteps the inherent pitfalls of other behavioral tests, which require patients to maintain attention. (Note that the FFR is sometimes called different names, including the auditory brainstem response to complex sounds [cABR] and the speech-evoked auditory brainstem response [sABR]). A video demonstration is available at https://www.brainvolts.northwestern.edu.

FFRs are collected similarly to auditory brainstem responses (ABRs). A vertical recording montage is used with a differential recording from Cz to A2 and a ground electrode at FPz. Stimuli are presented to the right ear through insert earphones. Each FFR should be preceded by a click-evoked ABR to screen for retrocochlear pathology. (See **Chapters 13** and **14** for more information about auditory evoked response testing and use of higher-level potentials.) Electrode impedances should be kept < 5 kΩ with < 3 kΩ differences between electrodes. All stimuli are delivered in alternating polarities, which are averaged prior to analysis.

Skoe and Kraus[63] provide a comprehensive guide to setting up an auditory evoked potentials system to collect FFRs. Stimuli and software to analyze FFRs are available at http://www.brainvolts.northwestern.edu. For a general reference on clinical and research applications of the FFR beyond RI, please see the anthology by Kraus et al.[64]

15.5.2 Protocol 1: FFR to /da/ in Noise

This protocol involves responses to a 170-ms /da/ presented in a background noise of 6-talker babble. The advantage of this protocol is that an algorithm has been developed to model the FFR statistically to predict phonological skills and an RI diagnosis. The disadvantage is that testing can take a relatively long time (~ 25 minutes once electrodes are set up). Additionally, while norms are available for children ages 3 to 5 years old,[65] they have yet to be delineated for a wider age range.

White-Schwoch et al[61] measured these FFRs in 37 children 4 years old who had not yet learned to read. They focused on the response period corresponding to the consonant-to-vowel transition of the /da/ and quantified the timing of four response peaks, the strength of coding the harmonics, and the stability of the response. When these aspects of neural processing were combined in a statistical model, they predicted children's scores on a test of early phonological skills with a high accuracy (generally with less than 10% margin of error, or two points on the test).

They next tested 20 children 3 years old in whom they could measure FFRs but who were too young to take the behavioral test. FFRs to consonants in noise predicted these children's performance on a rapid automatized naming test. In a combined group of children, FFRs predicted performance on several phonological and early word reading tests 1 year later.

Finally, they measured FFRs to /da/ in noise in 55 older children (ages 8–14 years) and showed that the same statistical model predicted performance on several reading tests and could identify which of the children had an RI diagnosis with about a 70% accuracy.

Thus, this approach can objectively predict current literacy skills, forecast the development of future literacy skills, and identify children with an RI diagnosis.

15.5.3 Protocol 2: FFRs to Contrastive Stop Consonants

This protocol involves measuring FFRs to multiple stop consonant stimuli (such as /ba/, /da/, and /ga/) and determining the extent to which the FFRs are distinct. The advantages of this approach include its strong theoretical grounding in the ideas that children with RI struggle to process acoustic-phonetic contrasts between speech sounds efficiently (see the discussion of theories of reading impairment earlier in this chapter) and that FFRs can be boiled down to a single test score. The disadvantages are that it is the longest protocol (responses need to be collected to at least two sounds, which can take up to ~ 45 minutes) and that, to date, norms have not been established. An additional disadvantage is that this protocol relies on FFRs occurring at high frequencies (~ 700 Hz), which can be susceptible to contamination by electrical noise in the recordings.

Two or three of the stop consonant–containing syllables /ba/, /da/, and /ga/ are used in this protocol. Due to the tonotopicity of the auditory system, these stimuli are expected to elicit FFRs with slightly different timings. Hornickel et al[26] measured the timings of peaks in response to these stimuli and showed that poor readers' responses are more similar than good readers'. However, this approach was labor intensive because it required manually identifying multiple peaks across three FFRs.

Skoe et al[66] introduced a *cross-phase* method that quantifies the difference between responses to two of these stimuli. The responses should differ in time within a circumscribed frequency range, so Skoe et al calculated the phase difference between these two responses in a time-frequency space corresponding to the acoustic differences between the stimuli (**Fig. 15.5**). The advantage of this approach is that it is automated and reduces the comparisons of two responses to a single number.

White-Schwoch and Kraus[67] used this approach after measuring FFRs to /ba/ and /ga/ in 26 children 4 years old. Children with good phonological awareness had a larger phase difference than their peers with poor phonological awareness, suggesting this might be an approach to the early identification of children at risk for RI. However, they did not evaluate the diagnostic utility of this measure in classifying children into groups, and their sample size was relatively small.

Neef et al[62] used the phase difference approach in a study of 62 children aged 11 to 13 years. They measured FFRs to /ba/ and /da/ and showed that the phase difference between the responses predicted multiple literacy skills, including phonological processing, spelling, reading comprehension, and word reading. They also showed that this approach was more accurate for classifying good and poor readers than a behavioral battery and that a combined model of the phase difference between responses and a test of word reading could predict 98% of good readers and 62% of poor readers.

While more work is needed to establish norms and validate this approach, these results suggest that comparing responses to contrastive stimuli can provide an objective and automated measure that aligns with literacy. While using any two of /ba/, /da/, and /ga/ might be informative, the work of Neef et al[62] suggests that the /ba/-/da/ contrast is most appropriate for evaluating RI in school-aged children.

15.5.4 Protocol 3: FFR to /d/

This protocol involves responses to a 40-ms /d/. This stimulus consists of an onset burst and a consonant-to-vowel transition; although it does not contain a vowel period, the burst is perceived as "da." The advantages of this protocol are that it is fast (~ 10–12 minutes once electrodes are set up) and that it has been normed on > 500 individuals up to age 73.[68] The disadvantage is that, in contrast to Protocols 1 and 2, abnormal results on this test may overlap profiles for other developmental problems.[12] Thus, this approach provides a platform to look at auditory processing in general using a normed and standardized approach as opposed to a test for RI sensu stricto.

With respect to RI, Banai et al[31] measured FFRs to this stimulus in 63 children (aged 7 to 15 years). They showed that the timing of several response peaks and the strength of coding stimulus harmonics correlated with phonological processing, word reading, and spelling. In contrast, the strength of coding of the fundamental frequency was not tied to literacy skills.

Because normative data are available, the FFR to /d/ can be used as a standardized test to evaluate children's auditory processing objectively relative to their peers. We recommend three analyses: (1) timing of response peaks; (2) strength of coding stimulus and

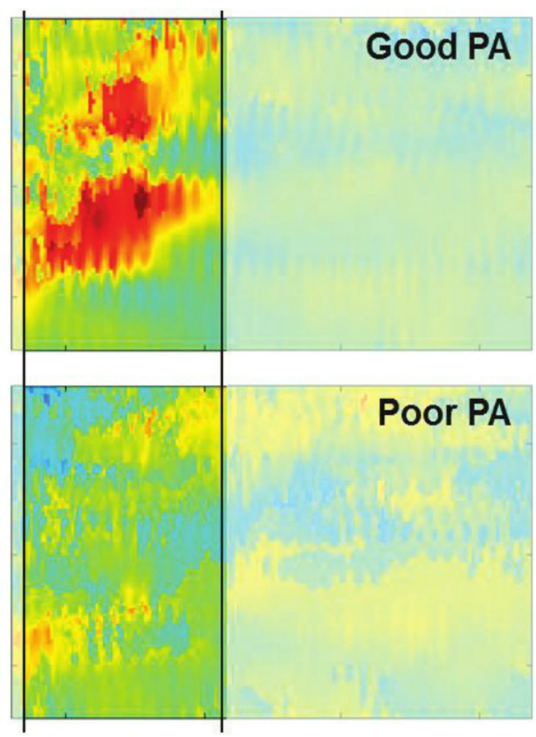

Fig. 15.5 FFRs to contrastive stop consonants are more robust in preschoolers with good early reading skills. The cross-phase method from FFR Protocol 2 involves measuring FFRs to a pair of stimuli and quantifying the timing difference between them in a time-frequency space corresponding to the acoustic contrast between the stimuli. Here, preschoolers' FFRs were measured to /ba/ and /ga/. Preschoolers with good phonological awareness (PA) had a stronger phase difference between responses, shown by the red swatch, than preschoolers with poor PA. This suggests this protocol could be used to screen for early challenges in PA.

harmonics; (3) stability of the responses. Scores can be referenced to age-matched norms, and a criterion such as scores > 2 standard deviations outside of normal limits can be used. Deficits in response timing, the harmonics, or response stability would pattern with RI.

Norm-referenced scores could also be used in the context of a larger battery. For example, the American Speech-Language-Hearing Association lists the FFR as a potential test in a battery for auditory processing disorder, and suggests that scores > 2 standard deviations below the mean on two or more of these tests could indicate an auditory processing problem.[69]

Pitfall

A normal ABR does not indicate a normal FFR. The ABR tells us whether signals from the ear reach the brain. The FFR tells us how well those signals are processed. All of the FFR studies cited above involved subjects with normal ABRs. The FFR is a more sensitive and granular measure of auditory function because it indicates how well the complex ingredients of speech are processed by the brain.

15.6 Audiologic Monitoring of Treatment Outcomes in RI

The FFR can be used to track treatment outcomes in RI interventions. While to date there has not been a large-scale clinical trial that has used the FFR as an outcome measure, several smaller studies support its use. Because the FFR is meaningful and robust within an individual, and there are no "learning effects" as on behavioral tests, the FFR may be an especially appropriate approach for tracking treatment outcomes in an individual.

Hornickel et al[56] investigated the efficacy of a classroom assistive listening device to boost literacy in children with RI. They partnered with a specialty school for children with RI and gave 19 children frequency-modulation (FM) assistive listening device to wear in their classes for one year. They also followed 19 control students who attended the same school (children were aged 8–14 years). After one year, children who wore the FM device had more stable FFRs than the controls did. They also exhibited larger gains in literacy skills, and the extent of the gain was predicted by their pretest FFRs. Thus, the FFR might be able to document neurophysiologic changes in auditory processes important for reading *and* identify specific candidates who might benefit from intervention. Additionally, Hornickel et al show how an audiological intervention—classroom assistive listening devices—can augment the benefits of traditional speech-language therapy through neural plasticity.

Sound-to-meaning training can reinforce other neural mechanisms important for literacy. For example, Earobics (Houghton Mifflin Harcourt, Boston, MA) was a software-based training program that emphasized listening in noise, phonological awareness, and language comprehension through interactive games. Warrier et al[70] followed 13 children with RI (ages 8-13 years) who underwent 8 weeks of Earobics compared to 11 controls. Following training, children had more robust neural responses to speech in noise and better performance on academic tests of phonological processing. Russo et al[71] showed similar gains using the FFR protocol to /d/ outlined earlier in this chapter in nine children with RI (aged 8–12 years) and also showed that the pretraining response could predict benefit from training.

While not focused on children with RI, additional studies show that auditory training programs improve auditory-neurophysiologic processes tied to literacy. For example, longitudinal studies of music training show that both responses to /da/ in noise[72] and the phase difference of FFRs to contrastive stop consonants[73] can be improved by training. Thus, the FFR could be a viable approach to monitor treatment outcomes in children with RI.[74]

15.7 The Future of Audiology and Reading Impairment

We have reviewed how auditory processing deficits are consistently observed in individuals with RI, and how they fit logically with several theories of the causes or RI. Additionally, we have presented three clinical protocols to evaluate auditory-neurophysiologic processes tied to literacy. But what does the FFR add? If we know that auditory processing is disrupted in RI, then why do we need a new set of electrophysiological measures?

We think there are several pragmatic advantages of using the FFR as part of an RI evaluation:

- *It's in the brain.* Behavioral tests are inherently complicated—especially in learning disabilities. The FFR can provide hard, biologic evidence of a bottleneck in auditory processing. We envision the FFR as a tool not just for evaluation but also for counseling. Imagine the power in showing a client his or her brainwave and being able to see strengths and weaknesses in processing specific cues in sound. Moreover, showing an individual evidence of brain changes during training can help reinforce and motivate sticking with treatment.
- *It's uniform and scalable.* The same FFR protocol can be used in individuals across the lifespan, from birth to senescence. It is not complicated by a client's ability to comply with the test; in fact, the FFR has been measured in unsedated infants and toddlers.[65,75] Thus, the FFR can provide a uniform approach to measuring auditory processing in any individual.
- *It's objective.* The FFR sidesteps the pitfalls of traditional tests of auditory processing and language because it requires no behavioral response from the client. This is crucial in the context of RI. Imagine a phonological processing test in a 5-year-old with language delays. Because of his poor language skills, he will reach ceiling on the test earlier than his peers. This means that his score will be based on fewer test items, meaning it will be a less valid index of his phonological skills. In addition, language delays often overlap attention and behavior problems that can also interfere with the validity of the behavioral test. Because the FFR does not require the patient to do anything, it is not complicated by behavioral factors.

Traditionally RI has been the province of speech-language therapy. This makes sense—after all, reading builds on knowledge of speech sounds and language. We hope, however, to have illustrated that audiologists have an important role as well. Objective measures of auditory function identify children with RI, predict which children are at risk for RI, and track outcomes following intervention. Audiologists have the unique skill set necessary to conduct tests such as the FFR. One can envision a day when, in addition to hearing screening, newborns receive a hearing brain screening to identify risk for language and reading problems.

Pearl

Audiologists can join speech-language pathologists and psychologists as part of a multidisciplinary team to manage RI.

Discussion Questions

1. What are three pieces of evidence that auditory processing is disrupted in poor readers, and which theories of reading impairment does this evidence map on to?
2. How can changes in auditory processing be objectively monitored, and how do these changes relate to improved reading skills?
3. For each of the FFR protocols presented in this chapter, describe a patient for whom FFR would be an appropriate evaluation, and discuss how positive and negative results would be interpreted.

Acknowledgments

The research in this chapter has been supported by NIH (R01 HD069414) and the Knowles Hearing Center.

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