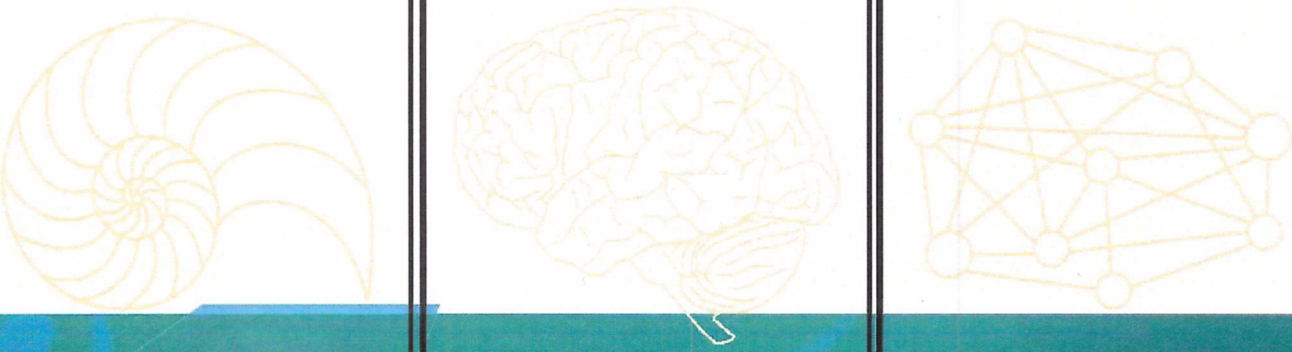

Culture and Neural Frames of Cognition and Communication

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ISSN 1867-4208 e-ISSN 1867-4216
ISBN 978-3-642-15422-5 e-ISBN 978-3-642-15423-2
DOI 10.1007/978-3-642-15423-2
Springer Heidelberg Dordrecht London New York

Cover design: Spi Publisher Services

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

The present volume of the book series *On Thinking* is organized based on the seventh Sino-German workshop on cognitive neurosciences in Beijing in October 2008. This workshop is one of the series conferences that are organized by the Department of Psychology at Peking University, Beijing, China, and the Human Science Center of Munich University, Germany, and attended by psychologists, cognitive neuroscientists, linguistics, anthropologists, psychiatrists, computer scientists, philosophers, economics, sociologists, and researchers in other related fields from China, Germany, Japan, Poland, the USA, the Netherlands, Hungary, and Russia. The goal of the series workshops is to promote the communication and cooperation in cognitive neuroscience between researchers from different disciplines and different countries.

The workshop in 2008 focused on the relationship between culture and cognition because there has been accumulating evidence during the last few years that sociocultural contexts generate strong influences on human cognitions and the underlying neural substrates. Since then, there has been increasing interest in studies of the interaction between sociocultural factors and multiple levels (e.g., gene, neuron, neural circuit) of the biological basis of human cognitive processes. Researchers have also started to examine neurocognitve processes in specific sociocultural contexts from the evolutionary point of view in order to understand the mutual interactions between environments and the human brain.

The present volume contains presentations from the workshop and some invited chapters. Two chapters give general views of the relationship between biological evolution and cultural evolution and recent cultural neuroscience studies of social cognition. Other chapters focus on several aspects of human cognition that have been shown to be strongly influenced by sociocultural factors such as self-concept representation, language processes, emotion, time perception, and decision making. The main goal of this volume is to address how thinking is conducted and how the underlying neural mechanisms are affected by culture and identity – a frame in which human cognition develops and evolves.

We very much appreciate the contributions of the distinguished authors from different disciplines who contribute greatly to both the series workshop and the present volume of the series *On Thinking*. We are also grateful to Anette Lindqvist from Springer Science+Businesses Media and Susanne Piccone from the Human Science Center of Munich University for their constant support which makes the series Sino-German workshop and the series book possible.

Peking, China
Munich, Germany
May 2010

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Hearing Loss and Auditory Processing Disorders: Clinical and Experimental Perspectives

Elzbieta Szelag, Henryk Skarzynski, Andrzej Senderski, and Monika Lewandowska

Abstract This chapter focuses on hearing loss and auditory processing disorders (APD) with reference to culture and identity. Hearing impairments constitute a world-wide problem. They affect both language communication and social interactions, and hence, influence personal identity. APD are discussed from both audiological and neuropsychological perspectives. We present demographic data on hearing impairment and the most important methods applied to assessment and treatment of hearing disorders. We also discuss major cognitive deficits associated with hearing impairments across the life span and their psycho-social consequences. We also emphasize the importance of temporal aspects of auditory information processing which are crucial for broad aspects of cognitive function with special reference to language communication and learning ability. The reviewed literature data are illustrated with some results from our studies indicating psychophysical, electrophysiological and neuroimaging correlates of temporal processing after application of *Fast ForWord* training.

Keywords Auditory Processing Disorders · Cochlear implantation · Evoked Potentials · Fast ForWord · fMRI · Hearing loss · Temporal order · Temporal training

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S. Han and E. Pöppel (eds.), *Culture and Neural Frames of Cognition and Communication*,
On Thinking 3, DOI 10.1007/978-3-642-15423-2_10,

1 Introduction: The Importance of Hearing in Our Everyday Life

Hearing is a complex process which involves both the auditory periphery's ability to detect environmental sounds and the brain's ability to interpret these sounds. The challenge for the auditory system is to process environmental sounds and to learn about their sources. The acoustic environment is crucial with respect to human everyday activity, language communication, and learning new information. Hearing disorders affect social behavior, make routine communication difficult, often interfere with vocational activity, and drastically reduce the quality of life. In addition to these individual effects, they affect substantially the social and economic development in communities and countries. In every society, the individuals with hearing deficits constitute a large group within society. Taking into account rehabilitation, special education and loss of employment, estimated costs to the economy in the USA are between US $170 and US $212 billion per year (Ruben 2000).

Hearing abilities are fundamental for human culture and personal identity. Over the last century or so, a "deaf community" has arisen whose purpose is to preserve a deaf culture.[1] The deaf community advocates deafness as a normal variant in the population and constitutes its own culture and heritage, rejecting cochlear implants and oral forms of communication with preference given to sign language (Ladd 2003). This is in contrast to the deaf community which includes individuals with profound to complete bilateral hearing loss and includes those that utilize various forms of amplification, including cochlear implants, and oral forms of communication. The past several decades, due to the development of advanced technologies such as otoacoustic emissions testing, universal newborn hearing screening, and enhanced hearing screening of school-age children, have heightened societal awareness and significance of early identification of hearing loss. Such early identification and technological advancements have seen significant improvements in socialization, academic achievements, and vocational–professional advancement in the deaf population, including the development of a high degree of oral skills and literacy in early cochlear implantation (Van Gent et al. 2007).

Currently, the appropriate intervention methods constitute an important goal of audiology and neuropsychology. In this chapter, we concentrate on both audiological and neuropsychological approaches applied to reduce hearing handicap. We will focus on language functions, as well as other cognitive functions. Finally, we present new directions in neuropsychological therapy, illustrating existing literature data with results of our studies on neural correlates utilizing specific auditory training.

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[1] When capitalized, "Deaf Community" refers to a group of deaf individuals committed to preserving a deaf culture. When not capitalized, "deaf community" refers to the general population of individuals with profound or complete hearing loss. This is an important distinction.

2 Cross-linguistic Demographic Data on Hearing Impairment

Hearing loss is one of the most common types of disability. In adults, disabling hearing impairment is defined as a permanent unaided hearing threshold level (measured usually for frequencies 0.5, 1, 2, and 4 kHz) of 41 dB HL or more in the better ear. In children, disabling hearing impairment is defined as a permanent, unaided hearing threshold level for the better ear of 31 dB HL or more. However, pragmatically, it has been shown that in adults a hearing loss greater than 20 dB HL and in children a hearing loss greater than 15 dB HL is functional disabling. The higher levels serve political definitions rather than pragmatic definitions. According to World Health Organization (WHO), 255 million people worldwide in 2002 suffered from such a disability and could benefit from hearing aids; among them, 192 million people showed adult-onset loss (above the age 20), whereas 63 million people displayed childhood-onset loss. The most common cause of hearing loss in children living in Western countries is *serous otitis media*, affecting up to two-thirds of preschool children. On the other hand, in developing countries, *suppurative middle ear disease* is common and frequently accompanied by *intratemporal* or *intracranial complications*. Sensorineural hearing loss (see below) occurs in developing countries almost twice as often as in Western ones, with a greater proportion of infectious etiology, such as *measles* and *meningitis* (NICD 2008).

In Western countries, a substantial problem is noise-induced hearing loss. This is common not only in industry where the problem is recognized and regulated by law but also in adolescents due to listening to loud music using headphones. It is estimated that, in the USA, 12.5% of children and adolescents aged 6–19 years and 17% of adults aged 20–69 years have suffered permanent damage to their hearing from excessive exposure to noise (Niskar et al. 2001).

A strong association between an individual's age and hearing loss is commonly reported. The loss of auditory sensitivity resulting from normal chronological aging is termed *prescybusis*.[2] The prevalence of presbycusis is associated with aging ranging from 40% to 66% of the general population in individuals older than 75 years of age, and more than 80% in individuals older than 85 years of age (Yueh et al. 2003).

The major causes of hearing loss worldwide according to WHO (Disease Control Priorities Project 2006) are summarized in Fig. 1 and show that the three most frequent causes of hearing loss are genetic, otitis media, and presbycusis. Except for otitis media which is easily treated medically, genetic hearing loss and hearing loss caused by presybcusis require specific intervention including cochlear implants, hearing aids, and aural rehabilitation.

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[2] The term *prescybusis* is a general term used to designate hearing loss that cannot be directly accounted for by any known etiology and is therefore non-specific. Most people agree it is primarily due to unaccounted environmental factors (McPherson et al. 2008).

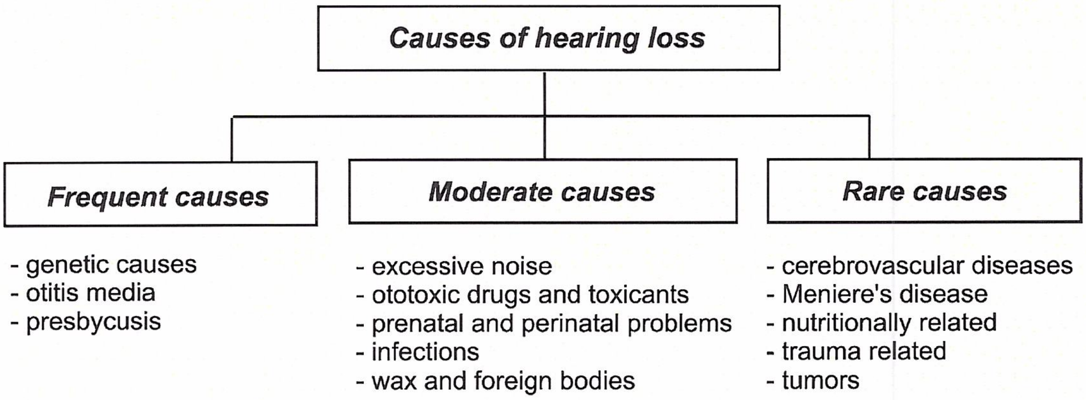

Fig. 1 Summary of major causes of hearing loss in accordance with WHO

3 Assessment and Management of Hearing Loss

Major determinants of the impact of hearing impairment include: type and degree of hearing loss, its pattern across different frequencies, laterality (unilateral/bilateral hearing loss), the locus (or loci) of abnormality within the auditory system (middle ear, inner ear, auditory neural pathway, subcortical or cortical brain structures), exposure to loud noises, and environmental or pharmacological toxicants to hearing. Each of these determinants, both separately and in combination, will have varying impacts on the auditory system and hence the functional ability of the individual. More specifically, the intervention techniques and procedures will vary considerably.

The scope of audiological diagnosis comprises the assessment of type and degree of hearing loss localization of damaged site and definition of possible causes of observed impairments. Such diagnosis is based on behavioral methods, i.e., pure tone audiometry which allows the assessment of hearing sensitivity across frequencies, speech audiometry, and a battery of auditory tests. An important part of audiological diagnosis, especially in young children, are electrophysiological objective methods, including impedance audiometry, otoacoustic emissions, auditory brainstem potentials, and middle and late latency auditory responses (Fig. 2).

In the audiology clinic, it is possible to distinguish three main types of hearing loss: *conductive*, *sensorineural*, and *mixed hearing loss*. Additionally, one can distinguish hearing disorders not related with loss of hearing acuity per se, but what is classified as *auditory processing disorders* (APD) which are located in the central portion of the auditory system. A *conductive* hearing loss is often due to ear infections and damage of the *eardrum* and *middle ear ossicles*. Appropriate medical care and reconstructive surgery of the middle ear may effectively treat these problems leading to recovery of normal or nearly normal hearing status in a substantial percentage of such problems. *Sensorineural hearing loss* caused by damage to the cochlea and auditory nerve is permanent and can only be alleviated using hearing aids or cochlear implants. APD constitute a deficit of neural processing of auditory information in the central nervous system that cannot be attributed

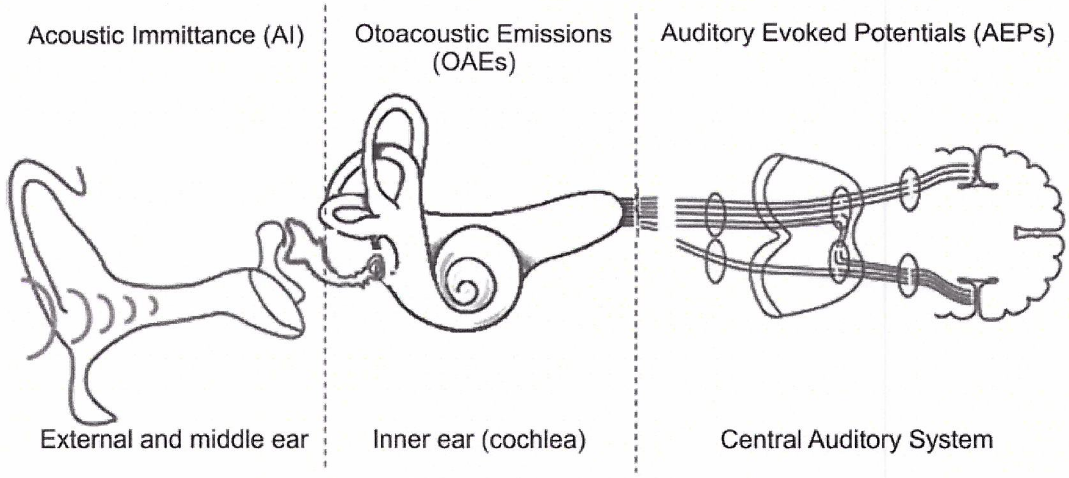

Fig. 2 Electrophysiological methods used for assessment of the auditory system

to other higher-order cognitive disorders, including those related to learning, attention, memory, or language-related skills caused by damage in the central nervous system.

The majority of the hearing impaired population can benefit from amplification. According to the WHO, there are currently 250 million people worldwide with hearing loss who could benefit from hearing aids. Two-thirds of these are in developing countries.

Cochlear implantation is a method of choice for treatment of children and adults with profound to severe bilateral deafness. In cochlear implantation, functional hearing is restored by direct electrical stimulation of the auditory nerve through an electrode placed in the cochlea (electric hearing). According to the Food and Drug Administration (FDA) as of April 2009, more than 188,000 people worldwide have been provided with cochlear implants (CI). Due to satisfied outcomes in both auditory receptive skills and the improvements of the quality of life following cochlear implantation, a clinical trend is observed in developing countries to expand the range of individuals who can benefit from this method of treatment. The new concept in treatment of hearing loss is combining acoustic and electric hearing. Individuals with normal hearing at low frequencies and profound hearing loss at middle and high frequencies (partial deafness) can benefit from using CIs, but have still preserved and useful hearing at low frequencies. The electric acoustic stimulation dramatically improves their communication abilities (Skarzynski et al. 2009). The particular method developed by Skarzynski and named "partial deafness treatment" is based on minimal invasive surgery and requires special surgical techniques and use of specially designed electrodes (Skarzynski et al. 2007).

For obtaining good outcomes, it is important not only to fit and appropriately program the hearing aid or cochlear implant but it is also paramount to instruct individuals on how to use the device. The crucial issue is that the individual's brain adapts to utilizing the new auditory information delivered from the periphery. The auditory rehabilitation greatly facilitates this adaptation. Although such adaptation is usually easier in young individuals because of higher brain plasticity, it is also observed in adults and may be fostered by new and unique rehabilitation programs. These programs constitute a major change in current thinking regarding auditory rehabilitation, and are discussed in details in following sections.

4 Deficits Associated with Hearing Loss Across the Human Life Span

If congenital hearing loss is not recognized and managed properly in early child development, it results in severe delay of speech, language and cognitive development. Therefore, universal newborn hearing screening is crucial in the early identification of hearing loss and early intervention such that rehabilitation begins prior to the critical periods for optimal language acquisition. Cohort studies have indicated that the proper diagnosis and intervention occurring prior to 6 months of age results in significantly better language and speech acquisition (Yoshinaga-Itano et al. 1998). The huge progress in audiological diagnosis and treatment in recent years (e.g., OAEs, automated ABR, bilateral or partial implants, early implantation) has resulted in integrative educational programs for deaf and hearing impaired children that significantly reduce the need for residential or special schools for the deaf, thus providing the individual with better education and integration into society. In school-age children, even a minimal hearing loss (20–30 dB HL) can have profound negative effects on speech and language comprehension, communication, classroom learning and academic achievement, and social development. Without proper intervention, there is a visible gap in school and academic achievements between children with mild-to-moderate hearing loss and their normally hearing peers (Bess et al. 1998). Moreover, communication difficulties often lead to social isolation and poorer self-concept (Brinton and Fujiki 2002, 2004).

In the elderly, high frequency sensorineural hearing loss is the most common type of hearing loss and is generally associated with *presbycusis*. It results in a loss of ability to hear consonants such as /s/, /f/, /t/, and /z/ (i.e., high frequency sounds) even though vowels may be heard relatively normally. Speech intelligibility is impaired in adverse acoustic conditions and in the presence of ambient noise. It decreases the ability to hear high-frequency auditory sounds like bird songs, rustling of leaves, and the voices of children and women. This may result in frustration, withdrawal from social activities, depression, and marital discord. Mulrow and others have shown in randomized trials that the use of hearing aids significantly improves communication, cognition and emotional function, including reducing the effects of depression (Mulrow 1990).

5 Auditory Processing Disorders from an Audiological Perspective

APD are distinct from peripheral hearing loss, language disorders and intellectual or cognitive problems and were recognized more than 50 years ago by Myklebust (1954). He identified children with normal peripheral hearing who demonstrated deficits in dealing with auditory information leading to communication, behavioral and social problems. Key behaviors seen in these individuals include: difficulties in listening in a background noise, oversensitivity to loud sounds, difficulties in location of the sound source, and deficiencies in phonological awareness leading to mishearing words or misinterpreting messages from verbal utterances, as well as delayed responses to auditory signals.

According to the American Speech-Language-Hearing Association, APD is defined as "perceptual processing of auditory information in the central nervous system and the neurobiological activity that underlies that processing and give rise to the electrophysiological auditory potentials" (American Speech-Language-Hearing Association 1996). The predisposing factors for APD include otitis media with effusion (sensory deprivation secondary to a peripheral disorder), neuro-maturational delay, and neurological insults to the central auditory system (DeBonis and Moncrieff 2008).

The diagnostic procedure for identification of APD is based on a series of psychoacoustic and speech perception tests. One can refer to five primary categories of behavioral tests that are sensitive for audiological diagnosis of APD, specifically, (1) dichotic listening, (2) monoaural low-redundancy speech tests, (3) auditory temporal processing and patterning, (4) binaural interaction and integration, and (5) auditory discrimination tasks. It is important to note that the classic tests of phonological awareness, phonemic synthesis and auditory comprehension are not diagnostic in the case of patients with APD (Cacace and McFarland 2009).

In audiological diagnosis, one of the commonly used dichotic listening tests is the dichotic digit test which has been shown to be sensitive to brainstem, cortical and corpus collosum dysfunctions. Moreover, monoaural low-redundancy speech tests (low-pass filtered speech, speech in noise, and time-compressed speech) assess the ability to "fill" the missing components of degraded speech signal and are sensitive to dysfunctions of the auditory cortex. Despite worldwide occurrence of APD, cross-linguistic comparisons on this deficit are still a neglected topic. Therefore, to form any general conclusions on cross-cultural aspects of APD, it would be necessary to develop corresponding versions of the above-mentioned tests for different languages. On the other hand, nonverbal stimuli are often used to evaluate a variety of auditory processes, including temporal resolution, temporal ordering, frequency or duration discrimination, and linguistic labeling, such as random gap detection test, duration pattern test, and frequency pattern test.

Despite existing several clinical diagnostic tests for assessment of APD, there are still controversies with respect to both the existence of this deficit and underlying neural mechanisms. Furthermore, there are also controversies with respect to the efficiency of methods applied in the rehabilitation of individuals suffering from APD.

Development of effective diagnostic tools and treatment methods of this disorder must be based on explicit theories of sensory information processing. One of the hypothetical concepts with a potential clinical value is temporal information processing theory. Taking such a hypothesis into account, in the following sections we present some existing evidence on importance of temporal processing as a possible basis for many deficits in audition, language, and cognition.

6 Central Auditory Processing from Neuropsychological Perspective

A broad overview on neuroanatomy and neurophysiology of hearing is beyond the scope of the present chapter because of the large number of observations, research articles, and books dealing with this issue. As we concentrate here on central auditory processing, we characterize only cortical structures involved in this processing.

Auditory information arrives to the *primary auditory cortex* (Heschl's gyrus, BA 21) by projections from the *medial geniculate body* via *internal capsule*, *insula* and *external capsule*. The *primary auditory cortex* is known to retain tonotopic organization of the *cochlea*. The *auditory association cortex* comprises Wernicke's area (BA 22), which is considered the region responsible for phonemic hearing and language, and thus for auditory comprehension. The additional auditory cortical structures comprise the inferior portion of the parietal and frontal lobes, the *supramarginal* (BA 40) and *angular* (BA 39) gyri, as well as the *fasciculus*; a larger fiber tract connecting Wernicke's and Broca's areas.

The posterior portion of Heschl's gyrus along the Sylvian fissure is the *planum temporal*, a part of the superior surface of the temporal lobe. Geschwind and Levitsky discovered that this structure is larger on the left than the right hemisphere in the majority of both right- and left-handed people. As such, asymmetry is also observed in prenatal brain maturation; the *planum temporal* is often thought as a neuroanatomical basis for left hemispheric specialization of language. A large number of clinical, psychophysical, and neuroimaging evidence has confirmed this specialization for broad aspects of language functions, including auditory comprehension, speech production, reading and writing (e.g., Hugdahl and Davidson 2003). Moving beyond the fact that functional hemispheric asymmetry exists, the question should be addressed on underlying neuropsychological mechanisms.

As all language functions require rapid changes within the auditory signal (e.g., formant transitions within single phonemes, proper sequencing of phonemes, syllables, words, etc.), they must engage specific timing mechanisms. Accurate temporal processing is crucial for language communication. Furthermore, left hemispheric specialization derives from timing (Tallal et al. 1996; Szelag et al.

2004). Combined data from various researches have indicated that the "clock," or timing, functions are relevant not only to language but also to the broader aspect of human cognition and behavior. It may be argued that temporal information processing constitutes a framework for human cognition, including auditory processing (Pöppel 1994).

On this basis, Steinbüchel and Pöppel (1993) proposed two classes of brain functions (see also Szelag et al. 2009). Functions of the first class, i.e., *what* functions, refer to their modular or local representation in the brain and are responsible for the mental context of our subjective experience. In case of auditory processing, *what* functions control the context of the incoming auditory signal and are represented in the cortical structures as described above.

In contrast, the functions of the second class, i.e., *how* functions, may be less localized in the brain and instead form a network of neural assemblies (see below for further discussion). These functions provide the formal basis for *what* functions creating the logistic basis for our mental activity. As temporal processing provides the crucial component of human cognition (including auditory processing), it should be concluded that, without a defined temporal structure, these activities would be chaotic. Hence, timing may be assumed as an example of *how* functions providing a framework for *what* functions and structure for auditory processing. Furthermore, imprecise timing may result in declined cognitive function reflected, e.g., in deteriorated language communication, movement control, memory, attention or decision making. These deficient mental functions may influence our personal identity leading to lower quality of life. It may be anticipated, therefore, that *how* functions provide the framework not only for our cognition but also for personal identity.

7 Temporal Patterning in Auditory Information Processing with Special Concern to Language

The accurate processing of temporal cues is crucial for perception of both verbal and nonverbal auditory information. It comprises not only our subjective experience of the time flow but also specific processing platforms or "time windows" within which incoming information is integrated into perceptual units within defined time limits (Pöppel 1994). In the existing literature, a few of these time processing platforms were distinguished, i.e., (1) gap detection corresponding to a few milliseconds, (2) event ordering related to some tens of milliseconds, (3) programming of motor acts in hundreds milliseconds, and (4) subjective present or feeling of "now" limited to a few seconds.

Taken together, at least two processing levels may be distinguished which are controlled by different neural mechanisms (Fraisse 1984; Pöppel 2004). One system concerns the low-frequency processing and reflects pre-semantic temporal binding of incoming events (both verbal and nonverbal) into larger units of a few seconds duration (Pöppel 2009; Szelag et al. 2004). In the case of language communication, such temporal integration can be reflected in segmentation observed in both oral and sign languages, where average duration of phrases (uttered or signed) is usually limited to a few seconds. Such a few seconds processing platform was indicated in human motor activity, perception of classic music, and many experimental paradigms (see Szelag et al. 2004, 2009 for an overview).

In contrast, the other domain is a high-frequency processing system, generating discrete time *quanta* of some tens of milliseconds duration. The existence of this time platform is also reflected in language communication, as spectrographic analyses of stop-consonants (e.g., /p/, /b/, /k/) in fluent speech in different languages is limited in time to around 40 ms (Fitch et al. 1993; Tallal et al. 1998). Additional support for these time windows in our brain computation comes from stimulus-triggered neurooscillations of typical 25–40 Hz, and from many psychophysical experiments, including choice reaction time, latency of eye movement, execution of simple ballistic movement, and perception of temporal-order (Szelag et al. 2004; Szymaszek et al. 2009).

Starting from Hirsh and Sherrick (1961), the temporal order paradigm was next employed in many experiments designed to study sequencing ability on the millisecond level which is strongly related to auditory comprehension and phonemic hearing. In the next sections, we focus on this aspect of auditory processing.

A large amount of psychophysical data have indicated that in normal young volunteers the temporal order of two stimuli presented in rapid succession can be properly identified if they are separated by a gap of at least some tens of milliseconds, independent of the stimulus modality and presentation mode. Results demonstrated that subjects characterized by the elevated gap often displayed parallel auditory comprehension deficits. Such coexistence has been confirmed in cases of language-learning-impaired children (Tallal et al. 1996), dyslexic individuals (Farmer and Klein 1995), aphasic patients (Fink et al. 2006), and some cochlear implant users (Szelag et al. 2004).

8 Auditory Perception of Temporal Order with Special Concern to Cognitive Aging

In series of experiments (Szymaszek et al. 2006, 2009), we indicated important age-related deterioration in auditory perception of temporal order using paired rectangular clicks presented monaurally (i.e., separately one click to each ear) and in rapid sequences. The subject's task was to identify the temporal order of two clicks presented within each pair, thus to judge whether it was "right–left," or "left–right." We assessed a threshold of such order identification, i.e., the minimum time gap between successive clicks within each pair at which the temporal order was correctly identified.

Age-related differences were studied in 86 healthy adults classified according to their age into five groups: 20–29, 30–39, 40–49, 50–59, and 60–69 years of age. We found that temporal-order-threshold remained relatively stable (approximately

65 ms) up to 60 years of life, but significantly declined (approximately 90 ms) beyond this age. The most interesting result was that chronological (biological) age was a poorer indicator of declined event ordering than cognitive competencies, i.e., attentional or intellectual resources. We interpret this as meaning that elderly individuals (beyond 60 years of age) with relatively preserved cognitive status may show less impaired sequencing abilities. The observed relationship between timing and cognition indicated that event ordering is probably not controlled only by "pure" timing mechanisms free of cognitive (nontemporal) influences. It seems important, because a large body of evidence has indicated age-related deficits in broad aspects of cognition; however, few attempts have related these deficits to deficient millisecond timing.

9 Neuroanatomical Loci of the Perception of Temporal Order

The empirical evidence of neuroanatomical loci of timing comes predominantly from clinical studies on brain-damaged patients and a growing body of neuroimaging data. The broader overview on brain representation of different time domains (milliseconds, seconds) was provided in our previous reports concerning clinical (Szelag et al. 2004) and fMRI data (Szelag et al. 2009). In this chapter, we focus only on neuroanatomy of event ordering, thus on the time domain of some tens of milliseconds which seems crucial to described auditory information processing.

Despite a growing body of neuroimaging data on temporal processing (e.g., duration judgment, duration discrimination), evidence on neuroanatomy of event ordering (millisecond timing) are rather limited and the results seem inconsistent. In general, there is evidence regarding the importance of the temporo-parietal junction as a neuroanatomical basis of temporal order detection (Davis et al. 2009). Moreover, the prefrontal cortex, basal ganglia, SMA and the cingulum have also been shown to be important in temporal order detection (Pastor et al. 2006). These results confirmed diffuse representation of event ordering and suggested the involvement of multimodal processes. Recent fMRI data do not support earlier theories postulating one common neural mechanism, such as an "internal clock" or "pacemaker," for timing operations.

Given the above discussion, in our fMRI block design study, we discovered a dynamic neural network engaged in event ordering, dependent on *task difficulty*. As task difficulty *increased*, activations were predominantly found in bilateral inferior parietal lobule (BA 40), and in the inferior frontal gyri (BA 45), with additional activations observed in the left medial and middle frontal gyri (BA 6, 8, 9); thus in classic regions related to attentional and working memory processes. Difficult event ordering engaged brain regions "working harder" and reflected the contribution of nontemporal cognitive processes to timing. Conversely, *decreased* task difficulty was accompanied by *increasing* involvement of other brain regions which in existing literature have usually been indicated as more specific to "pure" timing operations. These structures comprised bilateral medial frontal gyri (BA 10) and left cerebellum which were engaged in our study in *less difficult* timing tasks with lower cognitive load (no mental force).

These findings provide a strong support for dynamic neural networks engaged in difficult or easier event ordering, and may indicate the framework for understanding timing representation as the logistic basis (see above) of the brain. These data provide a strong support for earlier indications (Steinbüchel and Pöppel 1993) that the logistic basis for auditory processing (*how* functions) forms a network of neural assemblies, depending on the specific context of processed auditory information.

10 Timing Studies as a Starting Point to Modern Neurorehabilitation

The above evidence argued that many aspects of auditory processing derive, at least in part, from temporal processing. In a series of experiments, we therefore studied whether the application of specific auditory temporal training may ameliorate this processing.

In 36 normal volunteers (16 male, 20 female, aged 20–29 years), we compared the effectiveness of temporal training using the *Fast ForWord* program ($n = 15$) with that of a control nontemporal training ($n = 14$).

The *Fast ForWord* training (Scientific Learning Company 2009) comprised a set of computerized video games designed for auditory and language processing, using nonverbal or verbal stimuli and acoustically modified speech. Such programs may improve the speed of brain processes and is strongly rooted in improvement of timing. It provides intensive, highly individualized training across auditory attention, working memory, linguistic, and reading skills. Although *Fast ForWord* was originally designed to improve language competencies, in our studies we verified its effectiveness in improvement of nonlinguistic cognitive functions, like attention, short-term memory, and new learning ability in healthy young volunteers.

In our study, *Fast ForWord* training was composed of following three sets of adaptive exercises (1) language basics (*Drag Racer* and *Flying Saucer*), (2) literacy (*Spin Master*, *Space Racer*, *Lunar Tunes*, and *Galaxy Goal*), and (3) literacy advanced (*Sky Rider*, *Laser Match*, and *Meteor Ball*). All the exercises involve the ability to identify the temporal order of sounds, syllables, and words presented in rapid succession. The training was conducted during 8 weeks with four 1-h sessions per week. If the subject completed all these games earlier (e.g., after 6 weeks), the training was terminated.

The control nontemporal training consisted of seven adaptive games, specifically three different types of solitaires, *Marbles*, *Tetris*, *Mah-jong*, and *Checkers*. These games involved cognitive resources, i.e., attention or working memory, but were not related to auditory temporal processing. The control training was performed for the same period as the *Fast ForWord* training.

Before and after the training, we assessed both cognitive competences and auditory sequencing abilities using a few auditory temporal-order-threshold paradigms. All of them involved the perception of paired acoustic stimuli presented in rapid succession. The relationship "before–after" (temporal order) within each pair was identified by the participants. The assessment of cognitive function comprised two tests from the Cambridge Neuropsychological Test Automated Battery (CANTAB; Cambridge Cognition 2005) designed for the assessment of *new learning ability* (paired-associates learning, PAL) or *short-term visual memory* (delayed matching to sample, DMS). Additionally, two aspects of attention, i.e., *alertness* and *divided attention* were assessed using test for attentional performance (TAP; Zimmermann and Fimm 1997).

10.1 Before Versus After Comparisons: Psychophysical Evidence

Following *Fast ForWord* training, we observed significant improvements in both cognitive function and temporal processing. The former improvements comprised all tested functions, i.e., (1) alertness (shorter reaction times), (2) divided attention (more valid reactions and less omissions), (3) new learning abilities (less errors and less trails to perform on PAL correctly), and (4) visual short-term recognition memory (more correct responses in DMS). These improvements were accompanied by better sequencing abilities (lower values of temporal-order-thresholds) observed in all applied paradigms. The threshold values on average decreased from approximately 70 ms before training to approximately 30 ms after training.

10.2 Before Versus After Comparisons: fMRI Evidence

The improvements evidenced in psychophysical measurements had neuroanatomical correlates. Using an fMRI block design protocol, we verified neuroanatomical loci of auditory temporal order perception in easy and difficult timing tasks. As described above in detail, before training we discovered different neural network involved in easy and difficult event ordering. Interestingly, after *Fast ForWord* training, activation in more difficult timing tasks shifted from classic regions related to attentional and working memory processes to medial frontal gyrus (BA 10) which before the training was engaged only in easy timing tasks (compare above).

10.3 Before Versus After Comparisons: Electrophysiological Evidence

Additional support for the neural background of neuroplastic changes following *Fast ForWord* application comes from our electrophysiological studies in which auditory *evoked potentials* were recorded from 64 electrodes ("10–20" system) using a Neuroscan system. Participants were asked to detect a rare or *deviant* stimulus (30%) by pressing a button in the sequence of a frequent or *standard* stimulus (70%). The stimuli were pairs of white noises (short–long and long–short) separated by 160, 60, or 10 ms, corresponding to three levels of TOJ task difficulty, i.e., "easy," "moderate," or "difficult." In half the participants, the deviant stimulus was a short–long (standard: long–short) and in the other half: long–short (standard: short–long). We analyzed the mean amplitudes and latencies of *late positive component* (*LPC*), appearing at approximately 300 ms after stimulus presentation in response to deviant stimuli. According to existing literature, this component reflects the involvement of cognitive function, e.g., that of attention in a given task (see Linden 2005 for a review).

We showed increased amplitude of *LPC* in difficult timing tasks following *Fast ForWord* training which was accompanied by more correct deviant detections. Such elevated *LPC* amplitudes were observed at Pz the electrode. These results indicate that the *LPC* amplitude may constitute an electrophysiological correlate of neuroplastic underlying improved temporal order perception after *Fast ForWord* training.

11 Conclusions

In the light of presented evidence, a key factor in development of modern neuropsychological therapy addressing improvements in auditory processing are neural mechanisms underlying accurate timing of incoming auditory information. This "top–bottom" approach allows for the design of new rehabilitation programs taking into account temporal information processing as a logistic basis of human cognition.

The assessment of an individual's effectiveness in timing should be, thus, incorporated as a part of both audiological diagnosis and proposed therapy, tapped by not only language deficits but also improvements of broad aspects of cognitive functions in normal healthy volunteers. Such an approach, however, is frequently forgotten or neglected because of a lack of awareness among clinicians of the possible neurophysiological basis of observed deficits. We would argue, therefore, that an interdisciplinary auditory processing team should be established and take into account recent advances from the area of neuropsychology.

Acknowledgments Supported by the Polish Ministry for Science and Higher Education grant no.: 1082/P01/2006/31 and 507/1/N-DFG/2009/0. We thank *Scientific Learning Corporation* from Oakland, USA, for the opportunity to use *Fast ForWord* training in our research. We would like to thank Professor David McPherson for his valuable comments on this chapter.

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