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Brain Functional States of Spectral and Temporal Cues of the Phonological Processing

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Abstract: Speech and language are largely lateralized to the left cerebral hemisphere, while pragmatic competence appears to require an intact right hemisphere. Speech is known to be decoded in the brain by mechanisms engaging cortical areas within the left hemisphere, yet language experience may influence which brain circuitry is employed in processing auditory cues. The brain's processing of information involves simultaneous activation of widely distributed neural networks. These networks allow large-scale parallel processing but also include points of convergence and sequential routing. The distribution and the time course of the momentary brain electric field topography offer a unique possibility to obtain insights into important features of the brain's processing of information. The sequence of brain electric field topography represents the shift of the state of the brain from a representation of the input to a representation of the output.

Key words: Brain, sound, phonology, language, perception

INTRODUCTION

As language is one of the primary functions that unites us as humans, it is also one of the primary barriers within the human race. There nearly 7,000 different languages spoken in the world (SIL International, 2005). While these barriers do exist, knowledge of multiple languages is common in many countries. The study of speech and language in the present day has proceeded to the level of understanding the neural mechanisms underlying different aspects of speech and language and their localization of the brain. The research in the past has shown that both the production and perception of human speech and language involved specialized neural devices. The primary focus has been on hemispheric dichotomies in the processing of speech perception and the major focus has been shifted to the development of neural networks subserving speech perception. Two major, competing lines of investigation have emerged concerning hemispheric specialization for speech perception. One emphasizes task-dependent or domain-specific effects (Van Lancker, 1980; Ross and Mesulam, 1979) and the other cue-dependent effects that cut across task domains (Robin *et al*., 1990). In speech perception, task-specific hypotheses assume that unique, neural mechanisms are recruited for the speech domain, whereas cue-dependent hypotheses claim that speech processing is subserved by neurobiological mechanisms specialized for particular aspects of the acoustic signal, irrespective of communicative or linguistic relevance. However, these hypotheses has been against from some evidences of neurological impaired populations with unilateral lesions to the left or right hemisphere as well as from some studies using dichotic listening procedures or the Wada technique (Gandour *et al*., 2000). Within the past decade, empirical evidence has also begun to appear from both lesion-deficit and functional neuroimaging studies. Lesion studies tell us what areas are necessary for normal functioning, while functional neuroimaging studies tell us what areas participate in that function. The functional neuroimaging also give us a window on speech and language processing *in vivo* in the normal functioning human brain (Gandour *et al*., 2000). However, the physiological method of describing the anatomy of human speech still helps us to indicate what elements have a functional value with regards to speech and what anatomical elements are irrelevant.

Generally, when engaged in a conversation, listeners tune in to the relevant stream of speech and filter out irrelevant speech input that may be present in the same environment. Nonetheless, attention might be involuntarily diverted to meaningful items coming from an ignored stream, like in the well-known own-name effect. This brings up the question of to what extent speech and language are processed in the ignored streams. In addition, it remains a matter of controversy precisely what kind of neural mechanisms underlie functional asymmetries in speech and language processing. Whereas some studies support speech-specific circuits, others suggest that lateralization is dictated by relative computational demands of complex auditory signals in the spectral or time domains.

Human communication is made up of three domains: speech, language and pragmatics, which can be fully specified as a set of rules, units and practices. Prosodic function spans these domains. Speech and language are largely lateralized to the left cerebral hemisphere, while pragmatic competence appears to require an intact right hemisphere. The term "speech" is best used to refer to motor output and perceptual skills; "language" covers internal, mental knowledge; "pragmatics" expands the scope of study to overall, actual language use. Prosodic competence spans these domains. Prosody, or melody of speech, being made up of pitch, duration, intensity and voice quality, occurs in the domain of speech and in the capacity, can be quantified to a considerable degree. Prosodic meanings can be linguistic, as in the grammatical contrast between statement and question; or paralinguistic, as in the communication of attributes, emotional meanings and pragmatic factors. Changes in speech prosody can influence both linguistic and nonlinguistic aspects of the speech signal. Variations in these prosodic features provide auditory cues to phonological, lexical and grammatical units (linguistic prosody), as well as emotional states (affective prosody). Prosody is receiving increasing attention in unimpaired subjects and subjects with brain damage. Prosody cues linguistic, attitudinal, emotional and pragmatic information, but it has been most thoroughly studied in its role of signaling emotional meanings.

SCIENCE OF SPEECH AND LANGUAGE

Speech is known to be decoded in the brain by mechanisms engaging cortical areas within the left hemisphere, yet language experience may influence which brain circuitry is employed in processing auditory cues (e.g., pitch) (Van Lancker, 1980). Right hemisphere regions have been implicated in pitch perception of non-linguistic stimuli (Zatorre *et al*., 1994). Whether specialized neural mechanisms at higher cortical levels underlie pitch perception of linguistic stimuli is not known. Positron Emission Tomography (PET) was used in a cross-linguistic study to compare pitch processing in native speakers of English, a non-tone language, with those of Thai, a tone language (i.e., one in which pitch patterns are phonologically significant in monosyllabic words). When discriminating pitch patterns in Thai words, only the Thai subjects showed activation in the left frontal operculum. Activation of this region near the classically defined Broca's area suggests that the brain recognizes functional properties, rather than simply acoustic properties, of complex auditory cues in selectively accessing language-specific mechanisms in pitch perception. Thus, pitch processing in a linguistic context will preferentially activate specialized speech centers in the left hemisphere.

Speech perception clearly involves multiples, hierarchical stages of acoustical, lexical and sentence-level analysis. A task dependent hypothesis of speech perception that is based on hierarchical levels of linguistic structure attributes sentence-level aspects of speech prosody to global processing by right hemisphere mechanisms and word-level aspects of speech prosody to local processing by left hemisphere mechanisms. Evidence has been steadily accumulating in the behavioral and neuroimaging literature implicating the right hemisphere in the perception and production of linguistically relevant prosodic cues that extend over higher-level linguistic structures (e.g., sentence) and necessarily over longer temporal domains. Converging evidence strongly implicates the left hemisphere in the perception of lexical tones at the syllable level, the smallest linguistic unit to which prosodic features may be assigned (Gandour *et al*., 2000; Hsieh *et al*., 2001; Klein, 2003; Sittiprapaporn *et al*., 2003, 2005). Speech segmentation needed to perform phonetic discrimination tasks results in activation of posterodorsal aspects of the inferior prefrontal cortex. Previous PET/fMRI studies indicate that segmentation processes in speech perception may be lateralized to frontal regions of the left hemisphere (Zatorre *et al*., 1992). Moreover, activation of the left posterior inferior prefrontal cortex has been found in PET studies of the perception of suprasegmental units involving Thai tones (Gandour *et al*., 1998, 2000) and Chinese tones (Hsieh *et al*., 2001; Klein, 2003).

BRAIN, SPEECH AND LANGUAGE

Since the discovery by Broca more than a century ago that lesions in the left hemisphere produce language deficits while lesions in the right do not, lateralization of language processing has been investigated in patients and in normal subjects by a variety of means. A large number of studies on cerebral function have investigated left and right hemispheric specialization. For auditory stimuli, some researchers have asked whether lateralization to one cerebral hemisphere is based on acoustic features or on the functional context of the stimulus. Normal humans can be tested by dichotic listening. It has been repeatedly demonstrated that for most normal, right handed people, the left hemisphere is the dominant language hemisphere. One research technique used is dichotic listening, in which two different stimuli are presented simultaneously to the right and left ears of a subject wearing stereo headphones. Data accumulated over the past decade in this experimental paradigm confirm the belief that language is lateralized to the left cerebral hemisphere; these data include a consistent right ear preference for language stimuli.

There is a great deal of controversy regarding how multiple languages are represented in the human brain. Some researchers contend that the same brain regions are responsible for language processing and production. Several neuroimaging studies support this hypothesis, showing overlapping activations for words spoken in native and secondary languages, regardless of whether the two languages are linguistically similar (Klein, 2003; Sittiprapaporn *et al*., 2003) or dissimilar (Chee *et al*., 1999). These studies provide convincing evidence that multiple languages are mediated by the same processes, at least for single words. Furthermore, they suggest that age of acquisition of each language does not significantly affect the pattern of overlapping activation. However, other studies contest these claims. There have been several interesting case studies of bilingual patients with deficits in only one language (Gomez-Tortosa *et al*., 1995; Fabbro *et al*., 1997; Moretti *et al*., 2001). These studies conclude that different languages are mediated by distinct cortical regions. Their conclusions have been echoed from some neuroimaging studies, reporting that bilinguals have language-specific regions with differential activations when presented stimuli in different languages (Kim *et al*., 1997; Perani *et al*., 1996).

Up to now, it is well known that speech and language engage neural mechanisms in the left hemisphere. Yet the fundamental nature of these mechanisms underlying hemispheric lateralization for different aspects of speech (e.g., prosody) still remains controversial. Currently, two general types of hypotheses, cue-dependent and task dependent, have been proposed to account for hemispheric asymmetry in the perception of speech prosody, i.e., variation in the pitch, length and loudness of spoken utterances. One cue-dependent hypothesis posits that all acoustic cues of prosody are processed in the right hemisphere and integrated with information processed in the left hemisphere via the corpus callosum. Others are based on left and right hemispheres mechanisms specialized for particular acoustic cues; temporal vs. spectral cues (Van Lancker, 1980; Robin *et al*., 1990); high frequency vs. low frequency cues and rapidly changing vs. slowly changing acoustic cues. None of these cue-dependent hypotheses, however, appear to be able to account for left hemisphere lateralization of lexical tones, as found in the world's tone languages (e.g., Thai, Chinese). Lexical tones are characterized by pitch variation at the syllable level, i.e., slowly changing, low frequency and spectral information. Contrary to prediction, evidence for left hemisphere dominance in the perception of lexical tones is supported by lesion deficit, dichotic listening (Van Lancker, 1980) and neuroimaging data (Gandour *et al*., 2000; Hsieh *et al*., 2001; Klein, 2003; Sittiprapaporn *et al*., 2003; 2005; Sittiprapaporn, 2012a, b).

Hemispheric asymmetry underlying higher cortical functions such as speech and language is also well established in the human brain. Yet, elucidating the neural mechanisms underlying such functional asymmetry remains a central unresolved question. Divergent views have emerged based on premises derived in part from studies of complex auditory signals ranging from non-speech to speech. Speech perception studies addressing high-level processing have provided evidence in favor of speech-specific circuits in the left hemisphere of the human bran comparable to species-specific vocalization as posited in animals. Other studies, however, argue that left hemisphere lateralization for speech is a secondary consequence of left hemisphere specialization for the processing of rapidly changing acoustic information that happens to be crucially involved in speech perception.

It has been proposed that auditory cortical in the two hemispheres differ in their relative sensitivity to temporal and spectral features of sounds (Zatorre *et al*., 1999; Sittiprapaporn *et al*., 2003, 2005, 2006; Sittiprapaporn, 2010, 2011). Studies show that the left hemisphere extracts rapid temporal information using relatively short temporal integration windows (20-50 msec), whereas the right hemisphere extracts temporal information with longer integration window (50-250 msec). Signal-processing principles would dictate a temporal-to-spectral trade-off, with shorter integration times providing higher temporal resolution at the expense of lower spectral resolution, while the longer temporal windows providing for lower temporal but higher spectral resolution. Thus, hemispheric differences reflect the greater specialization of the left hemisphere for rapid temporal processing and the right hemisphere for fine spectral processing.

It has also been reported that the empirical data on low-level auditory processing remains conflicting and sometimes contradictory. For example, sound sequences mad up of pure-tone elements with randomized pitch and duration, instead of being lateralized to the right hemisphere and left hemisphere, respectively, appear to be analyzed by a common bilateral network. Moreover, it has been demonstrated that auditory analysis in the human brain may be based on a hierarchy of temporal levels. Fine temporal structure associated with pitch perception implicates the auditory pathway up to and including primary auditory cortex. Additionally, the evidence in support of low-level auditory specialization comes primarily from auditory processing asymmetries for non-speech sounds in humans and other species and anatomical asymmetries in human auditory cortex (Zatorre *et al*., 1992). Data are more equivocal for the perception of human speech sounds. Hemispheric differences clearly emerge from domain-specific functions (e.g., speech, music), which are independent of low-level auditory specializations. Especially interesting are hemispheric asymmetries in the perception of speech prosody, that is, variations in the pitch, duration and loudness of spoken utterances. Pitch variations at the syllable level that change the meaning of individual words are called lexical tones. The perception of both Thai (Gandour *et al.*, 2000; Sittiprapaporn *et al.*, 2003, 2005) and Chinese (Hsieh *et al.*, 2001; Klein, 2003) lexical tones is lateralized to the left hemisphere instead of right hemisphere. Indeed, Chinese consonants, vowels and tones are all lateralized to the left hemisphere (Klein, 2003). Pitch variations that are linguistically significant at the sentence level, on the other hand, are referred to as intonations. Both Chinese tone and intonation involve spectral processing, yet pitch contours associated with lexical tones are processed in the left hemisphere by Chinese listeners, whereas pitch contours associated with intonation are processed in the right hemisphere (Gandour *et al.*, 2000). It has also been shown that Thai vowel length is processed in the left hemisphere by Thai listeners (Gandour *et al.*, 2000; Sittiprapaporn *et al.*, 2004, 2005, 2006; Sittiprapaporn, 2012a, b).

An optimal window for exploring how the human brain processes linguistically relevant temporal and spectral information is one in which both vowel length and tone are contrastive. A language that exploits variations in duration and voice fundamental frequency, respectively, to distinguish vowels and lexical tones, is the best of choices. However, the co-occurrence of tone and vowel length distinctions in the same language is not uncommon. Numerous Asian languages exhibit complex tonal inventories (e.g., Vietnamese), but their vowel length contrasts are severely restricted to one or a few vowels. Tone languages (e.g., Thai and Chinese) are ideally suited for providing a condition in which tone or pitch is phonologically significant. In tone languages, pitch variations signal lexical contrasts (for example, Thai: /maa$^{\text{mid}}$/ ‘come’ vs. /maa$^{\text{rising}}$/ ‘dog’). Since variations in pitch patterns at the syllable level are linguistically significant, experimental manipulations with tone languages offer a unique opportunity to elucidate the functional neuroanatomy of speech prosody (Gandour *et al.*, 2000).

The search for an objective index of change detection in the human brain can be traced back to 1975, with the proposition that stimulus deviation *per se* (irrespective of, e.g., stimulus significance, attentional mechanisms) should produce a measurable brain response (Naatanen *et al.*, 1997). Experimental evidence for this suggestion was obtained in experiments conducted by Naatanen *et al.* (1978). In this dichotic listening study, the subject's task was to detect occasional deviant stimuli in the stimulus sequence presented to a designated ear while ignoring the concurrent sequence presented to the opposite ear. The irrelevant stimulus sequence included deviant stimuli that were physically equivalent to the deviant stimuli (targets) of the attended input sequence. The deviant stimuli were either tones of a slightly higher frequency or tones of a slightly greater intensity than the standard tones.

Human auditory cortical in the two hemispheres has been shown to differ in their relative sensitivity to temporal and spectral features of sounds. Specifically, hemispheric differences reflect the greater specialization of the left hemisphere for rapid temporal processing and the right hemisphere for fine spectral processing (Zatorre *et al.*, 1999). That is, signal-processing principles would dictate a temporal-to-spectral trade-off, with shorter integration times providing higher temporal resolution at the expense of lower spectral resolution, while the longer temporal windows providing for lower temporal but higher spectral resolution. However, the empirical data on low-level auditory processing remains conflicting and sometimes contradictory. For example, sound sequences made up of pure-tone elements with randomized pitch and duration appear to be analyzed by a common bilateral network and the auditory analysis may be based on a hierarchy of temporal levels. The fine temporal structure associated with pitch perception implicates the auditory pathway up to and including primary auditory cortex. The first evidence in support of low-level auditory specialization comes primarily from auditory processing asymmetries for nonspeech sounds in humans and other species and anatomical asymmetries in human auditory cortex (Zatorre *et al.*, 1999). The more equivocal data for the perception of human speech sounds shows that hemispheric differences clearly emerge from domain-specific functions (e.g., speech, music), which are independent of low-level auditory specializations. Especially interesting are hemispheric asymmetries in the perception of speech prosody, that is, variations in the pitch, duration and loudness of spoken utterances. Pitch variations at the syllable level that change the meaning of individual words are called lexical tones. The perception of both Thai (Gandour *et al.*, 2000) and Chinese (Hsieh *et al.*, 2001; Klein, 2003) lexical tones has been shown to be lateralized to the left hemisphere instead of right hemisphere (Sittiprapaporn *et al.*, 2003, 2005, 2006; Sittiprapaporn, 2012a, b).

The comprehension and production of language is a function of the human brain that is of crucial importance for the interaction between individuals. Language abilities are uniquely developed in humans and may be a prerequisite for high levels of abstraction in cognition. The partial or total loss of language abilities (aphasia) results in a clear loss of quality of live. Affected persons encounter major difficulties in coping with daily life tasks; they are in danger of loosing their employment and becoming isolated from their social environment. It is necessary to deepen our understanding of the organization of human language processing as a basis for the development of therapies. The detailed study of human language processing will also contribute to the understanding of general properties of human perception and information processing. Communication through language is based on a common agreement on what the things and concepts to be communicated are and how they relate to each other. If the brain's processing of language has features that are common across individuals, this will have implications on general models of brain functions. It will be of interest to establish which functions are normally invoked when language is perceived or produced and in what sequence the processing units are activated, how they interact and where in the brain they might be localized. It will also suggest that there are ways common to all humans how to organize the outer world and how to represent it internally. For example, a difference in the processing of nouns and verbs which is common over subjects will suggest that the human brain classifies the world a priori into things and actions and relates them in a common way. Finally, the perception of language contents evokes a sequence of processes that typically involves the level of conscious experience. The study of consciousness is a field of research and discussion that always has passionate scientists and philosophers and it is "just about the last surviving mystery" (Mesulam, 1990). Thus, a better understanding of the brain's language processing might very well be a useful contribution to the discussion on how conscious experience is generated and represented in the human brain.

However, it remains unresolved whether the human brain contains neural circuits that are uniquely engaged in speech and language perception. While it is evident that language is subserved by left hemisphere mechanisms, it is not clear whether speech, language, or something else is lateralized to the left hemisphere. Again, the neural basis underlying functional hemispheric asymmetries has been postulated as either cue dependent, in which basic neural mechanisms exist for processing of complex auditory stimuli regardless of linguistic relevance, or task dependent, in which specialized neural mechanisms exist that are activated only by speech. These competing hypotheses make fundamentally different claims about brain processing of auditory signals in linguistic and nonlinguistic contexts. In support of a cue-dependent approach, evidence from dichotic listening revealed that a right-ear advantage for discriminating speech sounds may be influenced by temporal parameters. It was subsequently proposed that left hemisphere regions that subserved speech perception may be fundamentally specialized for the processing of rapidly changing acoustic information. In a Positron Emission Tomography (PET) study, activation of the left frontal opercular region was found to be larger when subjects monitored target stimuli in words, syllables and tone sequences than in steady-state vowels. The absence of frontal opercular activation for vowels sue to their relatively long (250 msec) steady-state spectra was thus consistent with the assumption that this region on the left is specialized for processing rapid acoustic transitions.

BRAIN STATES AND HUMAN LANGUAGE PROCESSING

Information manifested as momentary state of the brain: It is generally agreed that the brain's processing of information involves simultaneous activation of widely distributed neural networks. These networks allow large-scale parallel processing but also include points of convergence and sequential routing (Mesulam, 1990). Ojemann (1991) applied electric stimulations of brain tissue during brain surgery and showed that these language-related networks consist of multiple essential areas as well as of widely dispersed neurons. The momentary state of all neural networks is equivalent to the global functional state of the brain (Ashby, 1952). This corresponds to what is momentarily represented in the mind (Bunge, 1977). When the brain receives information from the external environment, from the body or from itself it will produce an overt or covert response including also the possibility of not reacting at all (Koukkou and Lehmann, 1987a, b). In terms of brain states, this means that the state of the brain has to move from an initial representation of the input information towards an eventual representation of the internal or external response.

Adaptive shifts of the functional state of the brain: The determinants of the brain's information processing vary as a function of the progress of this processing. The activation of internal representations of stimuli will largely be based on automatic parallel processing whereas the outcome depends highly on the internal state of the brain at the moment of information income and eventually also on limited capacity processes like the use of different strategies guided by conscious control (Posner and

Snyder, 1975; Koukkou and Lehmann, 1983). It has been suggested that an incoming stimulus activates a large part of the system simultaneously so that all apparent stimulus properties are represented instantaneously. This state of activation of the brain would then be narrowed down gradually by filtering out irrelevant features and enhancing relevant features by adaptive template matching (Grossberg and Stone, 1986).

Brain microstates as building blocks of complex information processing: The relevant information of the stimulus is not always apparent in its physical properties; this is especially the case for human language. (The shape of a flower, for example, cannot be seen in the letter sequence "flower"). It is therefore reasonable to assume that for the (quite abstract) processing of language, several of these adaptive brain states are necessary. This would mean that the percept of a stimulus triggers a sequence of short adaptive brain states, each representing different emergent qualities of the stimulus and thus having different functional meanings. Brain states are suggested to represent both bottom-up and top-down processes (Dixon, 1981). The putative, short functional states will be called microstates following Lehmann (1990). They interact both with the brain's microstate (Lehmann, 1992), as covering arousal, motivation and emotional state and the anatomical structure of the brain which includes long term memory and genetically inherited information (Koukkou and Lehmann, 1983, 1987a, b). The sequence of adaptive functional microstates of the brain eventually can induce limited capacity processes like conscious experience.

Brain electric field maps and brain states: The distribution of the electric field on the scalp reflects the spatial patterns of neural activity in the brain. A change of this spatial distribution must have been caused by a change of the geometry of the neural activity in the brain, i.e., other neural elements must have become active. When this occurs, it is reasonable to assume that the brain has changed its functional state, that it "is doing something else". The examination of sequences of momentary field maps shows that these changes of the brain electrical field topography occur in jumps taking place in the millisecond time range; the transitions between one field topography to the next one are not smooth, but tend to occur quickly and stepwise, separated by longer periods of relatively stable field topography (Lehmann and Skrandies, 1980). This observation suggests that these periods of stable field topography are the electrophysiological correlates of the above-mentioned short adaptive functional microstates of the brain which represent a putative single step of information processing; the sequence of these stable periods of brain electric field topography then represents the shift of the state of the brain from a representation of the input to a representation of the output. The study of the distribution and the time course of the momentary brain electric field topography therefore offer a unique possibility to obtain insights into important features of the brain's processing of information.

CONCLUSION

Human communication is made up of three domains: speech, language and pragmatics, which can be fully specified as a set of rules, units and practices. Prosodic function spans these domains. Speech is known to be decoded in the brain by mechanisms engaging cortical areas within the left hemisphere, yet language experience may influence which brain circuitry is employed in processing auditory cues. The brain's processing of information involves simultaneous activation of widely distributed neural networks. The sequence of brain electric field topography represents the shift of the state of the brain from a representation of the input to a representation of the output.

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