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REVIEW ARTICLE

A look at the auditory scene analysis from the window of event related potentials

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Abstract

Background and Aim: Foundations and mechanisms of auditory scene analysis (ASA) including segregation and integration were especially reviewed in the study. I focused on the related studies using event-related potentials (ERPs).

Recent Findings: Publications on ASA using ERPs from 1971 to 2014 indicate neural mechanisms of ASA in central auditory system.

Conclusion: ASA results in recognition of different sound stimuli in the competing sound environment. The neural mechanisms of this process could be studied comprehensively using ERPs with good temporal resolution.

Keywords: Auditory scene analysis; event-related potentials; segregation; integration

Introduction

In order to receive target auditory information in complex environment, we should detect a discrete sound source. For this matter, acoustic features of the sound sources must be segregated and then integrated in the right fashion. The segregation process is conducted in both time (sequential segregation) and frequency planes (simultaneous segregation). Without this ability, auditory stimuli are received in a complex way and auditory perception is impossible [1].

We often experience a complex acoustic environment with auditory information originating from several simultaneously active sources that often overlap in many acoustic parameters. However, we are able to identify auditory events and hear distinct auditory objects. Auditory scene analysis (ASA) is the process involving the ability to segregate those sound inputs that originate from different sound sources and integrate those that belong together [2]. Accordingly, segregation and integration processes are two fundamental aspects of ASA [3].

Bregman believes that auditory segregation of different sound stimuli is conducted based on their different frequencies and harmonic relations. The formation of auditory streams is the result of processes of sequential and simultaneous segregation. Sequential segregation separates and connects sense data over time, whereas simultaneous segregation selects those components that are probably parts of the same sound, from the data arriving at the same time [1]. Both processes are foundations of auditory stream formation and finally perceptual representation in central auditory nervous system [1].

Generally, ASA theory explains how the auditory system makes a relation hypothesized so the Gestalt's regularities play an important

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role in the organization of sound elements [1]. From this point of view, ASA has the following procedures:

1- Procedures related to perceptual organization of concurrent acoustic elements

2- Procedures related to perceptual organization of sequential acoustic elements

These procedures are based on regularities such as physical similarity and temporal proximity induced to integrate and segregate components of the complex acoustic environment to perceptual representations of auditory sources or auditory objects [1]. For example, if sounds differ widely in frequency, intensity, and spatial locations, they are more probably segregated and represented. In contrast, if sound components have related harmonics or their intensity rises and falls are in the same relation, they are more likely to be perceptually grouped and assigned to a single source. Many of these procedures are indicated automatically or primitively because they could be found in infants [4] and animals such as birds [5,6] and monkeys [7]. The consequences of these pre-attentive processes (bottom-up) may be modulated and more detailed analysis by controlled processes (top-down). While the pre-attentive processes group sounds based on physical attributes, controlled schema-driven processes use prior knowledge to constrain the auditory scene and finally induce our perceptions to consistent with previous experience [1]. It is indicated that schema-driven processes depend on previous auditory experiences acquired through learning and a comparison of the incoming sounds with their representations. In a complex auditory environment such as the cocktail party situation, the use of prior knowledge and experience are especially important to correctly assign any sounds to their sources. The aforementioned information indicated ASA important role in auditory world and auditory object perception. Many studies using auditory electrophysiologic responses titled event related potentials (ERPs) have been conducted for ASA and its role in speech perception and auditory attention effects on this process. How the brain uses ASA in temporal domain is one of the most important questions in auditory related studies especially auditory neuroscience. There are a lot of ambiguities about the ASA such as its neurophysiologic mechanisms that could be studied in more detail with auditory electrophysiologic responses.

Auditory scene analysis and event-related potentials

ERPs are a powerful measure for examining time related information about ASA because these potentials allow for the examination of neural activity within hundreds of milliseconds after the presentation of a sound stimulus [8]. In addition, ERPs can be used to measure the effect of auditory and visual attention on ASA [9]. Generally speaking, ERPs reflect the synchronous activity from large neuronal populations that are time-locked to sensory or cognitive events [8]. Hence, auditory ERPs represent a processing pathway of auditory information from the cochlea through the brainstem to the primary auditory cortex and to more active cortical areas. Brainstem auditory evoked potentials have been recorded between 1 and 10 ms after stimulus onset. Middle-latency evoked potentials arise between 10 and 50 ms after stimulus presentation and are assumed to reflect the activity of the primary auditory cortex. Long-latency evoked potentials arise after 50 ms and include the p1, n1, and p2 waves. n1-p2 complex, mismatch negativity (MMN), and object-related negativity (ORN) have been studied more than the other potentials because their presence indicates acoustic signal detection and its variations. These responses are only present when a transient auditory stimulus is audible. One of the most important differences of these responses is stimulus paradigm that is introduced in the following sections. Finally, the conscious identification of an auditory event is often associated with a late positive wave peaking between 250 and 600 ms post-stimulus, referred to as the P300 or P3b [10,11].

n1-p2 complex

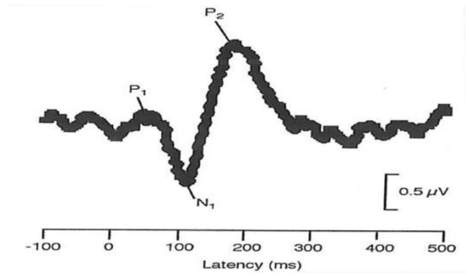

Fig. 1. n1-p2 complex with approximate latency of 100-200 ms [58].

The n1-p2 complex is an obligatory ERP that can reflect central auditory speech representation without active participation [11-15]. This complex opens a window to the brain and is one of the first auditory electro-physiologic evidence of ASA. The n1-p2 complex is also the appropriate index for evaluating persons with communication or cognitive problems. n1 response has peak amplitude in frontal and central regions [16]. Dependent on stimulus duration, n1 component has been displayed as a negative deflection approximately in 100 ms followed by positive peak with latency of 200 ms (Fig. 1) [17,18]. Based on some studies, n1-p2 complex is more stable on Cz electrode showing the reliable latency or amplitude results from test to retest [19,20]. It is thought that this complex is reflecting synchronous neural activation of structures in the thalamic-cortical segment of the central nervous system in response to auditory stimulation [18,21,22]. Many studies indicated that the n1-p2 complex is indexing neural underpinnings of spectral and temporal attributes of speech language, and demon-strating the initial levels of shaping ASA for speech perception with good temporal resol-ution [18,23,24]. In the following studies, the application of this complex was reported for investigation of ASA procedure between normal people and people with communication dis-orders such as hearing impairment. Talebi et al. compared the n1-p2 complex as an index of concurrent speech segregation between normal and hearing impaired children. In this study, responses of central auditory system have been evaluated by speech stimuli (double vowels). The results showed the significant decrease of n1-p2 amplitude in children with hearing loss. This study demonstrated the significant problem in speech stimuli detection because of segre-gation and/or ASA problems [25]. In another study, Talebi et al. indicated that this complex could be used to monitor the improvement of concurrent speech segregation in hearing impaired children receiving auditory rehabili-tation. Results showed the improvement of concurrent speech segregation skills and ASA indexed by amplitude increase and latency decrease of the n1-p2 complex (Fig. 2) [8]. Ohl and Scheich [26] and Gutschalk et al. [27] also showed the good correlation between n1-p2 amplitude and detection of F0 differences. This result was thought to reflect activity of higher-order auditory system during the presence of two sound sources. In addition, F0 differences have been assumed to activate a different population of neurons. Consequently, these findings indicated that changes of sensory evoked responses are not only reflecting stimulus-related activity but also sound stream perception.

Mismatch negativity

One of the most important components of ERPs is mismatch negativity (MMN) which reflects sound change detection (Fig. 3) [28]. This component is generated within auditory cortices and is usually evoked within 200 ms of sound change [29]. Like the n1-p2 complex, MMN indexes first levels of sound change detection; the reflection of auditory stimulus segregation. The difference between n1-p2 complex and MMN is related to generation regions and dependency on auditory memory. Evidence indicated that the underlying mechanisms of MMN involve sensory memory [30]. The neural representations of the acoustic regularities, often called the standard, which are shaped from the repetitive sound sequence, are maintained in memory and form the basis for the change detection process. New incoming sounds devi-ate from the neural trace of the standard elicit MMN. Thus, the presence of the MMN can be the index of standard stimuli store in the

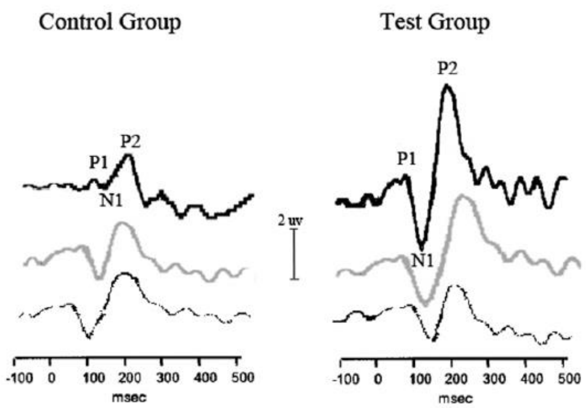

Fig. 2. Effects of auditory rehabilitation on improvements of n1-p2 components: latency decrease and amplitude increase. Dark, thin, and dotted waveforms have been recorded before, 3 and 6 months after auditory training respectively [8].

memory. Using a simple auditory oddball paradigm in which an oddball is presented randomly among frequently repeated sounds elicits MMN. The random stimulus can be deviant from standard stimulus in frequency, intensity, duration, or spatial location. It is important to notice that MMN is not simply elicited when there is a frequent and an infrequent tone presented in the same sequence. MMN generation depends on detection and storage of the regularities in the sound stimulation. The detected regularities make the auditory context from which deviance detection occurs. Thus, MMN is highly dependent on the context of the stimuli [4,31,32]. In the auditory environment, the auditory input segregation is a critical step that allows perception of complex sound such as speech in a crowd. There is considerable ERP evidence to suggest that auditory memory can hold information about independent multiple sound streams, segregation of auditory inputs to distinct sound streams, and attention effects this process [4,33]. Automatic segregation and following integration of sound stimuli could facilitate the ability to select information. From this point of view, attention does not have a role in the first levels of sound organization. However, it can modify the organization of the sound input, which then influences how the information is stored and used by later processes (e.g. the MMN process). Based on this information, auditory attention is needed for understanding complex auditory stimuli such as speech or music [33].

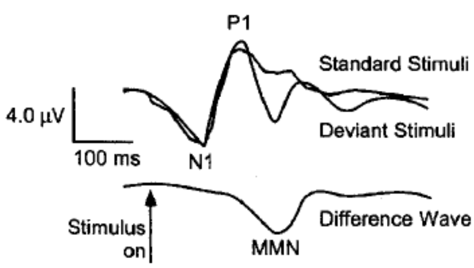

Fig. 3. Mismatch negativity (MMN) that has been recorded by oddball paradigm [59].

Integration processes and mismatch negativity

Most often, the perception of a sound event is dependent on the sounds that surround it even when the sounds are not in close temporal proximity. Thus, changes in the larger auditory context have been shown to affect processing of the individual sound elements [34]. The ability of the auditory system to detect contextual changes plays an important role in auditory perception. Sussman and Winkler, studied the contextual effects on auditory event formation [34]. They showed that the presence or absence of single deviants (single frequency deviants) in a sound sequence that also contained double

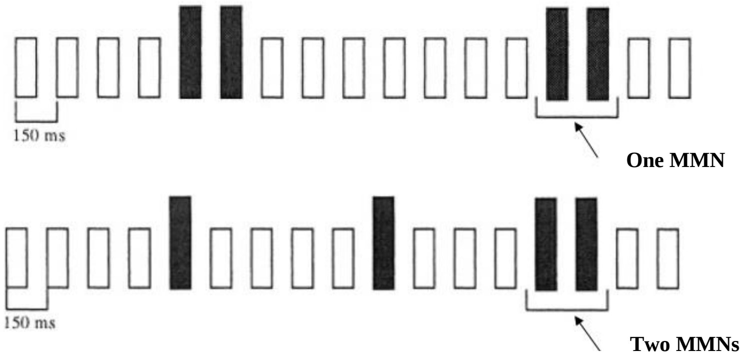

Fig. 4. Two deviant stimulus paradigms used to show one or two MMNs dependent to context of stimulus [34].

deviants (two successive frequency deviants) created different contexts for the evaluation of the double deviants (Fig. 4). In this study, the double deviant stimuli may be processed either as unitary auditory event (one MMN) or as two successive events (two MMNs). These results depend on the auditory context. It is indicated that the change of response to the one and double deviants eliciting one to two MMNs is gradual. It took up to 20 s after the onset or cessation of the single deviants before the MMN response to the double deviants reflected the context change. This condition shows the ability of the auditory system in maintaining the current context until enough evidence is accumulated to establish that a true change occurred, thus avoiding miscalculations in the ongoing sound environment. The results indicated that the auditory system maintains contextual information and monitors for sound changes within the current context, even when the information is not relevant for behavioral goals [34].

Relationship between segregation and integration in ASA

Based on the ERP results of the segregation and integration processes of sound stimuli, it is indicated that a) segmentation of auditory input can occur without paying attention to the sounds, and b) contextual factors can influence how auditory events are represented in memory. There is strong evidence that segregation is an earlier, primitive process (based on acoustic features of auditory inputs) than integration, which is schema-based (auditory experience and knowledge) [1,32,35,36]. Both processes make ~~a~~ hearing a single speech stream in a crowded room possible. The MMN is an index of using this information (the segregated input and neural representation of the relevant context) as the basis for detecting what has changed in the environment. Auditory attention modifying the initial organization of the sound input affects event formation and how the information is represented and stored in memory [9,37,38]. Kujala et al. using MMN investigated the segregation of speech sounds in children with dyslexia. They showed the differences between brain procedures of discrimination and recognition of sound changes between dyslexic and normal children. In addition, their results indicated that there were deficits in processing and attention procedures, and speech perception difficulties related to speech sound segregation in dyslexic children [39]. Lepisto et al. studied segregation and integration of auditory streams indexed by MMN in children with Asperger's syndrome. These children have some problems in detection of speech stimuli and attention to these sounds in crowded environments. In this study, there were MMN differences (amplitude decrease and no response) between these patients and normal children. The results of this study indicated difficulties in concurrent segregation and integration of auditory streams followed by speech perception difficulties in noisy environments [40]. It could be said that

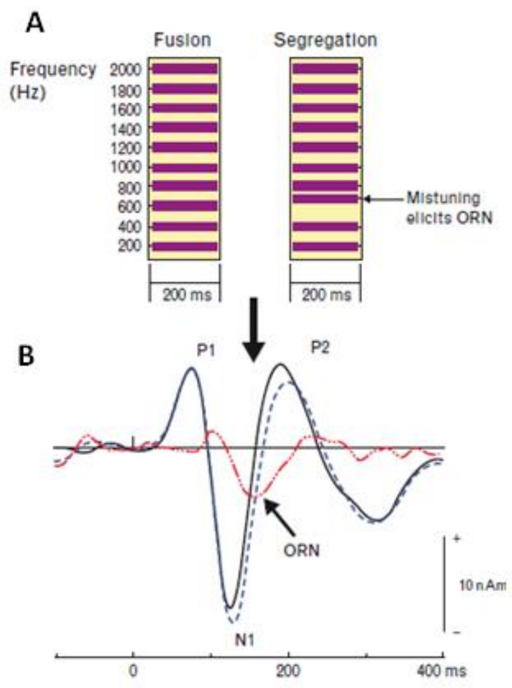

Fig. 5. A. Mistuned stimulus paradigm used to generate ORN. B. ORN (red color) elicited in the same latency limits of n1-p2 complex. Dark and dotted lines indicate responses of tuned and mistuned, respectively [60].

there is a unique connection between segregation, integration of auditory stimuli, and auditory attention effects indexed by auditory electrophysiologic responses such as MMN. Also, MMN component could be used to monitor the changes of ASA with good temporal resolution.

Object-related negativity

One way of investigating the neural bases of concurrent sound segregation is using the mistuned harmonic paradigm. In this paradigm, the listener is usually presented with two successive stimuli, one comprised of totally harmonic components, the other with a mistuned harmonic. The task of the listener is to identify the stimulus stream containing mistuned harmonics. Several factors influence the perception of the mistuned harmonic including the degree of inharmonicity and sound duration [41,42]. Alain et al. indicated that when the harmonic in the complex sound was mistuned from its original value by more than 4%, listeners heard it as a separate tone. This condition could be shown by Object-related negativity **(**ORN) [43]. This response overlaps in time with the n1 and p2 deflections and has a latency of 150 ms (Fig. 5). It is observed in school-aged children [44]. The ORN can be recorded for stimuli that are unattended, such as when participants ignore the stimuli and read a book of their choice or watch a subtitled movie. Recording this response in an unattended condition likely indicates that concurrent sound segregation occurs independent of a listener's attention. The ORN amplitude is usually the largest at central and frontocentral sites and inverts polarity at the mastoid sites. It is indicated that its generators are located in the supratemporal plane within the sylvian fissure [44]. The ORN shows some similarities in latency and amplitude with MMN. Like the ORN, the MMN also has a frontocentral distribution and its latency peaks at about 150 ms after the onset of deviation. Both ORN and MMN to acoustic stimuli could be assumed to index bottom-up processing of ASA [45,46]. Despite the similarities, there are differences between these responses. One of the most important differences is that while MMN is highly sensitive to the perceptual context, the ORN is not. In addition, the MMN is elicited only by rare deviant stimuli whereas the ORN is elicited by mistuned stimuli regardless of whether they are presented occasionally or frequently [46]. Hence, the MMN reflects a mismatch between the incoming auditory stimulus and what is expected based on recently occurring stimuli, whereas the ORN reflects a discrepancy between the mistuned harmonic and what is expected on the basis of the current stimulus. It is indicated that the MMN is an index of sequential integration because its elicitation depends on the extraction of regularities over several seconds. In contrast, the ORN is assumed to index concurrent sound segregation and depends on a simultaneous spectral analysis of the incoming acoustic waveform [43]. Also, the ORN and MMN can be differentiated based on their scalp distribution indicating different neural networks responsible for concurrent and sequential sound segregation. Another difference is different sensitivity of both responses to attention. In some studies, it was shown that the ORN was less affected than MMN by attention load [45,47]. This difference in attentional sensitivity may be related to the memory system and its grouping procedures. In other words, sequential integration depends on the integration of acoustic information over several seconds (mechanism of MMN) while concurrent sound segregation depends on the integration of acoustic information within hundreds of milliseconds (mechanism of ORN) [45,47].

Speech separation and ERPs

Based on the aforementioned information, ASA could be indicated as basic procedure in processing of complex auditory stimuli such as speech. From this point of view, acoustic elements could be integrated as linguistic units including phonemes, syllables, and words after the primary segregation of auditory inputs occurs. In this field, there are a lot of behavioral and electrophysiologic studies using speech stimuli such as vowels and consonants [48-50]. Psychophysical studies have shown that when listeners are presented with two different vowels simultaneously, the identification rate improves with increasing separation between the fundamental frequencies (F0) of the two vowels [48,49]. Some studies have been conducted with similar paradigm to investigate the time course of neural activity associated with concurrent vowel segregation [25,43,51]. In these studies, participants were informed that on each phase two phonetically different vowels would be presented simultaneously and they were asked to identify both by pressing the corresponding keys on the keyboard as the difference in F0 varied from phase to phase. These studies indicated that a listener's ability to identify both vowels improved by increasing the difference in F0 between the two vowels. Also, it is showed that the listener's ability to identify two concurrent vowels improved with training, and that improvement was associated with decreased n1 and p2 latencies and an increased p2 amplitudes [8]. These learning-related changes in sensory evoked responses may reflect functional and structural changes in auditory cortex reflecting an increase in listener expertise with such stimuli. The correct identification of concurrent vowels depends on a listener's ability to detect the presence of two signals (automatic segregation), identifying these individual signals and to initiate the appropriate response. With indicating these processes, two ERP indexes could be assigned for detection and identification of concurrent vowels, respectively (Fig. 6). The first is a negative wave that was superimposed on the n1 and p2 waves, and peaked around 140 ms after sound onset [44]. This component has maximal amplitude in central electrodes. The amplitude of this component was related to the detection of the discrepancy between F0's, signaling to higher auditory centers that two sound sources were present [26]. The second ERP component associated with concurrent vowel segregation was a negative wave that peaked at about 250 ms after sound onset and was larger over the right and central regions of the scalp. As mistuned harmonics do not generate this late modulation, it was likely related to the identification and categorization that followed the automatic detection of the double vowel stimuli. The first negative modulation was indexing automatic detection of the two different vowels in the mixture. The second negative peak was present only when listeners were asked to make a perceptual decision. This component may index a matching process between the incoming signal and the stored representation of the vowels in working memory. Given that vowels are before-learned, the second modulation may also reflect the influence of schema-driven processes in vowel identification [26].

Conclusion

After introducing ASA by Bregman, many consistent studies have been conducted about its role in sound source localization. It appears that investigation of neural generations and

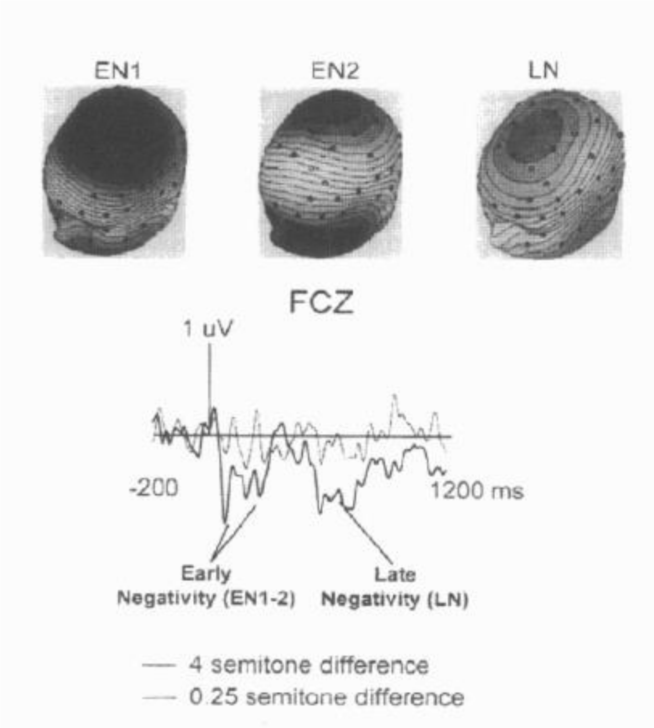

Fig. 6. Group mean difference waves between ERPs elicited by two vowels which their fundamental frequencies were separated by .25 or 4 semitones. Brain maps illustrate the amplitude distribution of the early (EN1 and EN2) and late (LN) negativity. The peak amplitudes of these waves were respectively 150, 250, and 650 ms after sound onset. FCZ=FrontoVentral electrode at the midline. The darker grey in the brain maps indicates greater negativity [26].

mechanisms of segregation and integration have been highlighted by auditory electrophysiologic responses or ERPs. At this time, many audiologists familiar to auditory neuroscience use these components to monitor ASA and identify its vague neurophysiologic mechanisms in a normal and abnormal population. It is thought that many abnormalities such as hearing loss, autistic spectrum disorders, and learning disorders may have some degree of difficulty in perceptual organization of auditory inputs followed by ASA problems. These patients report significant problems in identification and perception of complex auditory signals such as speech and music. For Example, it was reported that any disorders in concurrent and or sequential segregation of sound stimuli may be induced to speech perception problems in children and adults with hearing loss [43,52,55] and dyslexic children [56,57]. Thus, finding temporal-related mechanisms of ASA in central auditory system is one of the most important themes in auditory neuroscience. This objective could be investigated more comprehensively in temporal domain with ERPs. In addition, it is suggested that basic studies using auditory electrophysiologic responses would be conducted for better identification of ASA neural mechanisms and its role in speech and music perception. Also, it is suggested that auditory electrophysiologic responses such as n1-p2 complex, MMN, Speech ABR, and other auditory evoked responses could be used in hearing impaired persons to monitor auditory rehabilitation effects on ASA in lower and higher centers of central auditory system.

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