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論文内容の要旨

Title: Neural Encoding of Temporal Regularity in the Human Auditory Cortex

Temporal regularity provides an important cue for the identification of everyday sounds. Especially, temporally regular or periodic amplitude fluctuations of 4- to 16 Hz play an important role in comprehension of speech. As frequencies below 20 Hz cannot be place-coded in the cochlea, detection of these low frequencies relies on the central auditory system. How low frequency periodic sounds are processed in the central auditory system however, is yet to be clarified. In this work, auditory evoked human cortical magnetic fields were measured to investigate the neural encoding of temporal regularities that cannot be represented in the peripheral auditory system.
Previous studies investigating a cortical evoked response correlate of periodicity detection in the auditory cortex have revealed that the auditory sustained response, which appears as a stimulus-locked baseline shift following the transient responses to the sound onset, is very sensitive to temporal regularity of the acoustic stimuli. The sensitivity of the sustained response, which indexes the activity of the non-primary auditory cortex, has been associated with processing of high frequency periodic sounds above about 30 Hz that lead to pitch perception. In order to clarify whether sustained responses can probe the detection of low frequency temporal regularities below the pitch range, it is necessary to reevaluate the lower limit for periodicity processing in the non-primary auditory cortex.

In the first experiment, the sustained magnetic fields evoked by periodic and non-periodic noises were investigated in order to elucidate the relationship between the repetitive acoustic input and sustained field response amplitudes. Periodic noises were prepared as repeating frozen noise stimuli with repetition rates of 5-, 10-, 50-, 200- and 500 Hz. Repeating frozen noise consists of repetition of the same noise segment (frozen noise) without pauses and the reciprocal of the segment length defines the repetition rate. As the repetitive element is noise and there are no silent periods between the consecutive segments, it is possible to equate the sound energy of the periodic stimuli for a wide range of repetition rates. Therefore, repeating frozen noise stimuli are especially suitable to investigate the lower limit of periodicity detection and were expected to lead to stable sustained responses The study was conducted on twelve healthy subjects. The sustained field response, which is generated in the non-primary auditory cortex was significantly larger for all the periodic stimuli than for white noise. The enhanced sustained field responses to periodic noises show that cortical sensitivity to periodic sounds is maintained even for artificial basic sounds, and temporal regularities within the range of 5- to 500 Hz are detected by the level of non-primary auditory cortex.

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In the second experiment, the auditory evoked cortical magnetic fields evoked by 40 Hz amplitude-modulated periodic and non-periodic noises were analyzed. This novel sound stimulus enables simultaneous recording of auditory steady state (ASSR) and sustained responses, which index the primary and non-primary auditory cortices, respectively. Amplitude-modulated periodic noises of 40-, 20-, and 5 Hz were prepared in the form of repeating frozen noises where the same noise segment appears at either each period (40 Hz), every second period (20 Hz), or every eighth period (5 Hz) of amplitude modulation at 40 Hz. The study was conducted on eleven healthy subjects. The effect of periodicity exhibited prominent differences between the ASSR and sustained responses, and between right and left hemispheres. For the right hemisphere, in comparison to the non-periodic noises, ASSR source strengths were significantly enhanced for the high repetition rates (20- and 40 Hz). For the left hemisphere, however, ASSR source strengths evoked by periodic noises were not significantly different from non-periodic noises. For the sustained responses, significant source strength increments were observed for all repetition rates (5-, 20-, and 40 Hz) compared to non-periodic noises. In addition, similar to auditory steady state responses, there was a significant right-hemispheric dominance for the periodic stimuli.

The obtained results showed that encoding of periodicity occurs in a hierarchy, complex sounds that have a pitch character (> 20 Hz) are detected at or below the primary auditory cortex, while detection of low frequency periodicities requires further processing in non-primary auditory areas. The observed variation of the temporal regularity effect between evoked response components and hemispheres may reflect differences in the temporal integration window lengths adopted between auditory steady state and sustained responses generators and also between the right and left auditory pathways. Periodicities above about 20 Hz are processed at or below the primary auditory cortex that adopts a short integration time constant. The low frequency periodicities below 20 Hz however, are processed in the non-primary auditory areas that adopt a longer temporal integration window.

博士論文の審査結果の要旨

出願者の博士論文は以下のような内容であった。

音信号とは物理的観点からみると空気の振動であり、その周期性は音の知覚に重要な役割を果たしている。ヒトが知覚できる周波数には限界があり、20Hz 以下の純音は蝸牛において基底膜を振動させることができず知覚することができない。しかしながら、日常生活において複合音の 20Hz 以下の成分は知覚、特に音声や音楽の知覚に重要な役割を果たしていることが知られている。複合音の低周波成分の信号処理は末梢器官である蝸牛では不可能であり、聴覚中枢で行われていると考えられているが、詳細については未だ明らかになっていない。本研究では低周波で繰り返される雑音(repeating frozen noise, RFN)を用いることで、音の周期性がどのような神経活動を引き起こすかを脳磁図による２つの実験で調べた。

１つ目の実験では同一の音圧を有する５種類の RFN (5-, 10-, 50-, 200-, 500-Hz) と白色雑音を１２名の被験者に提示し、高次聴覚野由来と考えられる遅い潜時で持続性の反応である Sustained Field(SF)の振幅がどのように変化するかを調べた。その結果、SF 振幅は 10Hz および 50Hz RFN 条件で最大となり、すべての RFN 条件で白色雑音条件より有意に大きかった。この結果から高次聴覚野の神経活動は雑音の低周波での繰り返しにより賦活化されること、また音声で特に重要と思われる周波数領域で最大となることが示唆された。

２つ目の実験では 40Hz の振幅変調を加えた RFN(5-, 20-, 40-Hz)と白色雑音を用いることで、一次聴覚野と高次聴覚野の神経活動を同時に記録し比較検討した。その結果、一次聴覚野の神経活動は高次聴覚野に比べて、雑音の低周波での繰り返しによる影響を受けにくいことが分かった。また高次聴覚野における神経活動は一つ目の実験同様すべての RFN 条件で白色雑音条件より賦活化されていたが、一次聴覚野の神経活動振幅は 5-Hz RFN 条件と白色雑音条件ではほぼ同様であった。また雑音の繰り返しによる神経活動の賦活化は一次聴覚野、高次聴覚野とも左半球より右半球でより優位であった。これらの結果は、音信号処理に必要な解析時間幅は一次聴覚野より高次聴覚野で長いこと (200ms 以上)、また音信号解析時間幅は右半球の方が左半球より長いことを示している。このように異なった脳部位が異なった解析時間幅を用い、音信号の周波数構成や経時変化を効率的に処理することで、複雑な周波数成分を含む自然音に対応していると考えられる。

上記の成果は、ヒトの聴覚認知に関して新しい知見を示すもので、研究としての完成度も高い。また、既に出願者が第１著者として英文原著論文を１報発表し、さらに現在、欧米の一流誌に投稿中である。これらのことから、本論文は学位に値すると、審査委員全員が判断した。