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Research Article

INVESTIGATION OF MIDDLE EAR SOMATOSENSORY REPRESENTATIONS IN THE HUMAN CORTEX: INSIGHTS FROM FUNCTIONAL MRI

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ABSTRACT

This study aimed to explore the somatosensory representations of the middle ear within the human cortex. 15 subjects with normal hearing underwent a 3T-fMRI experiment, during which a minor change in tympanic membrane pressure was induced. Activation of the audiological association area 22 was observed bilaterally upon stimulation of the postcentral gyrus 40 and Brodmann area 43. Additionally, Brodmann area 43 exhibited activation in response to oropharyngeal pressure activities associated with oral intake, a process facilitated by the Eustachian tubes linking the tympanic membranes to the pharynx. Notably, BA 42 and BA 22 were activated bilaterally during changes in oropharyngeal air pressure, indicative of the cortical involvement in the acoustic reflex. These findings highlight the involvement of cortical regions (areas 43, 42, and 22) in processing somatosensory information related to middle ear function, particularly in response to pressure-induced movements of the tympanic membrane.

Keywords :- Somatosensory, Middle ear, Tympanic membrane, Auditory cortex, fMRI, Cortical activation

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INTRODUCTION

The functional organization of primary somatosensory areas in the cerebral cortex is crucial for understanding somatosensory input processing [1]. While the somatosensory homunculus extensively represents hands and orofacial regions, the representation of the ear remains unexplored [2]. To investigate the superficial sensitivity of the pinna, electrical stimulation of the primary somatosensory cortex can be employed. Studies have demonstrated activation of somatosensory areas in the face and neck regions through pinna surface stimulation [3]. However, measuring tympanic membrane pressure, an indicator of middle ear sensitivity, has not yet been accomplished using neuroimaging tools [4]. Clinical audiologists may potentially identify subclinical dysfunctions using somatosensory cortex assessment, preventing irreversible hearing loss. Conditions such as idiopathic mild otitis media can affect the tensor tympani, impacting middle ear function [5]. Although muscles in the middle ear, including the tympani and stapedius, are challenging to access, stretching may enhance their multisensory sensitivity, primarily proprioceptive. Additionally, studies have revealed Pacinian corpuscles in the tympanic membrane and described the presence of spindles and intrafusal fibers in the stapedius and tensor tympani muscles [6]. Proprioceptor signals are generated when the tympano-ossicular chain mobilizes, particularly during weak stretches. Functional MRI has been utilized to visualize tympanic movements induced by variations in air pressure [7].

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Overall, understanding the somatosensory representations of the ear and its associated mechanisms contributes to elucidating auditory health and function.

MATERIALS AND METHODS

A study approved by an ethics committee involved fifteen healthy, right-handed volunteers (mean age 36; 8 males, 7 females). All participants provided written consent after undergoing audiometry and otoscopy, which revealed no ear, nose, or throat issues or middle ear pressure abnormalities. Volunteers wore soundproof headsets fitted with an otoscope and tympanometric probe for pressure measurement. Air pressure in the ear canal was manipulated using syringes, with variations of up to +40 mm H2O monitored by a manometer. Tympanometry with stimulation (200 daPa) was conducted, employing 12-15 cycles of pressure changes randomly administered for 24 seconds each, with a 24-second interstimulus interval. Pre-SENTATIONVR software controlled the timing in MR scanners [8]. Participants were instructed to maintain focus during fMRI tests, keeping their eyes closed and abdomen held, while the tympanic membrane was gently moved before entering the 3T tunnel to minimize stimulation detection. Only one ear was stimulated to avoid bidirectional cortex stimulation, based on previous studies reporting intermittent effects with alternate vision and hearing stimulation.

fMRI Protocol

The Bruker Medspec's S300 scanner, equipped with a birdcage head coil, was utilized for acquiring 3T-whole-body MR images. Automatic second-order shimming minimized distortion and reduced nonhomogeneities in B0. Functional BOLD contrast images were obtained using a gradient echo planar imaging sequence. Slice thicknesses parallel to the AC-PC commissures were set at 38.3 mm. Three EPI sequences with spectral bandwidths of 2,400 ms and 30 ms provided isotropic voxels measuring 3 × 3 × 3 mm3. Each subject acquired six dummy images before equilibrium was reached. An alternative stimulus paradigm involved pressure variations of 24 seconds alternating with rest intervals. Imaging of the human brain was conducted with a TDR of 11.99995 milliseconds and a resolution of 457 milliseconds, utilizing a matrix of 256x256x176 and two segments. The acquisition time for each image was two and a half seconds.

FMRI Data Processing and Statistical Analysis

Functional volumes were normalized using a 6-mm full-width-at-half-maximum Gaussian kernel based on the T1 weighted template. Variations in BOLD signals were statistically analyzed using a general linear model. Air pressure variation periods were modeled by convolving a boxcar function with the canonical dynamic response function, considering the delay between the start of the stimulus period and the manipulator's pressure-variation onset. Realignment parameters were included as uninteresting regressors in the model. A 1/192 Hz high-pass filter was applied to remove slow drifts in the baseline. Contrast images based on Student's t-tests using pressure variations and resting periods for each subject were calculated. Random effects analysis was conducted on the contrast images to draw generalizations across subjects. Student's t-tests were utilized to identify regions with significantly different BOLD levels from the null hypothesis. A threshold of $P<0.001$ was applied for extended statistical t-maps covering 10 voxels. After correcting for the false discovery rate, no clusters were found at these thresholds.

Statistical Test for Hemispheric Differences

A study compared hemodynamic BOLD responses between the left and right hemispheres. Initially, a hemispherically symmetrical template was derived using the standard MNI template. Functional images were spatially normalized and smoothed using the same Gaussian kernel as in the standard analysis. Student's t-tests were then employed to assess differences between stimulation and rest periods across subjects. Symmetric contrast images, obtained by flipping the image along the antero-posterior y-axis, represented each individual's contrast between the two hemispheres. Individual contrast images were generated by subtracting a symmetric contrast image from a direct contrast image. A random effects analysis was conducted on the differential images of each subject. Voxels with significant differences exceeding 10 voxels were considered, with a significance threshold set at 0.01.

RESULTS

Six out of 15 subjects failed to follow instructions during the fMRI measurements, which led to variation in the right ear pressure. They reported feeling sensations in both ears in three out of four cases. There were no patterns observed in the participants' responses during the test. There is a need for attention in the Brodmann areas 42 and 23, as well as 43 in the postcentral gyrus, which belong to the auditory associative cortex. A statistically significant asymmetry exists between the right and left hemispheres.

DISCUSSION

Several studies have demonstrated that tympanic membranes project to BA 43 [9], a region involved in oral intake activities such as gustation and swallowing. Following our intriguing findings, we investigated the mechanical phases of swallowing.

Table 1: Based on maximal t values and MNI coordinates, activation clusters in temporal and parietal cortex are identified

Regions of interest	Side	Brodmann area (BA)	X	Y	Z	T
Temporal superior gyrus	L	BA 84	90	62	14	10.126
Temporal superior gyrus	L	BA 44	101	8	2	8.294
Temporal superior gyrus	R	BA 84	108	44	26	8.180
Temporal superior gyrus	R	BA 84	102	62	38	8.78
Parietal lobes Postcentral gyrus (caudal)	L	BA 86	114	8	14	10.98
Postcentral gyrus (caudal)	R	BA 86	108	20	32	8.68

Effective swallowing requires coordinated sensory and motor functions of the oropharynx, larynx, mandible, tongue, and face [10-12]. Swallowing consists of three phases: oral, pharyngeal, and esophageal. The bolus must undergo taste perception, heating, and tactile sensation in the mouth, as well as mastication facilitated by facial movements [13-15]. A study observed that air pulses elicit activation in nearby oropharyngeal regions following time in the postcentral gyrus [16]. Pharyngeal swallowing is mediated by the muscles of the Eustachian tube, including the tensor tympani, tensor veli palatini, and salpingopharyngeus. In previous study, it was found that the histochemical continuity in the long tendons of the tensor tympani and tensor veli palatini [17]. The tensor veli palatini plays a significant role in sucking, while sensory receptors on the tympanic membrane and Eustachian tube muscles are interconnected during swallowing, as suggested [18]. Activation was observed in the second and third auditory associative areas, BA 42 and BA 22, despite unilateral tympanic stimulation, indicating a bilateral effect. The middle ear can exhibit an acoustic reflex even with unilateral stimulation, as demonstrated. A study proposed that tensor tympani activity primarily controls prevocalization reflex activity, contributing to acoustic reflexes in humans. Transient contractions of middle-ear muscles increase middle-ear impedance, reducing nasopharyngeal resonance by controlling eardrum tension [19]. BA 22 may be involved in speech processing, as suggested. Bilateral activation of the auditory reflex may preserve interaural level differences and contribute to maintaining similar air pressures and impedances in both middle ears. Further research is warranted to investigate potential differences in auditory perception between the left and right ears under varying pressure conditions.

CONCLUSION

Variations in tympanic membrane pressure lead to alterations or distensions in associative auditory areas 42, 22, and 43. Involuntary reflexes are thought to regulate middle ear pressure during activities such as swallowing or listening to speech. A study has indicated that BA 43 influences both involuntary reflexes and oropharyngeal pressure. Although direct representation of membrane movement resulting from pressure was not identified in S1, the post central gyrus appears to transmit information closely associated with somatosensory perception.

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