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EFFECT OF SOUND INTENSITY ON LEVEL OF ACTIVATION IN AUDITORY CORTEX AS MEASURED BY FMRI

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

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Abstract

BACKGROUND: Despite rapid developments in fMRI, there is still ongoing debate on the optimal paradigm for evaluating the level of auditory cortex activation.

MATERIAL AND METHODS: A number of modern neuroimaging methods can be used to assess brain responses to acoustic stimulation, but new paradigms are still needed. Here the *sparse* fMRI approach is used to examine frequency-specific activation in auditory cortex in 12 normal hearing individuals.

RESULTS: The size of activation expanded with increasing sound intensity and decreasing sound frequency. At the same time, the main site of frequency-specific activation remained the same across intensities, indicating fixed tonotopic organization. The findings of the study are explained in terms of basilar membrane phenomena such as the travelling wave pattern and spread of activation.

CONCLUSIONS: Stimulation levels of at least 60 dB are necessary in order to obtain robust maps of group activation in auditory cortex.

KEY WORDS: functional magnetic resonance imaging, auditory cortex, sound intensity

IMPACTO DE LA INTENSIDAD SONORA SOBRE LA ACTIVACIÓN EN LA CORTEZA AUDITIVA

Resumen

INTRODUCCIÓN: Pese al rápido desarrollo de la disciplina, sigue debatiéndose el tema de la optimización del paradigma utilizado en la valoración de la activación de la corteza auditiva mediante el método de la resonancia magnética funcional.

MATERIALES Y MÉTODOS: Se había elaborado un paradigma a utilizar en la exploración de la activación de la corteza auditiva por el método *sparse* fMRI. En el estudio participaron 12 personas con audición normal.

RESULTADOS: Se demostró que la zona activa aumenta conforme se disminuye la frecuencia y se aumenta la intensidad sonora. Por otra parte, la localización principal de la activación relacionada con el rango de frecuencias dado no varía según la intensidad aplicada. Este efecto indica la preservación de la organización tonotópica. Los resultados del estudio han de entenderse en relación a los fenómenos que se desarrollan en la membrana basal, es decir el paso de la onda viajera y la distribución de la activación.

CONCLUSIONES: Para obtener mapas fiables de activación dentro de la corteza auditiva a nivel grupal se sugiere utilizar sonidos de 60 decibelios como mínimo.

PALABRAS CLAVE: resonancia magnética funcional, corteza auditiva, intensidad sonora.

ВЛИЯНИЕ ИНТЕНСИВНОСТИ ЗВУКА НА АКТИВАЦИЮ В СЛУХОВОЙ КОРЕ

Абстракт

ВВЕДЕНИЕ: Несмотря на интенсивное развитие области продолжается дискуссия об оптимизации исследовательской парадигмы для оценки активации слуховой коры методом функциональной магнитно-резонансной томографии.

МАТЕРИАЛ И МЕТОД: Современные методы нейровизуализации могут быть использованы для оценки реакции мозга на акустическую стимуляцию, и все еще существует необходимость в разработке новых парадигм исследования. Здесь был применен редкий подход к фМРТ для изучения частотно-специфической активации в слуховой коре у 12 лиц с нормальным слухом.

РЕЗУЛЬТАТЫ: Исследования показали, что активная область увеличивается с увеличением интенсивности звука и уменьшением частоты звука. При этом основная область возбуждения, связанная с определённым диапазоном частот, оставалась той же, вне зависимости от использованной интенсивности. Данный эффект указывает на сохранение тонотопической организации. Результаты исследования следует объяснять по отношению к явлениям, происходящим на базилярной мембране, таким как картина бегущей волны и распространение возбуждения.

ВЫВОДЫ: Для получения надежных карт активации в слуховой коре на групповом уровне рекомендуется использование звуковой стимуляции на уровне не менее 60 дБ.

Ключевые слова: функциональная магнитно-резонансная томография, слуховая кора, интенсивность звука

WPŁYW INTENSYWNOŚCI DŹWIĘKU NA AKTYWACJĘ W KORZE SŁUCHOWEJ

ABSTRAKT

WSTĘP: Mimo szybkiego rozwoju dziedziny, nadal trwa dyskusja na temat optymalizacji paradygmatu badawczego do oceny aktywacji kory słuchowej metodą czynnościowego rezonansu magnetycznego.

MATERIAŁ I METODA: W celu zbadania aktywacji w korze słuchowej, opracowano paradygmat do badania metodą *sparse* fMRI. W badaniu uczestniczyło 12 osób ze słuchem prawidłowym.

WYNIKI: Wykazano, że obszar aktywny jest tym większy, im niższą częstotliwość oraz wyższą intensywność dźwięku się zastosuje. Jednocześnie główna lokalizacja pobudzenia związana z określonym zakresem częstotliwości pozostawała ta sama niezależnie od zastosowanej intensywności. Efekt ten wskazuje na zachowanie organizacji tonotopowej. Wyniki badania należy rozumieć w odniesieniu do zjawisk zachodzących na błonie podstawnej, tj. przechodzenie fali wędrującej oraz rozchodzenie się pobudzenia.

WNIOSKI: W celu uzyskania wiarygodnych map aktywacji w korze słuchowej na poziomie grupowym sugeruje się stosowanie dźwięków na poziomie minimum 60 dB.

SŁOWA KLUCZOWE: czynnościowy rezonans magnetyczny, kora słuchowa, intensywność dźwięku

BACKGROUND

Functional magnetic resonance imaging (fMRI) has proven a valuable tool for studying central mechanisms of auditory perception. A number of works have been published which use this method to examine the relationship between sound parameters, including frequency and intensity, and activation patterns in the auditory cortex [1–3]. Notably, it has been shown that tonotopic organisation is preserved throughout the whole auditory system. This means that the systematic tuning of the basilar membrane in the inner ear, with filters tuned sequentially in frequency, is also reflected in the auditory cortex. The area most evidently organised tonotopically is the primary auditory cortex, lying on and around the Heschl gyri (HG) in the superior temporal lobes. Recent fMRI studies in human have indicated a dominant low-frequency field represented laterally on the HG, with high-frequency regions located posteriorally and anteriorally around it [3]. However, the effect of sound intensity has been studied in only a few fMRI works, all showing that higher intensity increases the extent of active regions detected in the auditory cortex (and/or a local BOLD signal change) [2,4–9].

To assess the tonotopic organisation of auditory cortex with high frequency selectivity, quiet stimulation is preferred. Therefore, threshold acoustic stimulation has been applied in animal studies using invasive techniques, such as single-cell recording of auditory neurons [10,11]. However, the fMRI method, which can be safely used in human participants, suffers from high background noise and low signal-to-noise ratio. High-field MR scanners generate acoustic noise at levels of up to 100 dB SPL during gradient switching, together with sound from air conditioning and helium pumps which can produce noise at 65–80 dB SPL [12]. Due to these limitations, tonotopic fMRI studies need to employ sounds of 50–90 dB SPL [3,10,13,14]. Another strategy is to use special *sparse* paradigms which present sounds to the participant during the quieter periods between times of loud data acquisition [15–20].

Although the fMRI field is rapidly developing, there is still ongoing debate on the optimal paradigm for evaluating auditory cortex activation. The current study seeks to evaluate the volume and distribution of activated cortical clusters in response to complex tones presented at five central frequencies and three intensities. A unique study paradigm is used, inspired by the work of Humphries and collaborators (2010) [19]. The sound parameters are chosen to reflect the particular peripheral physiological effects of sound intensity, while corresponding to the wide range of frequencies coded on the basilar membrane. A certain trade-off is suggested between elucidating the pattern of frequency processing in auditory cortex and the intrinsic limitations of the fMRI technique.

MATERIAL AND METHODS

Material

Twelve right-handed volunteers (3M, 9F, 36 ±11 years) with normal hearing (<20 dB HL for 0.25–8 kHz) participated in an fMRI study. All subjects provided written informed consent. The trial was approved by the Bioethical Committee of the Institute of Physiology and Pathology of Hearing and conformed to the Declaration of Helsinki.

MR imaging

The study was performed at the Bioimaging Research Center at the World Hearing Center of the Institute of Physiology and Pathology of Hearing in Warsaw. Functional and anatomical scans were collected on a Siemens

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Table 1. Results obtained for contrasts of signal (400 Hz_{CF} – 6400 Hz_{CF}) vs silence for three sound intensities; FWE p <0.01

contrast	hem.	main AAL region	40 dB(A)				60 dB(A)				80 dB(A)			
			region size (vox.)	max. t-value	MNI coordi-nates (X, Y, Z)	total cluster size (vox.)	region size (vox.)	max. t-value	MNI coordi-nates	total cluster size (vox.)	region size (vox.)	max. t-value	MNI coordi-nates	total cluster size (vox.)
0.4 kHz vs silence	R	STL	147	5.84	52 -15 5	236	580	7.39	50 -19 5	796	1239	12.25	48 -17 3	2017
		HG	60	5.25	52 -13 5		122	6.98	52 -23 5		235	11.77	48 -16 6	
		MTL	-	-	-		-	-	-		108	6.33	66 -33 5	
		STP	-	-	-		-	-	-		93	6.7	51 4 -5	
	L	STL	209	5.53	-46 -29 7	252	730	8.78	-50 -17 3	890	967	11.47	-38 -31 11	1615
		HG	34	4.3	-47 -14 6		86	6.24	-38 -30 10		173	11.47	-37 -30 11	
		MTL	-	-	-		-	-	-		249	7.47	-46 -29 3	
0.8 kHz vs silence	R	STL	207	6.35	58 -7 3	326	615	8.25	58 -7 5	954	1103	10.93	56 -9 3	1727
		HG	78	5.74	52 -9 5		170	7.96	54 -7 5		214	9.39	48 -15 5	
		STP	-	-	-		-	-	-		78	6.66	52 3 -7	
		MTL	-	-	-		-	-	-		36	4.98	60 -33 1	
	L	STL	182	6.17	-50 -11 3	217	732	8.91	-44 -25 7	994	1070	12.56	-46 -23 5	1599
		HG	-	-	-		116	7.18	-38 -30 10		151	10.27	-37 -30 11	
		MTL	-	-	-		-	-	-		142	7.63	-46 -23 1	
1.6 kHz vs silence	R	STL	207	6.88	50 -5 -5	303	255	7.91	54 -9 3	396	843	12.34	54 -9 3	1427
		HG	48	5.31	54 -9 5		89	7.6	54 -9 5		232	11.57	54 -7 5	
		STP	-	-	-		-	-	-		39	8.74	50 3 -7	
	L	STL	182	6.32	-50 -25 7	206	246	6.01	-58 -21 9	326	808	10.31	-46 -21 1	1207
		HG	-	-	-		42	5.49	-34 -31 13		177	9.26	-37 -30 11	
3.2 kHz vs silence	R	STL	44	6.7	50 1 -7	73	243	7.58	64 -26 -41	376	755	10.20	52 -11 3	1237
		HG	-	-	-		79	6.2	38 -25 11		206	8.35	50 -13 5	
		STP	-	-	-		-	-	-		39	6.34	51 4 -5	
	L	STL	53	5.48	-48 -11 -1	62	167	7.54	-58 -23 9	302	684	7.77	-44 -17 1	1029
		HG	-	-	-		87	7.58	-36 -27 11		143	7.73	-34 -29 11	
6.4 kHz vs silence	R	STL	-	-	-	-	99	5.88	48 -13 -3	123	712	9.98	46 -15 -1	1123
		HG	-	-	-		-	-	-		200	8.93	37 -26 11	
	L	STL	-	-	-	-	75	6.51	-40 -24 4	154	577	8.3	-42 -35 13	864
		HG	-	-	-		44	4.66	36 -25 11		121	7.16	-34 -27 9	

Hem. – brain hemisphere; R – right, L – left; AAL – Automatic Anatomical Labelling brain atlas; STL – superior temporal lobe; HG – Heschl gyrus; STP – superior temporal pole; MTL – medial temporal lobe; MNI – Montreal Neurological Institute brain atlas

3T Magnetom Trio scanner using a 12-channel head matrix coil.

The scanner produced noise of up to about 98 dB SPL during gradient switching, and the air conditioning system, helium pumps, and radio-frequency pulses were present permanently and reached levels of up to 65–80 dB SPL. Special headphones attenuated the noise by 15–20 dB. Because the current study focused on auditory responses, a *sparse* paradigm was employed for functional imaging. During 10 seconds of Time of Repetition (TR), sounds were presented for 8 seconds in relative silence; the remaining 2 seconds were for data acquisition. A single-shot GE-EPI technique was applied with the following parameters: TR = 10 s, time of echo (TE) = 30 ms, time of acquisition (TA) = 8:09 min, matrix = 96 × 96, field of view (FOV) = 192 × 192 mm, no of slices = 28, voxel size = 2 × 2 × 2 mm, pixel bandwidth = 1447 Hz/pix, iPAT = 2. In one fMRI session (3 runs), 144 brain volumes were collected (24 for each of 5 complex tones and silence). Acquisition of one volume (28 slices) took 2 seconds. fMRI data was obtained in the temporal plane in an axial direction; the imaged slab was 6 cm thick (3 cm up and 3 cm down from the individually localised superior temporal gyrus).

After fMRI, anatomical brain structures were assessed with several high-resolution MRI sequences. The main sequence, T1-MPR, was registered isometrically in the sagittal plane with the following parameters: TR = 1900 ms, TE = 2.26 ms, inversion time = 900 ms, flip angle (FA) = 9°, FOV= 28.8 × 27.0 cm, matrix = 320 × 300, slice thickness = 0.9 mm, voxel size = 0.9 × 0.9 × 0.9 mm, pixel bandwidth = 200 Hz/pix, no of slices = 208, TA = 5:11 min.

Auditory stimulation

Complex tones with five central frequencies were used: 400 Hz_{CF}, 800 Hz_{CF}, 1600 Hz_{CF}, 3200 Hz_{CF}, and 6400 Hz_{CF}

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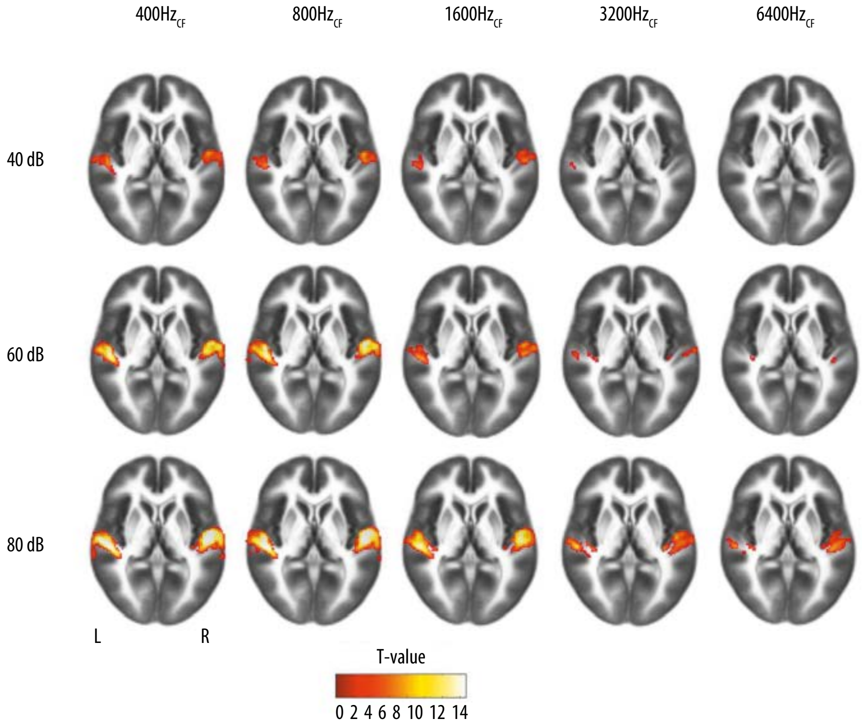

Figure 1a. Results obtained for contrasts of signal (400 Hz_{CF} – 6400 Hz_{CF}) *vs* silence for three sound intensity levels; FWE p<0.05

[19]. Each tone was 8 seconds long and included 80 periods of sound lasting 100 ms (10 ms rise time, 80 ms flat, 10 ms fall time). These 8-s periods were randomly alternated with 8-s periods of silence. Complex tones were used instead of constant and monotonous stimuli which cause faster decline of neuronal responses [19, 21– 25]. One fMRI run was 8:33 min in duration in which each tone and silence were presented 8 times. The order of stimuli presentation was optimised using a Genetic Algorithm (OptimizeDesign, Tor Wager, URL: http://wagerlab.colorado.edu/tools). Each subject participated in three fMRI runs for each sound pressure level, 40 dB(A), 60 dB(A), and 80 dB(A) (nine runs in total). Each single sound intensity was tested on a different day and the order was randomised across subjects.

Sounds were delivered via electrodynamic headphones which attenuated the scanner noise by approximately 20 dB (Confon GmbH). Sound intensity and harmonic distortion were regularly monitored with a GRAS calibration system (Audiometer Calibration Analyzer HW1001). All tones were stored as 16-bit 44.1 kHz digital waveforms. Participants were required to stay still in the bore and listen to the tones. For eye fixation a cross was presented in MRI-compatible goggles.

fMRI data analysis

fMRI data analysis was performed with Matlab and the Statistical Parametrical Mapping package (SPM 12, Wellcome Department of Cognitive Neurology, London, UK).

Pre-processing involved quality assurance and removal of images with spike artefacts or field distortions, estimation of temporal SNR and image intensity correction, slice-timing (adjustment of time series for each slice to the first slice), re-alignment (e.g. head movement correction using three 3D rigid body translations and rotations), scrubbing (additional head movement correction when movement exceeded 0.5 mm between volumes), co-registration of structural images to functional images, segmentation of the T1 structural image into tissue types, normalisation of individual MR T1 images to the Montreal Neurological Institute (MNI) stereotaxic space, smoothing using a 4 mm FWHM Gaussian filter, global intensity normalisation across sessions, and high-pass filtering to remove low-frequency physiological noise and signal drift.

Statistical analysis of individual data (*1st-level analysis*) was performed using general linear modelling (GLM). A GLM model was computed for each person and each fMRI session separately, using pre-processed functional images. For each person onset times of the presented complex tones and silent periods were implemented to the model, followed by model estimation (i.e. a correlation analysis between the time series of neuronal responses, the model series, and the canonical hemodynamic response function in each brain voxel separately). For each intensity level the results were averaged across three sessions. The last step of the individual analysis was designing contrast images (*one-sample* t-*tests*) comparing experimental conditions with one another, i.e. 400 Hz_{CF} *vs* silence; 800 Hz_{CF} *vs* silence; 1600 Hz_{CF} *vs* silence; 3200 Hz_{CF} *vs* silence; 6400 Hz_{CF} *vs* silence. The subsequent group data analysis (*2nd-level analysis*) was performed for the same contrast conditions. All procedures were identical for all three intensity levels, 40, 60, and 80 dB SPL.

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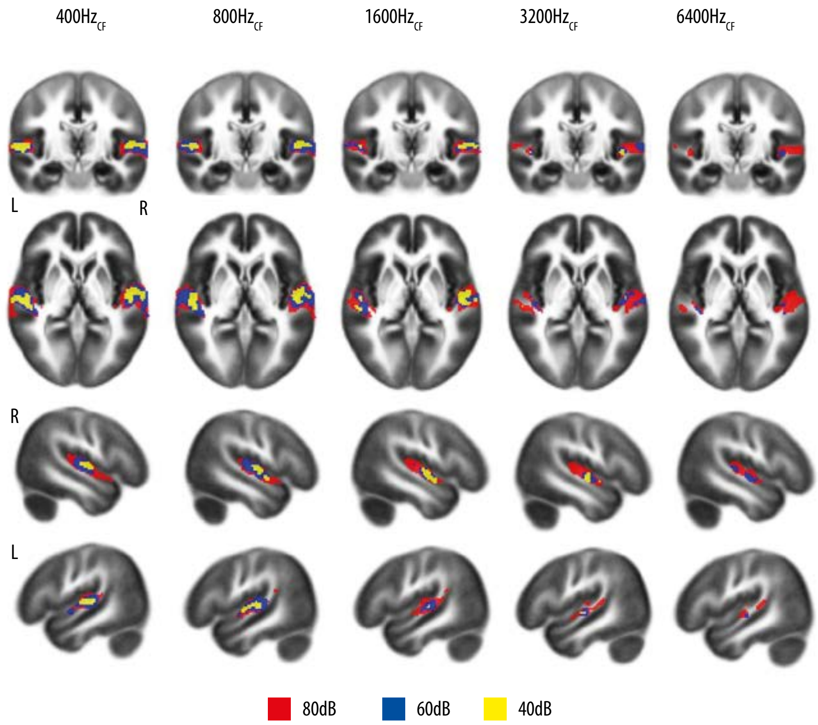

Figure 1b. Results obtained for contrasts of signal (400 Hz_{CF} – 6400 Hz_{CF}) *vs* silence for three sound intensity levels overlaid; FWE p <0.05

RESULTS

Group outcomes of the study are depicted in Figures 1 and 2, as well as in Table 1. The statistical threshold of p <0.05 was assumed with familywise-error (FWE) correction for multiple comparisons unless indicated otherwise [26].

Figures 1a and 1b show group outcomes (*one-sample* t-*tests*) for the five complex tones presented on various days at three intensity levels. Figure 2 plots the relationship between the intensity level and the size of active clusters revealed in auditory cortex. Table 1 includes data complementing Figures 1 and 2. In the table, the anatomical location and size of each active cluster have been listed, together with their maximum t-values and MNI coordinates.

All outcomes indicate that for each sound level and for all frequency ranges, activation was demonstrated in bilateral superior temporal lobes (except for 6400 Hz_{CF} presented at 40 dB which produced no activation above threshold). The cluster of activation corresponding to low-frequency sounds was centered on the lateral surface of the HG. Gradients of high-frequencies broke into small regions along the posterior and anterior side of medial HG. For the 80 dB intensity, and to a limited extent for 60 dB, 3200 Hz_{CF} and 6400 Hz_{CF} frequency gradients bifurcated around HG in a V-shape. The revealed regions included bilateral HG for 400 Hz_{CF} for all three intensities, for 400–1600 Hz_{CF} for 40 dB, for 800–3200 Hz_{CF} for 60 dB and 80 dB, and 6400 Hz_{CF} for 80 dB. In addition, activity in right STP was present for 400–3200 Hz_{CF} when sounds were presented at 80 dB, as well as bilateral MTL for 400–800 Hz_{CF} presented at 80dB. With increasing intensity, the area spread laterally, as well as in the inferior and superior directions in temporal lobes. As shown in Figure 2, the effect was most evident when moving

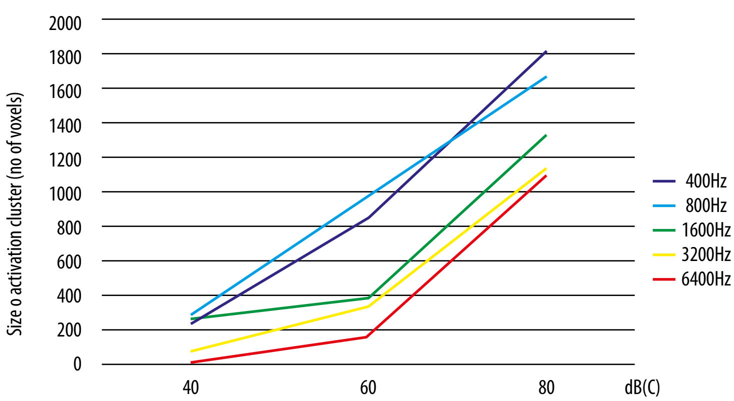

Figure 2. Relationship between sound intensity level (40–80 dB) and active volume size in the auditory cortex. The number of revealed voxels was averaged for both hemispheres across all participants (FDRc, 0.001)

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from 60 to 80 dB SPL – here the slope of the function is steepest. As can be seen in Figure 1b, however, regions showing up for low-intensity sounds were surrounded by regions responsive to high-intensity sounds. Nevertheless, voxels with the most statistically significant activity were localized in similar locations in the superior temporal lobes (see Table 1). There was, furthermore, an overall tendency for the area to diminish as the central frequency of the presented tone increased. This effect was evident for all three sound levels.

DISCUSSION

The study shows that preference of certain regions in the auditory cortex for sounds of low or high frequency is preserved regardless of intensity level. There are two tonotopic progressions shown on the rostral and caudal banks of the HG and for louder stimulation activation is only more extensive and spatially less specific. The location of peak activation is preserved across all intensity levels. Similar outcomes have been presented in fMRI studies by Hart and collaborators (2002) [6] and Sigalovsky and Melcher (2006) [9] who showed the same location of activity for a given frequency range at increased intensity levels with simultaneous spatial expansion of active regions. The high-frequency gradient forming a V-shape around the HG, revealed here for intensities 60 dB and 80 dB, has been reported in numerous papers using the fMRI technique to study auditory cortical responses [1,2,14,18,19,24,25,27–31].

There are several peripheral mechanisms responsible for the central effects of increasing intensity of the perceived sound. Intensity is mainly reflected in the number of impulses per second travelling via the auditory nerve, i.e. the firing rate. For low-level stimulation, i.e. below 40 dB SPL, the responses of the basilar membrane are relatively selective and only low-threshold neurons are involved in afferent sound transmission. In that case synchronous neuronal responses occur only every several sound presentations. With increased sound levels, the travelling wave induces deflection of broader regions of the basilar membrane (spread of excitation). Then larger populations of neurons are recruited and more inner hair cell stereocilia shear, including those beyond the preferred frequency range. Therefore the quantity of produced and transmitted neurotransmitters is higher. Also, at some point (around 40–60 dB HL), low-threshold neurons become saturated. When higher sound intensities are reached, high-threshold neurons also start to participate and increase their firing rates [4,14,25,32–34]. Although the exact relationship is still under debate, proportionality has been suggested between the average firing rate of cortical neurons and the BOLD signal measured with fMRI [35, 36]. Furthermore, it seems that cortical blood flow only becomes saturated at sound levels above 90–100 dB SPL [4–6], which is not the case here. In the current study, significant differences were noted for sound levels of 40 dB and 80 dB SPL, as has also been noted in the literature [6,7,9]. Furthermore, since the effects of increasing sound intensity are also shown within the area of the HG, this would mean that they also involve primary auditory cortex (see the review by Woods and Alain 2009) [8].

The fact that larger areas of activation were revealed for low frequencies, as compared to high frequencies, can also be explained in terms of physiological mechanisms occurring at the basilar membrane. The travelling wave in the cochlea commences at the base and terminates at the apex. Due to the mechanical features of the basilar membrane, a loud tone of low frequency will in addition stimulate nerve endings at the base of the cochlea, specific for high-frequency sounds. Furthermore, the excitation pattern of the basilar membrane is asymmetrical and spreads more to the high-frequency side which is determined by responses of the low-frequency side of auditory filters with central frequencies exceeding the applied signal frequency [34]. Also, auditory filters are broader for low-frequency sounds [38]. With the preferred frequency still inducing largest local deflections on the basilar membrane, these effects are mostly seen for high-intensity sound levels [33,39–44]. A number of fMRI studies employing sound stimulation have revealed larger and/or stronger activations for lower, as compared to higher frequency ranges [8,14,19,27–31].

In addition, the very limited extent of activity found for 40 dB SPL sounds might be related to the fact that fMRI studies are never silent. The sounds of the helium pump and air conditioning system are approximately 70 dB SPL and external headphones can only attenuate the noise by 20 dB. Although the noise of the scanner during data acquisition has been cancelled by using a *sparse* imaging paradigm, some masking of the experimental stimulation cannot be excluded [5,16,37].

The outcomes of the study indicate that fMRI studies of tonotopic organisation of auditory cortex require sound levels of 60–80 dB [4,8,13,18,19,24,25,27,30]. A sound intensity of 60 dB SPL can only be used, however, if a relatively large number of subjects participate in the study. Some authors have already suggested that if sounds below 50 dB SPL are used, statistically significant outcomes are difficult, especially if a stable group effect is to be achieved. The relatively small regions activated by high-frequency sounds, as well as considerable inter-subject location variability, yield a small group effect [4,14]. This has been shown in the current study when sounds were played at 40 dB.

In the presented study, intensity has been used as the sound parameter [19,29,30]. This is the approach used in most tonotopic fMRI studies, as intensity is relatively easy to control. Some authors do not even use any intensity normalisation [13,18,24,25,45,46]. However, it should be noted that, depending on sound parameters such as frequency and time pattern, the *hearing level* and the *perceived loudness* can differ among individuals, which in turn can affect the outcomes of an fMRI study. Several procedures have been suggested to balance study conditions across all participants. One way is to normalise all sounds (frequency bands) to one level, using the individual hearing level (SL, sensation level) [14,47]. Alternatively, perceived loudness is estimated with respect to a pattern sound (such as e.g. 1000 Hz, and then sounds are presented at normalised sound levels (EL, equal loudness) [5,31,48]. Such an approach will be applied in future studies.

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In conclusion, we propose an in-house fMRI paradigm that can be successfully applied to elucidate activation of the auditory cortex in response to a range of frequency bands and intensity levels. The findings confirm the existing literature reports and expand them in that the outcomes are briefly discussed in the frame of psychoacoustic mechanisms. Further recruitment of study participants has been undertaken, including patients with various kinds of sensorineural hearing loss (see Skarżyński et al. (2013) for initial findings in partial deafness) [49]. This will permit the central pathophysiological phenomena occurring in the inner ear to be seen and compared with those from normal hearing subjects.

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