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Review

# Human auditory neuroimaging of intensity and loudness

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## ABSTRACT

The physical intensity of a sound, usually expressed in dB on a logarithmic ratio scale, can easily be measured using technical equipment. Loudness is the perceptual correlate of sound intensity, and is usually determined by means of some sort of psychophysical scaling procedure. The interrelation of sound intensity and perceived loudness is still a matter of debate, and the physiological correlate of loudness perception in the human auditory pathway is not completely understood. Various studies indicate that the activation in human auditory cortex is more a representation of loudness sensation rather than of physical sound pressure level. This raises the questions (1), at what stage or stages in the ascending auditory pathway is the transformation of the physical stimulus into its perceptual correlate completed, and (2), to what extent other factors affecting individual loudness judgements might modulate the brain activation as registered by auditory neuroimaging. An overview is given about recent studies on the effects of sound intensity, duration, bandwidth and individual hearing status on the activation in the human auditory system, as measured by various approaches in auditory neuroimaging.

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## 1. Introduction

The goal of most neuroimaging studies of the auditory system is a fundamental understanding of the transformation of the purely sensory coding of acoustic stimuli in the central auditory system into the actual perception of auditory events, which in the end is the basis for the communication with spoken language or for listening to music. Changes of pitch and fluctuations of the loudness are two basic features in the perception of sound that contribute to the formation of meaning of acoustic stimuli. A large number of physiological investigations have contributed to a comprehensive characterisation of the sensory coding of the corresponding physical parameters periodicity and intensity in the periphery of the auditory system, including cochlea, auditory nerve and brainstem structures (Pickles, 2012). Still, the transformation of sensation into perception at cortical level is much less understood, especially, since non-auditory external and internal factors like the environment as a whole, the particular task or context, or even the personality may contribute to the way we listen to and interpret acoustic stimuli.

According to the classical definition by Fletcher and Munson (1933), loudness is the term used to describe the magnitude of an auditory sensation, ordered along an axis from “very soft” to “very loud”. Loudness is mainly a perceptual correlate of sound intensity (Florentine, 2011). The more intense a particular sound is, the louder it will be perceived. Sound intensity is usually expressed in dB SPL as a sound pressure level on a logarithmic scale relative to a reference pressure, i.e. for a plane wave $L = 20\cdot\log(p/p_0)$ dB with $p_0 = 20$ μPa, or, alternatively, $L = 10\cdot\log(I/I_0)$ dB, if $I$ indicates the intensity proportional to $p^2$. A sound level metre largely provides a measure of sound intensity.

The transformation of sound intensity into a measure of loudness is not straightforward, since the intensity is not the only physical parameter determining the perceived loudness of an acoustic signal. Loudness is also affected by the bandwidth of an acoustic signal, by the duration, by modulations, and possibly many more parameters that give a physical description of a signal (overview in Jestaedt and Leibold, 2011). In addition, there are also many more non-acoustic factors that may influence loudness judgements, if a listener was asked the simple question “How loud is this sound?” These include the procedure itself that is employed to gain loudness judgements (Marks and Florentine, 2011), possible context effects (Arieh and Marks, 2011), but also personal factors

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*Abbreviations:* AC, auditory cortex; BOLD, blood oxygen level dependent; CN, cochlear nucleus; EPI, echo planar imaging; FWE, family wise error; GTS, Gyrus temporalis superior; GTT, Gyrus temporalis transversus; HG, Heschl’s gyrus; IC, inferior colliculus; MGB, medial geniculate body; PAC, primary auditory cortex; PT, Planum temporale; SNR, signal-to-noise ratio; SOC, superior olivary complex; SPL, sound pressure level; TPQ, three-dimensional personality questionnaire

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like hearing status (e.g. Smeds and Leijon, 2011) or even non-auditory factors like, e.g., personality (Stephens, 1970; Ellermeier et al., 2001). All of these effects have been thoroughly studied in many psychoacoustic experiments with a huge variety of judgement tasks and scaling methods (Fletcher and Munson, 1933; Stevens, 1956; Zwicker, 1963; Hellman, 1981; Elberling, 1999; Heeren et al., 2013; for a concise review see Marks and Florentine, 2011). Based on these results, loudness models have been suggested that may help to determine the estimated loudness of a sound based on the acoustic signal itself, and, possibly, the individual hearing status (e.g. Zwicker and Scharf, 1965; Moore and Glasberg, 1996, 1997; Chalupper and Fastl, 2002).

In this article, an overview is given of attempts to learn more about the representation of intensity and loudness in the human auditory system based on results from neuroimaging experiments. While most of the work summarised here has been done with functional magnetic resonance imaging (fMRI), which has evolved as a widely available tool for auditory neuroimaging during the last 15 years, a few results from studies using other neuroimaging modalities (EEG, MEG, PET) are also included in the discussion.

In fMRI, a secondary, metabolic response based on the change of the oxygenation state of the blood is exploited. It can therefore only be considered an indirect measure of neural activation. Still, fMRI has proven to be a very useful tool in auditory neuroscience, with the strength that it provides a high spatial resolution of 5 mm or less, which is required for the anatomical structures of interest. Also the combination of structural and functional MR images gathered in the same session allows for a unique direct link of recorded brain activation maps and the respective anatomical structures involved.

Questions that have been asked in relation to the representation of stimulus intensity and loudness in fMRI activation maps are: (1) Which fMRI signal parameters are correlated with stimulus intensity? (e.g., Hall et al., 2001; Brechmann et al., 2002; Thaerig et al., 2008); (2) What regions in the brain are involved in coding stimulus intensity? (Bilecen et al., 2002; Brechmann et al., 2002; Sigalovsky and Melcher, 2006; Woods et al., 2010; Röhl et al., 2011); (3) From what stage in the auditory pathway can we identify a correlate of the individual loudness, i.e., a measure of perception, beyond the physical sound intensity? (Sigalovsky and Melcher, 2006; Röhl and Uppenkamp, 2012).

In section 2 of this short review, some methodological issues relevant for auditory fMRI in general are discussed, especially with respect to interference by the background noise produced by the scanner itself. In section 3, several fMRI studies are summarized, where stimulus intensity was chosen as one of the independent variables in the design. Most studies demonstrate a systematic change of the MRI signal with sound intensity. Nearly all of these studies have been performed in small groups of young, normal hearing participants. It might therefore be expected that the variability caused by a difference in loudness perception due to different hearing status should be comparatively small. Still, some of the results vary considerably across studies. In section 4, the association of sound intensity and perceived loudness and their correlates in the auditory brain are discussed. We will see that, while sound intensity as a physical parameter has been dealt with quite frequently so far, an analysis of the relationship between fMRI activation maps and individual loudness perception is still a topic which deserves more attention in future studies, especially in hearing impaired listeners. In the final section of this paper, some prospects are given towards possible future applications of auditory fMRI for the assessment of hearing disorders. The main argument here is that the individual degree of impairment due to a hearing loss varies a lot between people, even when the results from audiometric testing would suggest a similar hearing status. We listen with our brain rather than with the ears only. Neuroimaging of the auditory system might therefore help in individualising the diagnostics and to complete our understanding of how an individual hearing impaired person is experiencing his or her environment. This, in the end, should allow for an improved, successful treatment of hearing disorders.

## 2. Methodological issues

One problem with auditory fMRI in general, and with any study using sound levels possibly down to a fairly quiet sound in particular, is the background noise generated by the MRI scanner itself (Hall et al., 2000; Scarff et al., 2004), which needs to be controlled in one way or the other. Most recent auditory fMRI studies have been using echo planar imaging (EPI) sequences with clustered volume acquisition (Edmister et al., 1999) along with the sparse temporal sampling paradigm (Hall et al., 1999), to ensure as little interference by scanner noise as possible. This procedure comes at the price of comparatively long scanning times. It has, however proved very useful in many auditory fMRI studies for a variety of stimulus paradigms (e.g., Griffiths et al., 2001; Gaab et al., 2003, 2007a, b; Langers et al., 2003; Zaehle et al., 2004; Schwarzbauer et al., 2006). A typical repetition time (TR) in sparse imaging would be 10 s up to 16 s to ensure as low interference as possible between the brain responses to the acoustic stimuli of interest and the response caused by the scanner noise (Olulade et al., 2011). However, considerably shorter values of TR have successfully been used in various studies (TR = 7.7 s, Ernst et al., 2008; Röhl and Uppenkamp, 2010, 2012). This increases the efficiency of the use of scanning time, although possibly at the risk of more interference of scanner noise with the stimuli in question. It was recently argued that reducing the TR in a paradigm with clustered volume acquisition down to values of 7.5 s is still advantageous because more stimuli can be delivered within any given period of time. This will increase the number of activated voxels and also the estimated effect sizes in auditory fMRI (Liem et al., 2012). Other approaches to decrease the interfering noise are the use of less noisy MRI sequences for functional imaging, like a gradient echo sequence with long gradient-ramp times (Brechmann et al., 2002; Thaerig et al., 2008) and, obviously, sound attenuating headphones and additional cushions etc. to increase passive damping.

## 3. fMRI studies considering the representation of sound intensity in cortex

The effect of sound intensity on cortical activation maps has been a topic in multiple fMRI studies at least since 1995 (some early studies are Millen et al., 1995; Strainer et al., 1997; Jäncke et al., 1998), i.e., more or less since fMRI has been in use to investigate the human auditory system. In this section, an overview is given about the main findings of those auditory fMRI studies that looked at the activation in primary and secondary auditory cortices as a function of the level of an acoustic stimulus. In some of the studies, the brain activation maps also have been analysed with respect to further aspects, like e.g., tonotopy, or speech and language. In these cases, only the results relevant for the aspect of sound intensity are discussed.

### 3.1. Stimuli

The stimuli employed for analysing intensity effects vary a lot across studies, from tones and tone pulses (e.g. Millen et al., 1995; Bilecen et al., 2002; Woods et al., 2009), FM tones (Brechmann et al., 2002; Langers et al., 2007), complex tones (Hall et al., 2001; Reiterer et al., 2008), noise (Sigalovsky and Melcher, 2006; Röhl and Uppenkamp, 2012), speech or speech-like stimuli (Jäncke

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