Neurophysiological correlates of Somatosensory tinnitus modulation

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Abstract

Background Tinnitus is the subjective perception of a sound without a physical sound source. Neuronal activity in various brain areas contribute to its generation. Research has highlighted somatosensory processes associated with tinnitus. We here investigate if differences in tinnitus perception mediated by the somatosensory system are reflected in brain oscillations.
Methods 24 tinnitus patients performed relaxing versus straining exercises with their jaw. After each condition, participants' brain activity was measured with Magnetoencephalography and participants rated tinnitus loudness and annoyance on visual analogue scales. Brain activity was contrasted for the strained versus relaxed state on sensor level using a cluster-based permutation test. Derived significant clusters were localized using a beamformer approach. Additionally, for every patient and condition a mean loudness and pleasantness score was determined and differences between conditions tested using student's t-tests. *Results* After completion of straining compared to relaxing exercises participants experienced their tinnitus as louder and more annoying ($p<.05$). Tinnitus worsening was accompanied by a significant increase of gamma power (32-46 Hz) showing up mainly in right secondary auditory cortex, and a significant decrease of alpha power (7-14 Hz) peaking in left and right sensorimotor cortex after completion of the straining versus relaxing exercises. *Discussion* We here show that tinnitus perception can be reduced by preceding relaxing exercises with the jaw. Tinnitus improvement is accompanied by reduced auditory gamma power and increased sensorimotor alpha power. These results point to a functional role of the cortical sensorimotor system in maintaining tinnitus.

Introduction

Tinnitus is the subjective perception of a sound without a physical sound source (Lockwood et al., 2002). With regard to the world population, the prevalence of this phantom sound is about 14% and more than 2% have bothersome tinnitus (Jarach et al., 2022). Bothersome tinnitus is attended by severe distress and comorbidities like anxiety, depression, and insomnia and thus impairs the lives of tinnitus sufferers (Cima et al., 2019). The therapy of tinnitus mainly depends on the classification of tinnitus in acute (<3 months), sub-acute (3-6 months) and chronic (>6 months) tinnitus (Cima et al, 2019). For the treatment decision, it is also crucial to differentiate between a compensated (no suffering) and decompensated (bothersome) tinnitus (Hesse, 2016). However, so far there is no effective treatment for the elimination of tinnitus. This lack of a proper therapy is probably related to the deficient knowledge about processes generating and maintaining tinnitus and the changes in brain areas associated with tinnitus (Demopoulos et al., 2020).
It is generally accepted that in most cases tinnitus is caused by hearing loss. This hearing loss is often a consequence of ageing processes or noise exposure (Eggermont and Roberts, 2004). However, the exact pathophysiology is very complex, based on multifactorial influences, and has not been fully clarified. Based on various studies, it is presumed that tinnitus is initially caused by peripheral damage (hearing loss) which triggers plastic brain changes and thus leading to tinnitus (Haider, 2018). Research indicates the association between tinnitus and an increase in spontaneous activity, an increase in burst firing and increased neuronal synchrony

(Wu et al., 2016). Additionally, tinnitus is probably attended by neuroplastic changes, like a shift of the cortical representation of the tinnitus frequency to an area next to the expected localization (Mühlnickel et al., 1998). The important role of brain changes in tinnitus can also be seen in various alterations in neuronal activity. According to this, studies have reported reduced alpha activity in auditory brain regions in tinnitus patients (Lau et al., 2018, Schlee et al., 2014), especially in patients with chronic tinnitus (Weisz et al., 2005). Other studies underline the crucial role of gamma activity. Accordingly, gamma activity in the right auditory cortex is associated with transient hearing loss and tinnitus following music exposure (Ortmann et al., 2011). Furthermore, it is also assumed that auditory gamma activity is the neuronal correlate of the phantom perception (Weisz et al., 2007). Other studies assume that there is a relationship between the loudness of the phantom sound and auditory gamma activity (Van der Loo et al., 2009, Sedley et al, 2012, Balkenhol et al., 2013). Although numerous studies have found evidence for the central role of alpha and gamma activity, other studies also showed changes in the theta (Czornik et al., 2022) and delta (Adjamian et al., 2012) frequency band. In summary, there is numerous evidence that tinnitus is associated with changes in auditory brain areas and different frequency bands, but the exact alterations and the relevance for generation and maintenance of tinnitus are still not fully understood.

However, also non-auditory networks seem to play a role in tinnitus. Thus, brain regions and networks, related to attention processes, memory and emotions are involved in this phantom perception (Shore et al., 2016). As reported by Schlee et al. (2009) there are differences between individuals with chronic tinnitus and a control group in the prefrontal cortex, orbitofrontal cortex, and posterior brain regions. Other studies found differences in the limbic system (Golm et al., 2013, Leaver et al., 2011). Furthermore, also parts of the attention network and default mode network are involved in the perception of tinnitus (Burton et al., 2012). According to Vanneste and de Ridder (2012), the different brain regions are responsible for individual aspects of tinnitus perception and have a specific oscillatory pattern. This is in line with an observation that greater tinnitus related distress (compared to milder forms) was associated with differences in frontal regions in the theta frequency range (Czornik et al. 2022). Furthermore, another study found that tinnitus distress (as measured with the Tinnitus Handicap inventory, THI) is positively correlated with activity in anterior cingulate Cortex, prefrontal cortex and parahippocampus. These differences showed up in the alpha, beta and gamma frequency bands (Mohsen et al., 2019). Despite intensive research, it is still not fully understand what role the individual frequency bands in auditory and non-auditory brain regions play in tinnitus perception.

Rather recent research has highlighted somatosensory processes associated with tinnitus. According to this, a majority of tinnitus patients can manipulate their tinnitus by moving their head and neck (Ralli et al., 2017, Ostermann et al., 2016). Research indicates that there is a connection between functional disorders of the cervical spine, the jaw joints or musculoskeletal structures and ringing in the ears. For this reason, somatosensory tinnitus is now also assumed an independent entity (Algieri et al., 2016). Beyond, even in “normal” tinnitus, modulation of tinnitus by pressure points on muscles and joints is possible in some patients (Biesinger et al., 2008, Biesinger et al., 2015, Levine, 1999). Altogether, tinnitus is more prevalent in tinnitus patients with Temporomandibular Disorders (TMD) and furthermore an increase in severity of TMD symptoms leads to an increase in tinnitus related distress (Algieri et al., 2016). So far, the specific mechanism responsible for the connection of somatosensory processes and tinnitus is

still unclear. Research suggests that the Nucleus Cochlearis seems to be an important hub in the circuitry of auditory and somatosensory information (Marks et al., 2018, Shore, 2011, Shore et al., 2008). Thus, the dorsal cochlear nucleus (DCN) appears to be the place where somatosensory input is integrated into the auditory pathway (Langguth et al., 2019). According to this, an fMRI study was able to show that somatosensory input (protrusion of the jaw) led to increased activity in auditory pathways. Furthermore, this study found significant differences in the Nucleus Cochlearis and Inferior Colliculus when comparing patients with tinnitus and a control group. According to this, the tinnitus group demonstrated an increased response to protrusion of the jaw, presumably because of hearing loss (Lanting et al., 2010). The association between the somatosensory system and tinnitus is also evident as studies show that muscle contraction-based exercises resulted in increased improvements in tinnitus (Sanchez et al, 2007). However, the causal link between somatosensory processes and tinnitus is still unclear and several unsupported theories exist (Skog et al., 2019).

In summary, tinnitus is associated with numerous brain changes. Tinnitus is attended by alterations in various brain areas and frequency bands. The neurophysiological correlates of tinnitus have not yet been fully clarified and further research is needed for a better understanding of the relevant processes. It is still unclear to what extent the somatosensory system has an influence on tinnitus and if such a potential interaction between the sensorimotor and auditory system is reflected in accordant cortical neuronal activity. Therefore, the aim of this study is to clarify if differences in chronic tinnitus perception mediated by the sensorimotor system are reflected in cortical auditory and sensorimotor brain oscillations. We hypothesize that straining and relaxing exercises of the jaw affect tinnitus perception and oscillatory activity in the auditory and sensorimotor areas, and that these effects are still evident after the exercises are completed.

Methods

Participants

Twenty-seven right-handed (one bilateral) volunteers with tinnitus (mean duration 7.9 ± 6.8 years, range 6 months to 22 years) participated in the current study. The measurements took place between October 31, 2019 and March 13, 2020 in the laboratory for magnetoencephalography (MEG, Schwabachanlage 8 in Erlangen). Participants were recruited via flyers posted online on social media. Exclusion criteria were previous neurological diseases and metal in the body that could not be temporarily removed. Four participants had to be excluded due to an excessive amount of artifacts in the MEG data (n = 4). The remaining N = 23 participants (eleven males) had a mean age of 38.5 ± 12.2 years (range 24-61 years). 16 participants perceived their tinnitus bilaterally - two reported left-sided tinnitus and two right-sided tinnitus – (3 missing). All patients were informed about the content of the study, gave their written informed consent prior to taking part in the study and were paid 10 Euro per hour after participation. The ethics committee of the University Hospital Erlangen approved the study.

Experimental Procedure

The experiment described here was one part of an experimental setting with four different tasks in four consecutive blocks (modulation of mood, modulation of jaw exercises on tinnitus and on external sounds). The present study focuses on the second part of the experiment, where participants were asked to perform relaxing versus straining exercises with their jaw. In the following text, we will describe only the parts relevant for the current study.
Participants arrived in the MEG lab, were informed about the study and then gave their written informed consent. After that head position coils (HPI) were placed on points of participants heads. The individual head shapes of the participants were collected with a 3D-digital pen. This pen was also used to mark five anatomical points (nasion, LPA, RPA, Cz, inion) which are necessary as references for later co-registration steps for source reconstruction.
After that, they were positioned supine in the MEG and participants completed different experimental tasks while their brain activity was measured with MEG. In the experimental task described here, participants were instructed to complete relaxing or straining exercises with their jaw for 2 minutes. After completing the exercises of the first condition (relaxed or strained, counterbalanced), participants saw fixated a black cross in the middle of the screen for three minutes while their brain activity was measured with MEG. In addition, participants were asked to rate perceived loudness and pleasantness of their tinnitus on visual analogue scales every minute (loudness scale ranged from 0 to 1 and pleasantness/unpleasantness scale ranged from -1 to 1). After a short break, the second block started (again exercises, fixation cross and rating).
After the actual MEG experiment, participants underwent thorough anamneses, including audiometry, the assessment of perceived stress (PSS; Cohen et al., 1983), tinnitus characteristics (TSCHQ, Langguth et al., 2007), and severity (tinnitus questionnaire, Goebel and Hiller, 1994). Furthermore, participants filled out the sound sensitivity questionnaire (GÜF, Nelting and Finlayson, 2004), the tinnitus handicap inventory (THI, Newman et al., 1996), the hospital anxiety and depression scale (HADS-D, Herrmann-Lingen, Buss and Snaith, 2011) and the symptom-checklist-90®-standard (SCL-90®-S, Franke, 2014).

Data Acquisition

The MEG recordings were accomplished with a 248-channel whole-head-system (Magnes 3600 WH; 4D-Neuroimaging, San Diego, CA, USA) in a magnetically shielded chamber (Vacuumschmelze GmbH, Hanau, HE, Germany). Data were high-pass filtered online at 1 Hz and recorded with a sampling rate of 678.17 Hz. The presentation of visual stimulus material during the MEG recording was controlled using Psychopy (Peirce et al., 2007) and delivered through a projector via a mirror system.
Structural MRIs were acquired using a high-resolution 3 T MRI-System (Siemens Magnetom Trio, Department of Neuroradiology, Universitätsklinikum Erlangen).

MEG Data Analysis

The MEG data was analysed with the "MNE-Python" software version v0.24.0 (Gramfort et al., 2013, https://mne.tools/stable/index.html). The data was first preprocessed and after that, an analysis on sensor level and a source analysis was performed. Furthermore a region of interest analysis was performed. The separate steps are explained in more detail below.

<u>Preprocessing</u>

The raw continuous data were segmented into 1-s epochs and notch filtered at 50 Hz and harmonics to eliminate line noise. Furthermore, data sets were down-sampled to 200 Hz. We then did a visual artifact rejection, removing trials including any visible artifacts due to electromyographic (EMG) noise or technical disturbances. To identify and remove blinks and heartbeat related artifacts we performed an independent component analysis (ICA) using the method "picard"(Ablin et al., 2018). The components were then visually inspected and artifact-components were removed.

Sensor level analysis

Oscillatory activity was contrasted for the strained versus relaxed state on sensor level by computing the power spectral density (PSD) using multitapers (Percival and Walden, 1993) for each experimental condition (tension/relaxation) and applying a cluster based permutation test (Maris and Oostenveld, 2007) for low (1-40Hz) and high (40-90Hz) frequencies separately. Significant clusters in the corresponding frequency bands were then projected to source space.

Source Spectral Power Analyses

Source power was assessed with a beamformer approach using the frequency-domain adaptive spatial filtering algorithm Dynamic Imaging of Coherent Sources (DICS, Gross et al. 2001). First, we calculated a volume conduction model using the FreeSurfer Toolbox (https://surfer.nmr.mgh.harvard.edu/) and the individual MRIs of the participants. The volume conduction model includes the tissues of the head and is necessary for the forward model. In a next step, the surfaces of the inner and outer skull and the scalp were created. These surfaces were then used to calculate the volume conduction model using the boundary element method. In the next step we did a "co-registration" (mne.gui.coregistration()) to transform MEG data and sensor locations in a common coordinate system. For participants without an individual MRI (n= 10) we used a standard brain ("fsaverage") co-registration. After that, we created a surface-based source space for each participant and calculated the forward model. The next step was to calculate the cross spectral density matrix (CSD), using morlet wavelets. Based on the forward model and CSDs we could estimate spatial filters using DICS (Gross et al., 2001). According to the retrieved significant clusters on sensor level, we set the alpha frequency range to 8-14 Hz and the gamma frequency range to 32-89 Hz. We then applied these filters for each frequency band and condition separately to the data. In this way, we obtained power values for the two frequency bands separately for the two conditions. To compare alpha and gamma activity between the strained and relaxed condition we performed a grand average analysis. Furthermore, we analysed significant clusters in more detail using a region of interest (ROI) analysis. Cortical parcellations were derived from the Destrieux cortical atlas (aparc.a2009s, Destrieux et al., 2010). The following regions were analysed for the alpha and gamma frequeny range in both hemispheres: Precentral gyrus, postcentral gyrus, anterior transverse temporal gyrus (of Heschl), lateral aspect of the superior temporal gyrus and middle temporal gyrus (T2). To analyse differences in ROIs between the two conditions tension and relaxation we calculated dependent t-tests for each region and hemisphere with a directed hypothesis. According to the derived clusters on sensor level, we hypothesized that gamma activity is higher with tension and alpha activity is higher with relaxation in corresponding brain regions. The results were interpreted as significant from a p-value of $p < .05$.

Behavioural data analysis

To examine whether there are differences in subjective tinnitus perception, a t-test for dependent samples was used. Therefore, for every patient and condition a mean loudness and pleasantness score was determined and differences between conditions tested using student's t-tests. The results were interpreted as significant from a p-value of $p < .05$.

Results

Behavioural data

Behavioural data was contrasted for the strained versus relaxed condition (**Figure 1**). Mean loudness ratings were 0.52 ± 0.24 (scale 0 to 1) after the straining exercises. After the relaxing exercises, the mean loudness ratings were reduced to 0.47 ± 0.26. This reduction in tinnitus loudness is statistically significant ($p<.05$). Therefore, participants perceived their tinnitus significantly louder in the strained compared to the relaxed condition. A similar observation could also be made for the ratings of the pleasantness of the tinnitus. Mean pleasantness ratings after the straining exercises were -0.23 ± 0.36 (scale -1 to 1) and after the relaxing exercises the mean ratings raised to -0.16 ± 0.41. Participants perceived their tinnitus significantly more unpleasant in the strained compared to the relaxed condition ($p<.05$).

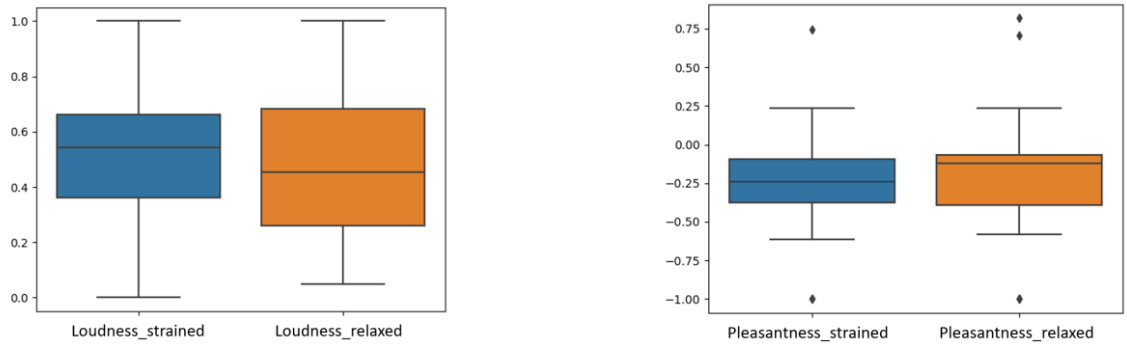

FIGURE 1: Boxplots for the contrast of the behavioural data between relaxed and strained condition. Left side: Boxplots for the perceived loudness of tinnitus for the strained (blue) and relaxed (orange) condition. Participants perceive their tinnitus significantly louder in the strained compared to the relaxed condition ($p<.05$). Right side: Boxplots for the perceived pleasantness of tinnitus for a strained (blue) compared to relaxed (orange) condition. Participants perceive their tinnitus significantly more unpleasant in the strained compared to the relaxed condition ($p<.05$).

Results on sensor level analysis

In sensor level analysis, we found two significant clusters, one for low and one for high oscillatory activity (**Figure 2**). For the contrast between strained versus relaxed state we found in cluster-based permutation tests a significant positive cluster in the frequency range of 32-89 Hz (**A**, cluster $p<.05$). Furthermore, we found a significant negative cluster in the frequency range of 7-14 Hz (**B**, cluster $p<.05$).

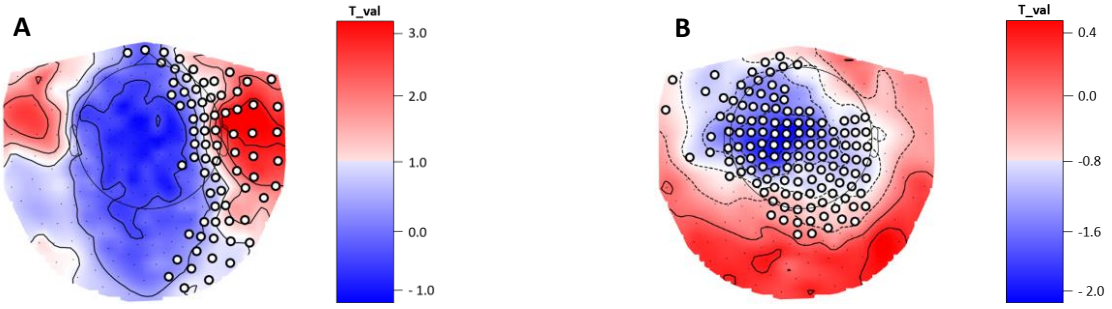

FIGURE 2: Results of the sensor level analysis for high (A) and low (B) oscillatory activity. For the contrast between strained versus relaxed state we found in cluster-based permutation tests a significant positive cluster in the frequency range of 32-89 Hz (cluster p<.05) peaking at right lateralized sensors. A significant negative cluster was found for 7-14 Hz (cluster p<.05) for a group of bilateral central sensors. The white dots represent the sensor positions, which form together a significant cluster.

Results on source level analysis

In the grand average analysis, we were able to locate the significant clusters we found on sensor level more precisely (**Figure 3**). Strained compared to relaxed condition of jaw muscles, is accompanied by increased activity in the gamma frequency range (32-89 Hz). This increase in activity is mainly evident in regions of the secondary auditory cortex and middle temporal gyrus of the right hemisphere. For the alpha frequency range (7-14 Hz) we found a reduction in activity. This reduction is mainly evident in somatosensory and motor cortex in the left and a bit less pronounced in homologous areas of the right hemisphere.

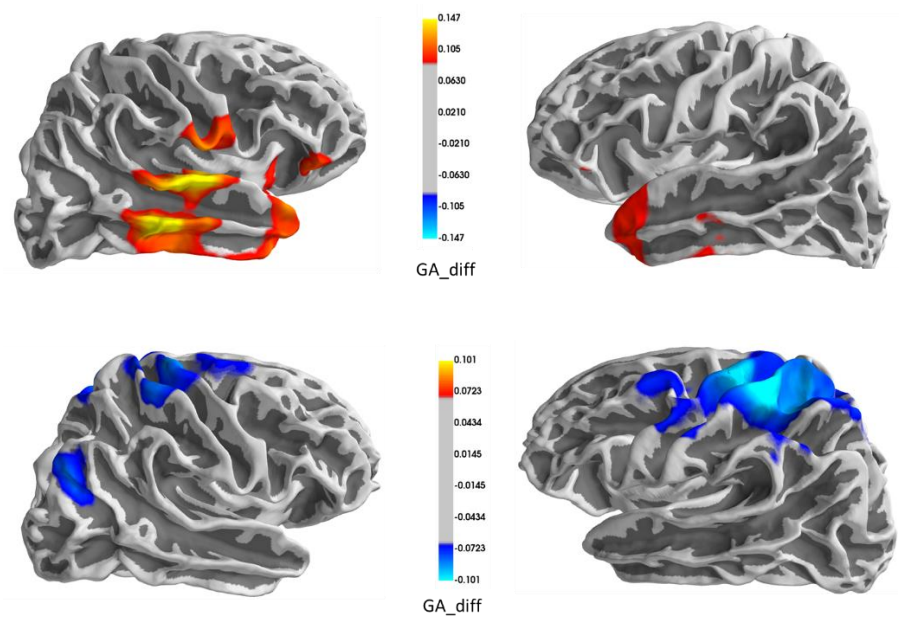

FIGURE 3: Grand average analysis for the contrast between the strained and relaxed conditions for gamma (A) and alpha (B) frequency band. GA_diff is calculated from strained minus relaxed divided by relaxed power values. Strained compared to relaxed condition of jaw muscles, is accompanied by increased activity in the gamma frequency range (32-89 Hz). This increase in activity mainly showed up in regions of the secondary auditory cortex and middle temporal gyrus of the right hemisphere. For the alpha frequency range (7-14 Hz) we found a reduction in activity. This reduction is most prominent in somatosensory and motor cortex in the left and a bit less pronounced in homologous areas of the right hemisphere.

Results of region of interest (ROI) analysis

The results of the ROI analysis (aparc.a2009s atlas, Destrieux et al., 2010) for the comparison of the strained versus relaxed condition support our previous results (**Figure 4**). For the contrast between strained versus relaxed condition, we found in dependent t-tests significant differences in the precentral and postcentral gyri of both hemispheres for alpha activity. Alpha activity was significantly higher in the strained compared to the relaxed condition. For gamma activity, we found significant results in the right hemisphere for the lateral aspect of the superior temporal gyrus (G_temp_sup-Lateral), the transverse temporal gyrus (G_temp_sup-G_T_transv) and the middle temporal gyrus (G_temporal_middle). We also found a significant difference for the left middle temporal gyrus. In these regions, gamma activity was significantly higher in der strained versus the relaxed condition.

ROI_label	t-Test	p-value
Pre_rh_alpha	-3.22	0.004
Pre_lh_alpha	-3.61	0.002
Post_rh_alpha	-3.19	0.004
Post_lh_alpha	-3.70	0.001
Pre_rh_gamma	0.58	0.565
Pre_lh_gamma	-1.46	0.159
Post_rh_gamma	0.90	0.380
Post_lh_gamma	-0.88	0.390
G_temp_sup_Lateral_rh_gamma	3.16	0.005
G_temp_sup_Lateral_lh_gamma	1.88	0.074
G_temporal_middle_rh_gamma	2.96	0.007
G_temporal_middle_lh_gamma	2.26	0.034
G_temp_sup_G_T_transv_rh_gamma	3.24	0.004
G_temp_sup_G_T_transv_lh_gamma	0.11	0.911
G_temp_sup_Lateral_rh_alpha	-1.05	0.306
G_temp_sup_Lateral_lh_alpha	-0.85	0.407
G_temporal_middle_rh_alpha	-0.73	0.474
G_temporal_middle_lh_alpha	-0.44	0.664
G_temp_sup_G_T_transv_rh_alpha	-0.65	0.523
G_temp_sup_G_T_transv_lh_alpha	-1.05	0.304

Fig 4: Results of the ROI analysis (aparc.a2009s atlas, Destrieux et al., 2010). For the contrast between strained versus relaxed condition, we found in dependent t-tests significant differences in the precentral and postcentral gyri of both hemispheres for alpha activity. Alpha activity was significantly higher in the relaxed compared to the strained condition. For gamma activity, we found significant higher activity in the right hemisphere for the lateral aspect of the superior temporal gyrus (G_temp_sup-Lateral), the transverse temporal gyrus (G_temp_sup-G_T_transv) and the middle temporal gyrus (G_temporal_middle) for the strained condition. We also found a significant higher gamma activity for the strained versus relaxed condition for the left middle temporal gyrus. Significant differences between conditions are printed in green ($p < .05$).

Discussion

The present study shows that chronic tinnitus perception is modulated up to three minutes after the execution of relaxing versus straining exercises with the jaw and is accompanied by parallel modulations in cortical oscillatory activity in the auditory and sensorimotor system. In detail, participants experienced their tinnitus significantly weaker and more pleasant in the relaxed compared to the strained condition (both $p<.05$). In line with that, the relaxed condition is

accompanied by a weaker gamma-activation in auditory brain regions, especially of the right hemisphere. These regions comprise the lateral aspect of the superior temporal gyrus, the transverse temporal gyrus and the middle temporal gyrus. We also found a significant difference between the relaxed and strained condition for the left middle temporal gyrus. In addition to the auditory gamma decreases, we disclosed a significant increase of alpha activity in sensorimotor regions, encompassing the precentral and postcentral gyri of both hemispheres, for the relaxed compared to the strained condition. Importantly, the behavioural and neurophysiological effects described were assessed after the actual straining and relaxing exercises (data analysis refers to a time interval of three minutes after the corresponding exercise, behavioural data was measured every minute after the exercises).

Modulation of tinnitus perception by the sensorimotor system

The analysis of the behavioural data showed that participants perceived their tinnitus significantly louder and more unpleasant after the straining exercises. Interestingly, in an interview conducted before the actual experiment (TSCHQ, Langguth et al. 2007), only 8 out of 23 (35%) participants stated that movements of the jaw, head or neck could influence their tinnitus. In other studies, up to 2/3 of the subjects were able to influence their tinnitus with movements of the head or neck (Levine, 1999, Sanchez et al., 2002). However, these manoeuvres were partially performed by an examiner and not by the subject himself. Furthermore, the participants rated during each manoeuvre the loudness of their tinnitus and not, as in our study, after the exercises. In line with our observation was the fact that prior to the exercises, participants were unaware that movements of the head or neck could manipulate their tinnitus. Thus, only 23% of the participants reported that they could modulate their tinnitus by specific movements (Levine et al., 1999). These results suggest that subjects are often unaware of the connection between head, neck or jaw movements and their tinnitus. Perhaps movements in daily life do not seem to have a direct impact on tinnitus or participants do not directly associate movements of their head or neck with changes of their tinnitus. Another study showed also a connection between movements of the jaw and tinnitus, as repeated muscle contraction-based exercises resulted in increased improvements in tinnitus (Sanchez et al., 2007). The importance of the somatic influence on tinnitus can also be seen from the fact that somatosensory tinnitus is now also assumed an independent entity (Algieri et al., 2016). In our study, the connection between the sensorimotor system and tinnitus becomes visible through a direct comparison between relaxing versus straining exercises with the jaw and their influence on perceived tinnitus loudness and annoyance. Our results show that straining versus relaxing exercises indeed had an impact on the loudness and pleasantness of tinnitus, crucially in a sample of chronic tinnitus patients, mostly not aware of any potential sensorimotor influence on tinnitus perception. This finding confirms previous findings (Levine et al., 1999) that exclusive questions about a possible modulation of the tinnitus by certain movements are not sufficient. Most importantly, however, this finding suggests that a relaxing training, involving the jaw muscles, could represent a therapeutic tool, which could reduce tinnitus loudness and annoyance for the majority of chronic tinnitus patients, even though future studies will have to clarify if e.g. repeated interventions will induce longer lasting tinnitus curative effects. This is consistent with the finding that patients with TMD benefit from relaxation or stretching exercises in a way that reduces muscle tension (Sanchez and Rocha, 2011). Furthermore, relaxation exercises are also applied in the therapy of chronic tinnitus, mostly as part of

multimodal therapy such as cognitive behavioural therapy (CBT). Results of a study show that group CBT with different relaxation exercises (muscle relaxation and breath exercises) as on component are effective in alleviating tinnitus-related suffering (Schecklmann et al., 2023). Since relaxation exercises are only one component of CBT, it is difficult to say which component is the key factor in reducing symptoms. In combination with our results, however, this shows that relaxation exercises could be a crucial tool for improving tinnitus symptoms.

Reduced tinnitus perception is accompanied by reduced auditory gamma activity

Relaxing exercises with the jaw did not only lower tinnitus loudness and annoyance, but also had an effect on gamma activity, which was reduced in auditory brain regions, especially of the right hemisphere, after completion of the relaxing compared to the straining exercises. The affected regions comprise the lateral aspect of the superior temporal gyrus, the transverse temporal gyrus (or Heschl's gyrus) and the middle temporal gyrus. We also found a significant difference between the relaxed and strained condition for the left middle temporal gyrus. Importantly, our beamformer approach unambiguously assigned the strongest gamma power differences to right superior and middle temporal areas and not to regions at the bottom of or inferior to the brain, which could have indicated confounding activity from remaining muscle activation. To further rule out the possibility of remaining muscle tension, we assessed electromyography of the jaw within pilot measurements and could not prove any remaining muscle activity and are therefore highly confident that the observed gamma power modulations indeed stem from the auditory cortex. Higher gamma activation in the primary auditory cortex after completion of the strained exercises, when tinnitus was perceived as louder and more annoying, is consistent with results from other studies that revealed increased auditory cortical gamma activity in chronic (Weisz et al., 2007) or acute tinnitus perception (Ortmann et al., 2011, Ginnan et al. preprint). Furthermore, results are in line with other studies showing that gamma activity is associated with tinnitus intensity (Weisz et al. 2005, Van der Loo et al., 2009, Balkenhol et al., 2013). Apart from tinnitus, increased gamma power is generally assumed a neural correlate of sensory stimuli processing (Başar, 2013) and increased auditory gamma power thereby a neural correlate of the processing of acoustic stimuli (Pantev et al., 1991, Galambos et al., 1981). Thus, the gamma increase could be related to a more general processing of the acoustic stimulus, in this case the tinnitus. The significant gamma increase in the lateral aspect of the superior temporal gyrus also match a stronger processing of the tinnitus in the straining condition, since the superior temporal gyrus is associated with auditory processing, especially of sounds (Yi et al., 2019). Furthermore, a study on epilepsy patients was able to show that induced auditory hallucinations and illusions are related to different auditory regions and revealed a connection between the superior temporal gyrus and auditory hallucinations (Jaroszynski et al., 2022). The function of the middle temporal gyrus is not yet clear, but this region is associated with sound recognition, among other things (Xu et al., 2016). Therefore, it is not surprising that these regions are also activated in this study, since tinnitus is also a form of sound processing. In conclusion, our results show an ongoing decrease of gamma power in primary and secondary auditory cortex after the completion of relaxing compared to straining exercises with the jaw, when tinnitus is perceived as weaker and more pleasant.

Reduced tinnitus perception is accompanied by an increase of alpha activity in the sensorimotor system

Most interestingly, besides the auditory gamma power modulations, we found a significant increase of alpha power in the sensorimotor cortex of both hemispheres after completion of relaxing versus straining exercises. An increase of alpha activity has been associated with the inhibition of the respective brain regions in different modalities (Jensen and Mazaheri, 2010), including the sensorimotor cortex (Haegens et al. 2011, Stolk et al. 2019). Alhajri and colleagues (2018) e.g., disclosed that sensorimotor alpha activity is suppressed during, but also after physical practice (Alhajri et al. 2018). This suggests that the alpha power modulations in the current study, which were revealed after completion of the actual exercises, indeed reflect a sustained state of relaxation or contraction resulting from the preceding exercises. The increase of alpha power in the sensorimotor system after the execution of relaxing compared to straining exercises thus points to the ongoing inhibition of that region in the apparently ongoing relaxed state. Such an ongoing inhibition or deactivation of the sensorimotor cortex after relaxing exercises is in line with a finding from Flüthmann and colleagues (2019) who showed an increase in sensorimotor alpha activity during muscle relaxation which they relate to corresponding inhibitory processes (Flüthmann et al., 2019).

We speculate that the increase of sensorimotor alpha power after relaxing exercises leads to inhibition of the sensorimotor cortex, putatively resulting in the suppression of auditory gamma power and tinnitus processing. In contrast, in the strained state, the sensorimotor system is disinhibited, possibly resulting in increased auditory gamma activity and tinnitus processing. Even though this interpretation is speculative and will have to be tested with further analyses using directed connectivity measures, the idea of a direct impact from the somatosensory system on the auditory system and tinnitus is not new. The somatosensory and auditory system are anatomically closely connected (Shore et al., 2011, Marks et al., 2018) and the influence of the somatosensory system on tinnitus receives growing interest (Algieri et al., 2016). Tinnitus seems to be modifiable on a perceptual level through the sensorimotor system (Levine et al., 1999, Sanchez et al. 2007, present study) and somatosensory brain regions contribute to the generation of tinnitus (for review see Shore et al., 2016). The exact mechanisms, however, of how sensorimotor alpha power modulations relate to auditory gamma power modulations and perceived tinnitus have to be clarified in future analyses and studies.

Conclusion

Our findings show that participants experienced their tinnitus significantly weaker and more pleasant after relaxing compared to straining exercises. This implicates that a relaxed state of the jaw goes along with tinnitus improvement and emphasizes that relaxing exercises targeting the muscles in the jaw and probably head and neck area can have a positive effect on tinnitus loudness and pleasantness. Tinnitus improvement was accompanied by a significant reduction of gamma power in the auditory cortex in the relaxed condition after completion of the exercises. Moreover, the preceding exercises were reflected by ongoing condition-specific modulations of alpha power in the sensorimotor cortex, where alpha power was significantly increased in the relaxed compared to the strained condition. We hypothesize that alpha activity in the sensorimotor system, which reflects the sustained relaxed versus strained state of the jaw, modulates auditory gamma power and thereby tinnitus perception. Our results underline the

crucial role of the somatosensory system in generating and maintaining tinnitus, both on a perceptual and neurophysiological level.

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