

Chronic tinnitus is quietened by sound therapy using a novel cross-frequency de-correlating stimulus modulation

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ABSTRACT

We introduce a novel modulation of broadband sounds which eliminates correlations between all frequency pairs close to the tinnitus frequency, to reduce cross-frequency neural synchrony and thereby quieten tinnitus. Fifty-three unselected participants completed a blinded randomised crossover trial, which was run completely online using their computers or smartphones, comparing active to perceptually-near-identical sham stimuli, comprising two 6-week listening periods and 3-week washout periods. Results showed a significant, persisting, reduction in self-rated tinnitus loudness after the active ($p = 0.012$), but not sham ($p = 0.916$) intervention. Tinnitus distress scores decreased in both listening periods, indicating tolerability of the intervention and trial process. Due to its automation, generalisability across tinnitus types, and deliverability with generic hardware, this intervention could be made available to most of the worldwide tinnitus community at minimal cost. Next steps involve optimising the intervention parameters to maximise efficacy, and development of a software package for wholescale delivery.

1. Introduction

Chronic tinnitus is a persistent sound heard by an individual without an environmental source, which affects 10–15 % of the population (Adjamian et al., 2009). Tinnitus can be non-bothersome, but over 20 % of people with tinnitus seek treatment. However, patients with tinnitus tend to find treatments difficult to access and largely ineffective, or misaligned from their main concern; patients mostly want to reduce tinnitus loudness, while majority of available treatments are focused on reactions to tinnitus, as widely-available evidence-based treatments to quieten the tinnitus sound itself are lacking (Carmody et al., 2023; Husain et al., 2018). Due to the large mismatch between the very high prevalence of tinnitus and the much lower capacity of specialist audiology or tinnitus clinics, any treatment aiming to become a mainstay of management should be deliverable either in primary care, or outside of a clinical setting altogether.

Sound-based therapies are attractive as a treatment option for tinnitus due to deliverability with widely available hardware. They are easily accepted by tinnitus patients, for whom external sounds are used to provide relief from tinnitus symptoms (Folmer and Carroll, 2006;

Searchfield and Searchfield, 2021; Wang et al., 2020). Modulated sounds can be used with the goal of reducing tinnitus loudness, with modulations generally tailored to the tinnitus features of each individual, particularly frequency, and aim to alter processes associated with tinnitus causation and maintenance, such as lateral inhibition, cortical reorganisation, pathological central gain or neural synchrony (Angeloni et al., 2023; Auerbach et al., 2014; Eggermont, 2003; Eggermont and Tass, 2015; Haider et al., 2018; Noreña, 2015; Roberts and Salvi, 2019; Sedley, 2019; Shore and Wu, 2019). While some therapies involve concomitant psychological therapy or other forms of in-person treatment (Jastreboff and Hazell, 1993; Vernon, 1976; Vernon and Schleuning, 1978), other types focus purely on modulated sounds. Some examples of sound therapies are described below.

2. Types of sound therapy

2.1. Tailor-made notched music training

Tailor-made notched music training (TMNMT) is a treatment for tonal tinnitus, in which a frequency band surrounding the tinnitus

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frequency is removed from an auditory stimulus (Pantev et al., 2012; Stein et al., 2016). Therefore, it requires accurate estimation of tinnitus frequency conducted by a specialist, and a single tinnitus sound with a clearly defined and consistent frequency. A randomised controlled trial (RCT) and a stratified double blind two-arm study were conducted at different time scales, and the comparison between them showed that 3 months was likely not enough to create a significant effect on self-rated tinnitus loudness scores, while after 12 months the effects were more apparent (Okamoto et al., 2010; Stein et al., 2016). However, researchers reported a considerable number of participants experiencing adverse effects during the study (Stein et al., 2016).

2.2. Enriched acoustic environment

Enriched acoustic environment aims to prevent tonotopic reorganisation by playing high frequency stimuli soon after noise trauma, with matching done under specialist supervision (Noreña and Eggermont, 2005). The difficulty with this treatment is that tinnitus may appear gradually, and patients may not access treatment during initial tinnitus development (H. Wang et al., 2020). Another study found that compensating for hearing loss with this treatment was not beneficial, due to potential worsening of the symptoms if the treatment stimulus overcompensated for hearing loss (Vanneste et al., 2013).

2.3. Broadband noise

The Levo® device is a custom specialised earbud system that plays broadband noise, shaped to the tinnitus spectrum of each patient, while they are asleep (Pedemonte et al., 2014). In an RCT, participants were assigned either the Levo® system with a tinnitus-like stimulus, Levo® with white noise stimulus, or a bedside sound generator device. Audiological testing was performed at a clinic. All participants also received some educational tinnitus counselling. After 3 months of intervention, the tinnitus-like group showed the largest absolute reduction of mean loudness score. This Levo® device is commercially available, costing around \$4500 (Theodoroff Sarah et al., 2017).

2.4. Coordinated reset neuromodulation

In coordinated reset (CR) neuromodulation therapy, a specifically-timed sequence of various short tones is played at frequencies around a precisely matched tinnitus frequency, aiming to desynchronise tinnitus-related neural networks (Tass and Hauptmann, 2009). This method requires patients to have tonal tinnitus. While some randomised studies show positive effects on tinnitus perception after CR neuromodulation therapy, subsequent larger studies have not shown a significant effect on tinnitus loudness (Adamchic et al., 2017; Hall et al., 2022). Due to, in part, inconsistent tinnitus and sample groups (in NICE 2020 clinical evidence summary, CR modulation studies were rated as ‘very low’ quality of evidence), commercialisation of CR neuromodulation has so far not been successful (Tinnitus: assessment and management 2020).

2.5. Auditory discrimination training

Auditory discrimination training (ADT) is based on lateral inhibition, aiming to disrupt neural synchrony (Rodríguez-León et al., 2022). Patients with tonal tinnitus are trained to separate sound frequencies in complex stimuli based around (but not identical to) their tinnitus frequency and learn to re-categorise and ignore the tinnitus sound (Hoare et al., 2010; Rodríguez-León et al., 2022). A comprehensive tinnitus ENT assessment is required. In an RCT, participants completed 20 min discrimination tasks for 30 days (Herraiz et al., 2010). While the Tinnitus Handicap Inventory (THI) (C.W. Newman et al., 1996) score of the ADT groups did decrease significantly after the treatment compared to a waiting list group, tinnitus loudness scores did not improve.

Additionally, a later double-blind RCT showed that training at any frequency, not just around hearing loss frequency, improved Tinnitus Handicap Questionnaire scores, so the ADT resulted in generic, not tinnitus-specific, improvements (Hoare et al., 2012).

2.6. Bimodal therapies

The somatosensory system may be involved in hearing loss-related tinnitus (Hamilton and al., 2016). An example is trigeminal nerve stimulation through an electrode put on the tongue, paired with auditory stimuli particularly at frequencies affected by sensorineural hearing loss, which has been shown to reduce tinnitus impact symptoms according to THI and Tinnitus Functional Index (TFI) scores (Conlon et al., 2020; ; Hamilton and al., 2016; Meikle et al., 2012). However, there was no sham/placebo control group, and participants needed to visit the clinic every 2 weeks.

Bimodal treatment with vagal nerve stimulation was shown to be effective for tonal and non-blast-induced tinnitus in a double-blind RCT (Tyler et al., 2017). But, based on the confidence intervals, treatment and control groups had a lot of overlap in THI scores. Additionally, on average, there was an increase in tinnitus loudness, particularly in the treatment group. A recent systematic review of vagal nerve stimulation trials identified limitations such as adverse effects from implantation, and consequently the effectiveness cannot yet be concluded (Stegeman et al., 2021).

A preliminary RCT compared one group with non-somatosensory sensorineural tinnitus that received sound stimulation alone to another group who received simultaneous sound and transcutaneous microcurrent stimulation applied to the bone behind each ear (Lee et al., 2024). Both groups listened to broadband noise, notch filtered around the tinnitus frequency, through bone-conduction headphones. Participants were assessed by audiologists and trained to use microcurrent stimulation devices in person. After 3 months (though not 1.5 months), both groups showed significant decreases in visual analogue scale (VAS) loudness scores, but the effect size for the simultaneous stimulation group was larger than for the sound therapy only group, though there was no blinding or sham/placebo control.

Combined sound therapy and occipital nerve stimulation is an encouraging sound therapy method for somatic tinnitus (Jones et al., 2023). In a double-blind RCT, patients with tinnitus who had clinical indicators of somatosensory system involvement were split into two groups (active: combined auditory and somatosensory followed by auditory only, or control: the opposite order). Both groups showed reductions in TFI scores, however the combined treatment produced a larger decrease than the auditory only treatment. The tinnitus loudness levels also decreased in both groups; however, the decrease was more significant in the combined group. Moreover, the TFI and loudness level continued to reduce in the combined group through the washout period.

3. Summary

Overall, available sound therapies are not yet showing large average clinical effects in terms of tinnitus loudness. Many work only for specific types of tinnitus, as part of a comprehensive treatment programme involving psychological intervention, need specialised equipment, are expensive, are not fully accessible to the public for various reasons, and/or require in-person accurate matching with the supervision of an audiologist or a researcher. Furthermore, tinnitus frequency matching is unreliable even when performed by expert clinicians and researchers. Therefore, there remains a need both for more effective forms of sound therapy, and for further forms of sound therapy that have similar benefits to existing therapies, but are deliverable cheaply, safely and effectively on a large scale.

3.1. Aims, hypotheses and approach

Our aim was to develop a type of sound therapy for tinnitus that is effective in reducing tinnitus loudness, does not require direct clinician or researcher input, can be delivered with ordinary smartphone or computer equipment and headphones, and can be applied to all subtypes of tinnitus without requiring precise tinnitus frequency matching (but only approximate).

Our novel type of sound modulation was created, aiming to reduce synchrony of neuronal activity in different frequency channels within and surrounding the tinnitus frequency (or frequency range), as neural synchrony models (which are dominant in current theory) suggest that tinnitus results in large part from excessive synchrony between neurons in the auditory pathway (Eggermont and Tass, 2015; Shore et al., 2016). This also accords with the sensory precision model of tinnitus, as sensory precision is most fully understood in terms of a *precision matrix*, which is related to the covariance or correlation matrix across neuronal populations (Hullfish et al., 2019; Sedley et al., 2016; Sedley et al., 2019; Yukhnovich et al., 2023). Stable relationships over time between the activity patterns of multiple different neurons thus increase the precision of that activity, and increase its influence on perception. We hypothesised that disrupting these established inter-frequency relationships in neural populations related to tinnitus (i.e. those representing high frequencies close to the tinnitus frequency) would therefore reduce the perceived loudness of tinnitus (Sedley et al., 2016), and could be achieved by regular exposure to auditory stimuli that contained spectral energy at all these frequencies but no stable correlation between frequencies.

Motivated by (but not contingent upon) these theories, in our novel approach, broadband pitch stimuli were modulated within a one-octave frequency range approximately (but not needing to be exactly) centred on the tinnitus frequency. The two approaches we arrived at are an extension of 1) amplitude and 2) frequency modulation methods (H. Wang et al., 2020), with the additional key feature that either the amplitude or frequency modulation characteristics continuously vary over time, so as to eliminate all net correlations between any frequency pairs (except for each frequency with itself). For the de-correlating sound stimulus, the modulation applied to the sounds was based on a down-sloping dynamic spectral ripple, modified in one additional novel way. Standard dynamic spectral ripples are sound stimuli containing regular temporal and spectral modulations with a limited number of parameters, which result in a spectral ripple drifting in time along the frequency axis. However, these still create high levels of off-diagonal correlation between frequencies, as the time-frequency drifting is constant, and therefore the activity in one frequency band has a highly predictable relationship to current, past and/or upcoming activity in other frequency bands. In our modulation, the spectral modulation rate of the dynamic ripple constantly changed over time (specifically, it was sinusoidally modulated over a one octave range), and through this it was constantly changing the relationships between spectral frequencies, nullifying any enduring correlations.

A third condition, featuring a different kind of sound therapy, was also included, in which frequency-specific noise replacement sound was presented to participants, with the aim to encourage the brain to reduce estimated precision in tinnitus-related frequency channels by removing informational content whilst preserving acoustic spectral energy. Informational content is the complexity profile of a sound segment (Guerrero et al., 2021). This approach differed from the TMNMT approach, which is thought to work by lateral inhibition, and removes acoustic energy also (Pantev et al., 2012).

To understand the tolerability and effectiveness of these three sound types, we compared them to a perceptually similar sham version of the same stimuli (i.e. modulation applied at non-tinnitus frequency ranges) in a blinded randomised crossover trial format. A recent review concluded that there is a need for better controlled, randomised trials in order to identify the most effective tinnitus management techniques,

and the current study design was constructed with this in mind (H. Wang et al., 2020). As this is the first trial using our de-correlating sound modulation, there is no established period of time to eliminate carry-over effects from the first sound stimulus to the second (whether active or sham). Therefore, a three-week gap between the first and second rounds of listening was estimated to provide a reasonable balance of reducing potential carry-over effects, whilst limiting attrition from the study.

Finally, the study aimed to establish the feasibility of running a fully automated online interventional study in which participants with tinnitus were asked to perform daily listening. If successful, such an approach would prove useful not just for testing, and delivering, this form of sound therapy, but a potentially limitless range of other types of sound therapy with much greater numbers than in-lab studies. Importantly, as no direct clinician or researcher involvement was required in the setup or delivery process, any techniques used in this study could potentially be rapidly rolled out on an unlimited scale to both tinnitus patients and to people living with tinnitus who are not patients within a healthcare system, and with little or no cost attached.

4. Methods & materials

4.1. Participants

This online randomised blinded study was fully completed by 77 participants. Volunteers were recruited from affiliated volunteer lists at Newcastle University, via the Tinnitus UK, and via the Tinnitus Talk online forum. Inclusion criteria were being over 18 years of age, with chronic tinnitus for over 6 months that did not have an objective physical source, and ability to make an informed choice about volunteering. Exclusion criteria included having pulsatile tinnitus, or profound hearing loss in the range of the higher frequencies as it was unlikely that the sounds used in this study would have effect on their tinnitus. Participants were discouraged from participating if they had prior experience of their tinnitus being made worse by exposure to moderately loud sounds or environments. No eligibility criteria related to the subtype of subjective tinnitus.

4.2. Ethics & inclusion statement

Recruitment and data collection occurred between October 2020 and April 2022. Approval was given by the Newcastle University Research Ethics Committee, and all participants gave electronic informed consent, in accordance with the Declaration of Helsinki (reference number 11,138/2018). No information was collected about race, ethnicity, national or social origin, sexual orientation, political or religious beliefs, or health conditions unrelated to tinnitus. The study was registered with the ISRCTN registry, reference number ISRCTN18390012.

4.3. Assessment & experimental design

4.3.1. Questionnaires

Participants accessed the information sheet online via Outlook Forms and were able to ask questions to the research team via e-mail if they had outstanding queries. The information sheet contained frequently asked questions. Participants were given an anonymised identifier code to preserve their identity. They could come back to the form again if they wished to think about their participation first. Once they decided to take part, participants signed an electronic consent form. After this, they answered the following questions: gender, any difficulty hearing, any difficulty following a conversation when there is background noise, whether they use a hearing aid or a cochlear implant, age, tinnitus duration, laterality of their tinnitus, type of their tinnitus sound, numerical rating scale (NRS) scores of tinnitus loudness (0 = completely inaudible to 10 = extremely loud) and distress, whether their tinnitus is affected by moderately loud sounds either during or after exposure.

Participants also completed the following standardised questionnaires: Tinnitus Handicap Inventory (THI) (C.W. Newman et al., 1996), Tinnitus Functional Index (TFI) (Meikle et al., 2012) and Hyperacusis Questionnaire (HQ) (Khalfa et al., 2002).

4.3.2. Hearing slope and tinnitus frequency estimation

Before the trial, each participant underwent approximation of their slope of hearing loss (Fig 1) and tinnitus frequency using a procedure involving listening to sound files provided on the study web page, and reporting on the best fitting sound or file (Table 1). Specifically, each hearing loss estimation sound file comprised a series of 17 pure tones in ascending frequency order (frequencies corresponding to the columns of Table 1). Sound files differed according to how much the intensity of tones increased with increasing frequency, with a flat frequency spectrum being the smallest slope ("normal hearing"). Participants were asked to listen to the four different files and choose the file in which all 17 frequencies sounded most similar in volume to each other. Using the same file with 17 tones of different frequencies, participants were asked to select one specific tone that most closely matched their tinnitus frequency (in the case of tonal tinnitus) or select one narrowband noise stimulus from an equivalent series of narrowband noise stimuli for non-tonal tinnitus (Table 1). This process did not need specialist software or researcher/audiologist input.

4.3.3. Trial organisation

Participants were randomly assigned to receive either sham or active sound therapy first, and then crossed over to the other type subsequently (Fig 2). Subjects were also randomised to receive one of three types of modulated sound: 1) Amplitude modulation ($N = 27$), 2) Phase modulation ($N = 26$), or 3) noise replacement ($N = 24$). Each participant received only one type of modulated sound in the study, but both active and sham versions of that type. Interaction with a researcher was by e-mail only, for the purposes of sending the appropriate sound files for the subject's tinnitus match, hearing profile, modulation type and active/

sham phase, and answering questions from participants if applicable (which was rarely required). Automated e-mail prompts to submit daily listening figures and tinnitus symptom data at appropriate times were sent to participants. Participants were blinded as to their group and active/sham stage, and sound files were cryptically named so as to not convey information about their contents. Whilst the researcher had access to information the groups to which participants were allocated, they did not refer to this when corresponding with participants. Overall, we believe the possibility of any degree of inadvertent unblinding to be negligible. In the sham condition, the modulation was applied to a different range of frequencies, usually below their tinnitus frequency (Table 1). The modulations were perceptually subtle, with perception dominated by the carrier stimulus to which it was applied, and feedback from participants was that they could not knowingly differentiate active from sham sounds. Each participant completed the two listening periods (active and sham, 6 weeks each), with 3-week washout periods after each listening period (Fig 2). Before and after each listening period, participants provided an NRS tinnitus loudness score and NRS tinnitus annoyance score, and completed the THI, TFI and HQ questionnaires. Participants were asked to listen to the sounds each day of the listening period and complete a daily listening log via Google Forms where they recorded how long they listened to the sounds for. Participants were not instructed to listen to the sounds for a specific duration per day, though audio files were 60 min long, which provided an implicit cue for listening duration. As with the initial questionnaires and matching process, responses were submitted using Outlook Forms. Specific instructions were given regarding safe listening practices. These included: 1) No more than 60 % of their device's maximum volume; 2) No more than 60 min listening at a time; 3) Leave 60 min break between listening sessions. Participants were allowed to use any sound delivery device (speakers or headphones), and could listen whilst doing other activities, as long as the sounds were audible.

The primary outcome measure was the NRS loudness score, reflecting the intent being to quieten tinnitus itself rather than simply change

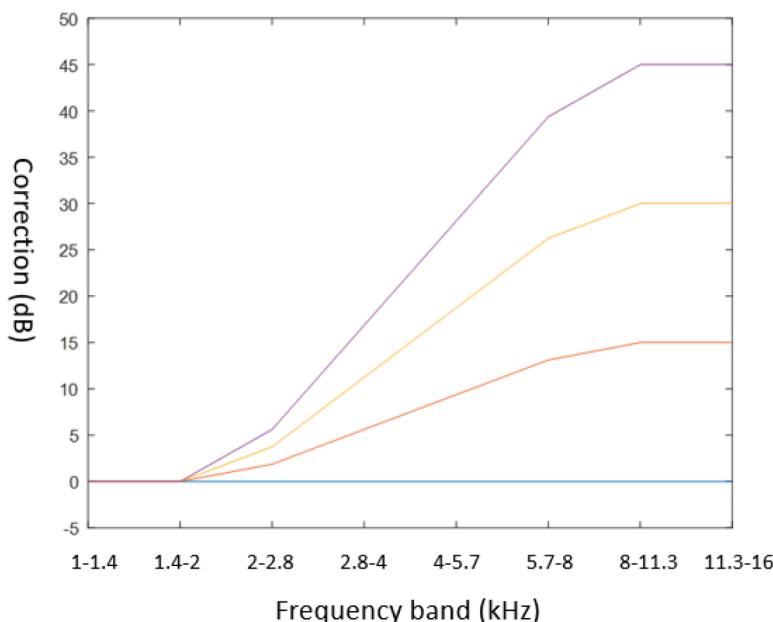


Fig. 1. Hearing correction profiles. Audio files used for hearing estimation and tinnitus matching included 8 sounds at ascending frequencies, from 1 kHz to 16 kHz. The four different frequency profiles are shown here. The blue line represents a normal hearing slope, in which each frequency band was equally loud. The red, yellow and purple curves illustrate the 'mild', 'moderate' and 'severe' hearing loss correction profiles, respectively. These hearing correction slopes were modelled on the same shape, and differed only in the maximal correction (at the highest frequencies): 0, 15, 30 or 45 dB. Correction was 0 up to 2 kHz, 1/9 of maximum at 2.8 kHz, increased linearly to 8/9 of maximum at 8 kHz, and were at maximum above 8 kHz. This profile shape was intuitively determined so as to achieve reasonable high-frequency hearing correction without involving extreme differences likely to lead to inaudibility at low frequencies or discomfort at high frequencies. Each subject's own preferred frequency-intensity correction profile was also applied to their active and sham therapeutic sounds used in the study. This method aimed to correct for sensorineural hearing loss, in which hearing thresholds of higher frequencies become elevated.

Table 1

Selection of active and sham modulation bands based on approximate tinnitus frequency match.

	1–2 kHz	1.4–2.8 kHz	2–4 kHz	2.8–5.7 kHz	4–8 kHz	5.7–11 kHz	8–16 kHz
1.0 kHz	A1		C1				
1.2 kHz	A1		C1				
1.4 kHz	A1		C1				
1.7 kHz	A2	A1		C1			
2.0 kHz		A1		C1			
2.4 kHz	A2	A1		C1			
2.8 kHz		A1		C1			
3.4 kHz		A2	A1		C1		
4.0 kHz			A1		C1		
4.8 kHz	C2	C1	A2	A1			
5.7 kHz		C1		A1			
6.7 kHz	C2	C1	A2	A1			
8.0 kHz		C1		A1			
9.5 kHz		C1		A1			
11.0 kHz			C1		A1		
13.0 kHz			C1		A1		
16.0 kHz			C1		A1		

Each participant selected the best match to their tinnitus frequency from 17 stimuli at the frequencies shown here (tones or narrowband noise stimuli, according to their stated tinnitus type) presented to them in a pre-recorded online file. This gave the researcher an estimation of the tinnitus frequency around which the sound therapy sound file should have the modulation applied. The 17 stimuli were of frequencies corresponding to those in the table. There were 7 possible frequency bands to which modulation could be applied (to serve as either active or sham), indicated by the column titles of the table. The optimal modulation frequency band was selected to place the best tinnitus match frequency as close to the centre of the modulation band as possible. A1 indicates the preferred active frequency band, and C1 the preferred sham frequency band. A contingency option was specified in case either the active or control modulation band contained frequencies the participant could not hear at all (A2 and C2, respectively).

participant reactions to it. A detailed map of the experimental design can be seen in Fig 2.

4.3.4. Therapeutic sound creation

The carrier sounds, to which the active or sham versions of the three modulations were applied, were hour-long sequences of non-overlapping 4 s broadband (spectrum 1–16 kHz) harmonic complexes (flat spectrum unless adjusted to hearing profile), each with randomised fundamental frequency selected from a specific range (96–256 Hz), with 1 s onset/offset cosine ramps. To approximately compensate for sloping high frequency hearing loss, the spectra of the carrier stimuli were either flat, or contained additional energy in the higher frequencies, based on the hearing slope estimation of the individual participant. One of the four frequency correction profiles shown in Extended Data 3 was used for each subject.

Modulations 1 and 2: De-correlating amplitude and phase modulation

Two alternative implementations of the de-correlating modulation were applied (Fig 3–4): as 1) an amplitude modulation (range 0–2, yielding mean 1, i.e. unchanged mean amplitude), and 2) a phase

modulation (range 0 to 2π), constituting phase advancement to a maximum of 1 cycle), the latter being equivalent to a frequency modulation (e.g. phase advancement going from 0 to 1 cycle over one second would be equivalent to a frequency modulation of +1 Hz).

Modulated harmonic complexes were generated as

$$s(t) = \sum_{n_{min}}^{n_{max}} A_n(t) \sin(2\pi n f_0 t + \phi_n + \psi_n(t)), \quad (1)$$

where $s(t)$ is the stimulus waveform at time t (in seconds), n is the number of the harmonic of the fundamental frequency f_0 , min and max refer to the lowest and highest harmonic numbers falling within the range of 1–16 kHz, ϕ_n is a random phase offset per harmonic (range 0 to 2π).

The amplitude modulation term $A_n(t)$ was fixed at 1 for the phase modulation stimuli, and for harmonics outside the modulated frequency band. For amplitude modulated frequencies it was defined as

$$A_n(t) = 1 + d \sin(2\pi[\omega t + F_n S(t)] + q), \quad (2)$$

where d is the modulation depth (1 in our implementation), ω is the fixed temporal modulation rate (1 Hz in our implementation), and q is a random phase offset for each stimulus (range 0 to 2π).

The phase modulation term $\psi_n(t)$ was fixed at 0 for the amplitude modulation stimuli, and for harmonics outside the modulated frequency band. For phase modulated frequencies it was defined as

$$\psi_n(t) = \pi(1 + d \sin(2\pi[\omega t + F_n S(t)] + q)), \quad (3)$$

F_n is the octave distance of the harmonic from the logarithmic centre (c) of the modulated frequency band, calculated as

$$F_n = \log_2\left(\frac{nf_0}{c}\right). \quad (4)$$

$S(t)$ denotes the time-varying spectral modulation rate, defined as

$$S(t) = \mu + r \sin(p + 2\pi\nu t), \quad (5)$$

where μ is its mean (4.5 cycles per oct in our implementation), r is its extent of variability (3 in our implementation), p is a random phase offset (range 0 to 2π), and ν is a constant defining its rate of change (0.125 in our implementation, i.e. a full SMR cycle duration of 8 s).

Stimuli were generated in Matlab (version R2019a), and code for generating all stimuli is available online (see Data Availability Statement).

For readers unfamiliar with Matlab code or the mathematical specification above, an overview of the creation process for each stimulus is as follows:

- Define a vector of time points based on stimulus duration (4 s) and sampling rate (44,100 Hz)
- Define the value of a sinusoidal SMR waveform at each time point (Eq. (5), Fig. 3B)
- Determine a random fundamental frequency (range 96–256 Hz)
- Perform the following steps for each harmonic (integer multiple of the fundamental frequency) falling within the range of 1000 to 16,000 Hz
 - o If it falls outside the modulated range, then simply specify the harmonic as a sinusoid with a frequency of the fundamental frequency times the harmonic number, and a random starting phase
 - o If it falls within the modulated range then calculate its modulation waveform (Eq. (2) for Amplitude or 3 for Phase modulation, or the horizontal row of the modulation matrix in Fig. 3C corresponding to the harmonic's frequency)
 - o For Amplitude modulation within the modulated range, generate the harmonic as a sinusoid with random starting phase, and at each time point multiply it by the modulation waveform

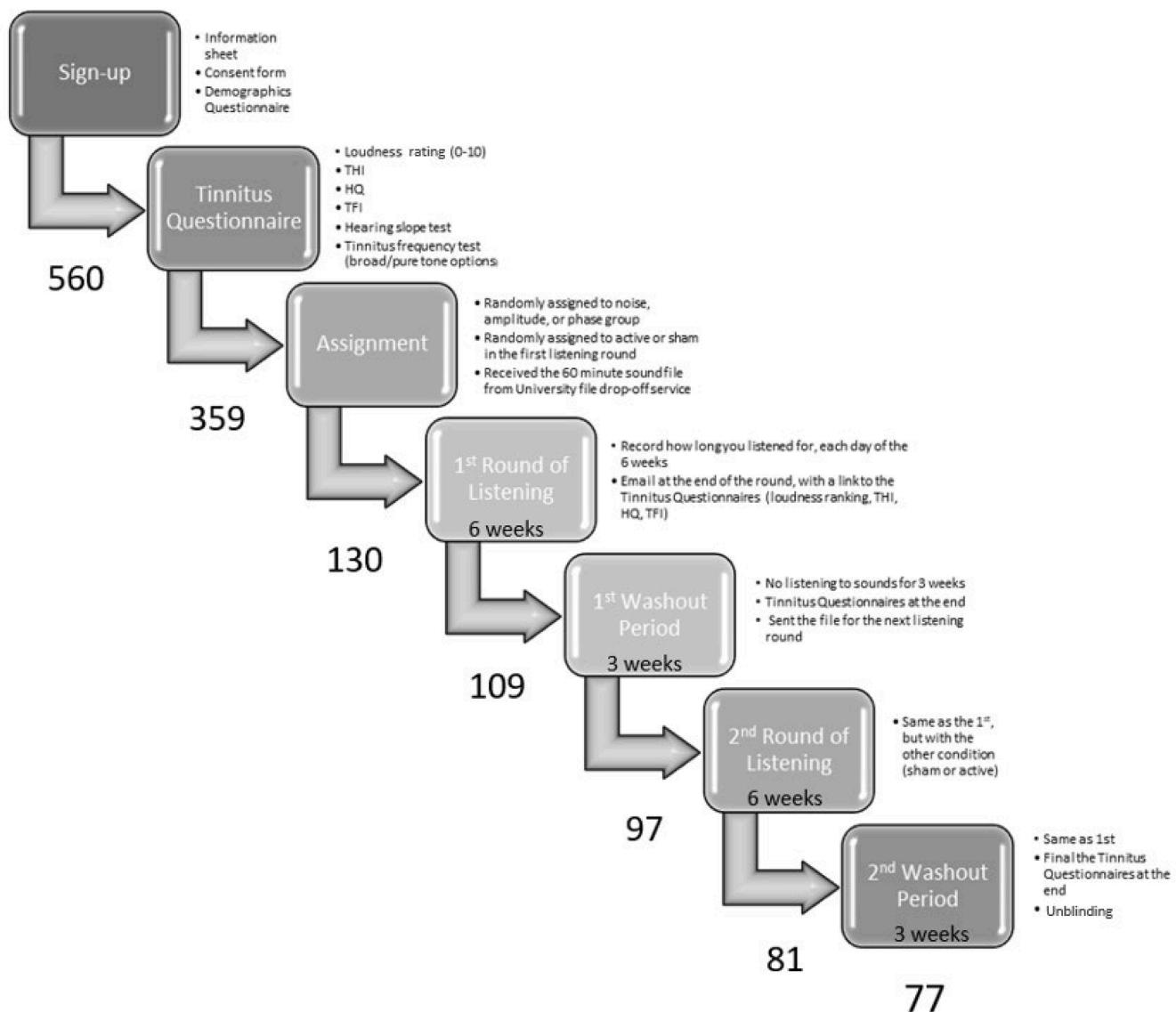


Fig. 2. Study procedure. Under each box, the number of participants who completed that step is indicated.

- For Phase modulation within the modulated range, generate the harmonic according to the formula $\sin(2\pi n f_0 t + \psi_n(t))$, which forms part of Eq. (1). This is simply an ordinary sin function, but with the phase advancement value ψ_n added for each time point t .
- Summate all harmonics at each time point to yield the final stimulus waveform.
- Apply 1 s raised cosine onset and offset ramps

Stimuli of 4 s each generated with this process were then concatenated to produce hour-long audio tracks.

In the amplitude modulation implementation, the amplitude envelopes of any off-diagonal pair of frequency channels were temporally uncorrelated, but temporal fine structure was unaltered. In the phase implementation, amplitude envelopes were unaltered, but phase correlations between frequency pairs were eliminated. We tested both modulations, as we were not aware of any a-priori reason to favour either one of amplitude or temporal fine structure over the other as a determinant or (disrupting) the kind of cross-frequency neural synchrony relevant to tinnitus. The modulations were perceptually subtle and had minimal effect on intelligibility or tolerability of the sounds.

Modulation 3: Noise replacement

To produce the noise replacement sounds, we replaced the

harmonics in the tinnitus band by an octave-wide noise matched to the frequencies in the tinnitus band. This was done to preserve its time-frequency power spectrum whilst eliminating informational content in the form of fine temporal structure. Harmonic complexes were otherwise generated as for modulation types 1 and 2, including organisation into 4 s stimuli with 1 s onset/offset ramps, and concatenation into hour-long audio tracks.

4.3.5. Outcome measures and statistical analysis

The primary outcome measure was a reduction in NRS loudness score, however THI, TFI and HQ scores were also analysed as secondary outcomes. The questionnaire and NRS loudness scores at the beginning of a listening round were compared to the scores at the end of the listening round using paired *t*-tests, in both active and sham. Then, the start score minus the end score value was calculated for each participant in active and in sham, and compared between the two conditions through paired *t*-tests; i.e. the value (*active_pre_treatment* – *active_post_treatment*) compared to (*sham_pre_treatment* – *sham_post_treatment*). This latter analysis, reflecting the difference in post- vs. pre-treatment scores between active and sham conditions, was used as the primary measure of treatment efficacy.

The amplitude and frequency modulation conditions showed near-

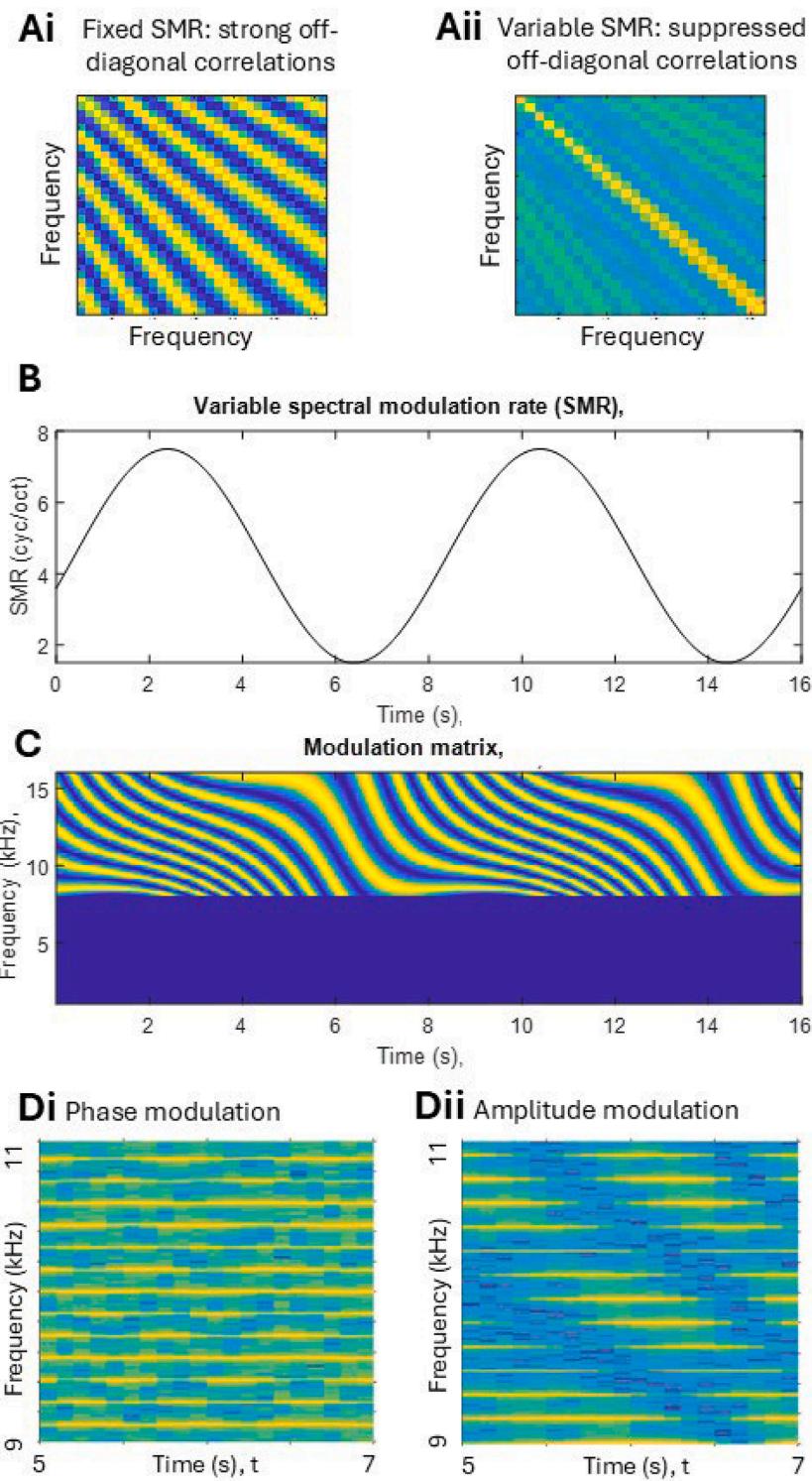


Fig. 3. Basis and examples of novel modulation. Ai: Ordinary dynamic spectral ripples (fixed spectral modulation rate; SMR) maintain strong cross-frequency correlations besides the diagonal (i.e. each frequency's correlation with itself), which are eliminated (Aii) by varying SMR over time (B). C: The spectrotemporal modulation matrix is generated from a fixed temporal modulation rate (TMR) and variable SMR. The colour scale indicates the modulation applied to each time-frequency point in the stimulus, with yellow indicating maximal modulation and blue no modulation. In this example, modulation is applied only to the octave spanning 8–16 kHz, whilst frequencies below 8 kHz are left unmodulated, as indicated by the blue colour (zero modulation). Modulation matrix ripples were down-sloping over time, in our study, due to constraining SMR to only positive values. Di: Magnified section of modulation matrix applied to a harmonic complex stimulus as phase modulation, evident in subtle fluctuations in the frequency of harmonics (horizontal lines). Dii: Section of modulation matrix applied to a harmonic complex stimulus as amplitude modulation, evident in variable amplitude (colour intensity) of each harmonic over time.

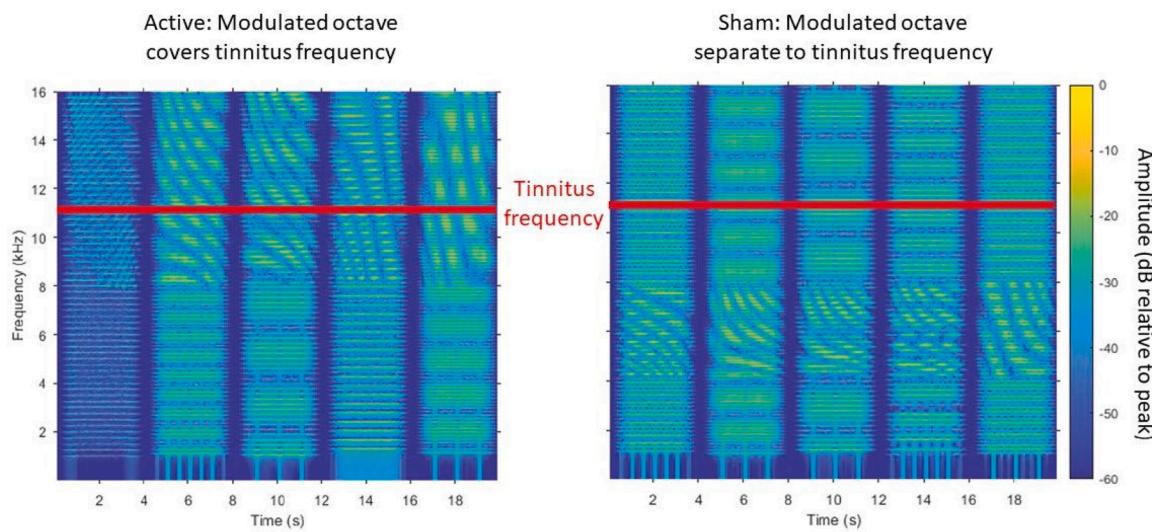


Fig. 4. Stimulus examples (amplitude modulation): Carrier stimuli consist of 4 s harmonic complexes, with 1 s onset/offset raised cosine ramps. Carrier stimuli had random fundamental frequency, and harmonics (horizontal lines) from 1 kHz upwards. Note undisturbed spectrotemporal fine structure and net power spectrum of stimuli, and the tolerance to inexact tinnitus frequency matching, which is widely regarded as notoriously unreliable by any method. Active (left): modulation applied to the predefined octave frequency range (here 8–16 kHz) closest to centring on the approximated tinnitus frequency match (red line, 11 kHz). Sham (right): modulation applied to nearest non-tinnitus octave frequency range (here 4–8 kHz). Because the ripple percept is subtle, it is extremely difficult to tell whether a stimulus is active or sham. Note that in our implementation, an entire cycle of the spectrotemporal modulation was 8 s in duration, whilst carrier stimuli were 4 s in duration; hence, a random portion of the modulation was used for each stimulus.

identical results in all outcome measures, so they were combined for further analysis.

5. Results

5.1. Days missed & average listening times

Demographic, tinnitus and hearing information for all 3 groups is shown in Table 2. Across the 3 modulations, out of the 130 people that started this largely unsupervised online longitudinal study, 77 finished it

Table 2
Participant demographic and symptom information.

	Amplitude (N = 27)	Phase (N = 26)	Noise replacement (N = 24)	Difference between groups
Age	54.33 (31–83)	58.15 (33–75)	57.54 (41–75)	$p = 0.373$
Tinnitus frequency match	1.4–13 kHz, mode: 9.5 kHz (both 18.5 %)	2–17, mode: 8 kHz (19.2 %)	4–17, mode: 8 kHz (25 %)	$p = 0.712$
Gender	8 f, 19 m	10 f, 16 m	9 f, 15 m	$p = 0.764$
Hearing slope match (Fig. 1)	8 NH 9 mild HL 5 moderate HL 5 severe HL	15 NH 6 mild HL 3 moderate HL 2 severe HL	11 NH 5 mild HL 5 moderate HL 3 severe HL	$p = 0.128$
Self-perceived hearing difficulty	10 yes, 17 no	10 yes, 16 no	17 yes, 7 no	$p = 0.028$; sig. dif. between amplitude & noise
Difficulty following conversations	4 yes, 12 no, 11 sometimes	3 yes, 8 no, 15 sometimes	9 yes, 6 no, 9 sometimes	$p = 0.077$
Hearing aids	3 use most of the time, 24 don't have	2 use most of the time, 20 don't have, 4 have but don't use	7 use most of the time, 14 don't have, 3 have but don't use	$p = 0.181$
Which ear is tinnitus in	2 entirely left 9 mostly left 11 roughly equal 2 mostly right 3 entirely right	3 entirely left 8 mostly left 9 roughly equal 3 mostly right 3 entirely right	1 entirely left 7 mostly left 12 roughly equal 2 mostly right 2 entirely right	$p = 0.971$
Is tinnitus affected during noise	17 quieter 8 unchanged 2 louder	17 quieter 5 unchanged 4 louder	13 quieter 10 unchanged 1 louder	$p = 0.876$
Is tinnitus affected after noise	6 quieter 17 unchanged 4 louder	4 quieter 12 unchanged 10 louder	2 quieter 17 unchanged 5 louder	$p = 0.193$
Related health conditions	None	1 acoustic neuroma, and 1 intracranial hypertension	2 antibiotics or other meds, 1 blast injury, 1 acoustic neuroma	

No significant differences were shown by paired *t*-tests between sham and active conditions within each group separately in terms of days of listening missed (amplitude modulation $p = 0.452$; phase modulation $p = 0.125$; noise replacement $p = 0.224$), or by one-way ANOVAs between all 3 groups in either active ($p = 0.068$) or sham ($p = 0.710$) (Table 3).

Table 3
Days missed & average listening times.

	Amplitude modulation		Phase modulation		Noise replacement	
	Active	Sham	Active	Sham	Active	Sham
Days missed	5.56 (5.91)	6.22 (5.61)	3.50 (4.13)	4.85 (4.51)	4.54 (3.51)	5.75 (5.05)
Average listening times	87.70 (82.44)	88.65 (4.93)	66.47 (36.51)	65.23 (33.46)	54.01 (17.60)	54.91 (21.38)

No significant differences were shown by paired *t*-tests between mean durations of listening within groups (amplitude $p = 0.730$; phase $p = 0.734$; noise replacement $p = 0.599$). No significant differences were shown by one-way ANOVAs between groups in either the active ($p = 0.118$) or sham condition (Kruskall-Wallis $p = 0.092$). In all conditions, the data for average listening amounts was skewed to the left, showing that most people listened for around 1 hour a day (note, the sound files sent to participants were 60 min long).

(Fig 2).

5.2. Combined amplitude & phase modulation results

The two novel de-correlating modulation conditions (amplitude and phase modulations) showed very similar results, so they were pooled for analysis (Table 4). While the starting NRS loudness score was on average higher at the beginning of the active condition than the sham condition, they were not significantly different ($p = 0.078$).

The primary outcome measure, NRS loudness score, was significantly reduced in the active condition ($t(52)=2.59, p = 0.012$; $d(\text{repeated measures})=0.51$) but not in the sham ($t(52)=0.106, p = 0.916$) (Fig 5). Moreover, the difference between start and end scores (start score – end score = difference) in active were significantly different compared to sham ($t(52) = 2.26, p = 0.028$) (Fig 6), which was even more evident for the difference between start and end-of-washout-period scores in active compared to sham ($t(52) = 2.61, p = 0.012$). There was a trend towards a further reduction between the start and end of the washout period following the active condition. These differences were also significant in the amplitude modulation group by itself ($t(26)=2.11, p = 0.045$). Note that the group receiving sham treatment second started from a baseline corresponding to the residual effect of active treatment (Fig 7). THI and TFI scores significantly reduced in both active (THI: $t(52)=3.40, p = 0.001$; TFI: $t(52)=2.99, p = 0.004$) and sham conditions (THI: $t(52)=2.77, p = 0.008$; TFI: $t(52)=2.45, p = 0.018$), but there was no significant difference between the reduction following active vs. sham listening. HQ (Khalfa et al., 2002) scores did not significantly change, which showed that listening to the treatment sounds did not affect general sound loudness tolerance of the participants. The results were similar for different hearing profiles and whether the participants

Table 4

Mean and (SD) of each measure at every time point of the experiment in the combined sample.

	NRS loudness	THI	HQ	TFI
A_Start	6.17 (1.89)	42.42 (24.04)	14.23 (7.41)	45.68 (21.69)
A_End	5.70 (1.88)	37.09 (22.28)	14.25 (8.00)	40.82 (19.97)
A_WP	5.62 (2.16)	38.98 (24.25)	14.58 (6.57)	42.05 (21.10)
S_Start	5.83 (1.84)	43.66 (22.76)	14.25 (6.83)	46.71 (18.61)
S_End	5.81 (1.59)	38.91 (21.77)	13.81 (7.70)	42.20 (20.29)
S_WP	6.00 (2.09)	38.68 (22.87)	14.72 (8.08)	42.24 (21.79)

In the time point titles, 'Start' refers to the beginning of a listening period, 'End' refers to the end of a listening period, and 'WP' refers to the end of the washout period in which participants did not have any daily listening. The prefix 'A' indicates that the title refers to the active condition, whereas the prefix 'S' refers to the sham condition. For example, S_WP means the end of the washout period after the sham condition. NRS = numerical rating scale (0–10). HQ = Hyperacusis Questionnaire.

indicated having pure tone or broadband tinnitus (Table 5).

5.3. Noise replacement results

The average outcome measure scores at each time point are shown in Table 6.

There was a significant difference between start and end NRS loudness scores in the sham condition ($t(23)=2.135, p = 0.044$), which was not seen in the active condition ($t(23)=-0.89, p = 0.381$). However, this was not sustained throughout the washout period. THI scores reduced by 6 points in the sham condition and were unchanged in the active condition. The difference between the start - end scores in active compared to sham was also significant ($t(23)=-2.14, p = 0.043$). No other measure showed significant differences between start and end, or in the differences scores between active and sham.

6. Discussion

Overall, our novel cross-frequency de-correlating stimulus modulation had a significant effect in reducing tinnitus loudness over 6 weeks of regular listening, in a broad and unselected real-world tinnitus population, and this reduction persisted for at least a further 3 weeks of no listening. This was not seen in the sham condition, which indicates a specific effect of the novel modulation. Furthermore, our results indicate an overall positive influence of this stimulus on reaction to tinnitus presence through the mean reduction in THI and TFI during both active and sham conditions, and through dropout rates between starting and completing the regular listening phases of the trial being favourable for an online study. Unexpectedly, the noise replacement stimulus modulation showed significant tinnitus loudness reduction in the sham but not active condition, but this reduction was not sustained during the washout period.

The method in the current study allows for a more inclusive treatment than existing sound therapy approaches. Many previously mentioned methods have been aimed towards tonal tinnitus, whereas in this study, the effects apply both to tonal and noise tinnitus types, and regardless of the underlying cause of tinnitus (Adamchic et al., 2017; Stein et al., 2016, 2021). Additionally, many approaches require regular visits and possibly extensive counselling, which can present a language barrier (Vieira et al., 2011), increase cost, and limit availability of treatment only to specialist centres. This also excludes people who cannot easily travel or take time away from their daily activities. For example, trigeminal nerve stimulation required clinic visits every 2 weeks while others required extensive initial testing and/or weekly counselling meetings (Hamilton and al., 2016; Jones et al., 2023; Krick et al., 2015; Lee et al., 2024). Therefore, the pure online therapy would be much more accessible to adults from a variety of working and nationality backgrounds, geographical locations, and mobility restrictions.

The majority of existing sound therapies need input of specialists to carry out precise tinnitus matching (e.g. (Adamchic et al., 2017; Pedemonte et al., 2014)). In the current study, the tinnitus tone and hearing slope matching was entirely unsupervised, and while participants chose a frequency that best matched their tinnitus, this was a subjective process without expert supervision and therefore it is not possible to know whether or not tinnitus frequency matching was accurate. Therefore any resulting inaccuracies might have, if anything, reduced the effect sizes seen in the data. However, research shows that self-guided 'multiple choice method', which was comparable to our matching process, has similar reliability compared to a more conventional 'method of adjustment' (Santacruz et al., 2023). 'Model of adjustment' method had high test-retest reliability and participant pitch-match satisfaction (Neff et al., 2019). Additionally, one study concluded that pitch matching in a lab and at home produced similar results (however, the method in this study was different to one used in our current study) (Lentz Jennifer and Liu, 2025). Our significant findings show that the approximate, online process can be successful despite any inherent inaccuracies in tinnitus

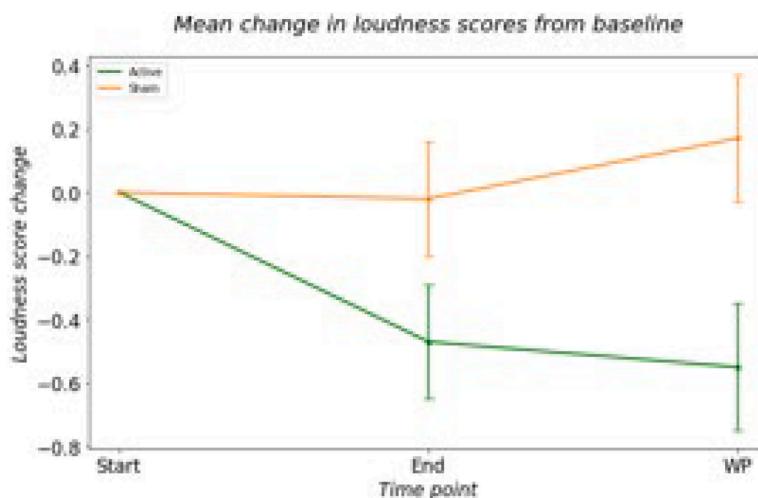


Fig. 5. NRS loudness score change from the original score at different timepoints. Relative change in mean loudness scores from a baseline (0.0) at the start of each type of condition is shown. Error bars indicate standard error of the mean.

matching, and therefore proved to be a strength of the procedure. Subsequent improvements in the unsupervised tinnitus frequency matching process will be carried out in order to increase the efficacy of the method.

While it is not possible to directly assess why the THI and TFI scores reduced both in sham and in active conditions of the de-correlating stimuli in our study by similar margins regardless of condition order (around 5 points in each questionnaire in each condition), the THI and TFI improvement may perhaps indicate an overall positive effect of participating in sound therapy. This is important for the feasibility of automated online studies, as it indicates that there is a net beneficial placebo effect, even without direct communication with a researcher or clinician. There is also a possibility that despite the different fundamental frequencies of pre- and post-dip stimuli, the slow rhythmicity of the off- and on-ramps within the structure of the stimuli could have produced a slow beat percept. This percept may have contributed towards an overall relaxing effect of the stimuli, and partially underlie the changes in THI and TFI scores.

However, the THI or TFI improvement effect was not found in response to the active noise replacement stimuli. This sound therapy condition also had shortest daily listening amounts and had more participants who had self-perceived hearing difficulty or struggled to hear in daily conversations (indicating higher possible amounts of hidden hearing loss), which may point towards either to being less pleasant than other conditions, requiring longer daily listening to have a therapeutic effect, or being limited in the amount of therapeutic effect that could be gained due to the modulations of informational content not being transmitted to the central auditory system by the potentially more dysfunctional peripheral hearing system. Alternatively, a potential explanation for the ‘sham’ condition having more therapeutic effect could be that attention was brought to the stimulus frequency region that was missing informational content, thereby increasing its weighting or precision in auditory processing. Thus, the ‘active’ version would cause overweighting of tinnitus-frequencies, and the ‘sham’ version increased weighting of non-tinnitus frequencies.

While the overall experiment in the current study was 18 weeks, the active condition only lasted 6 weeks. This is one of the shorter time periods in which a longitudinal sound therapy experiment has taken place, and in this context the magnitude of tinnitus loudness reduction of 0.47 on a 10-point scale from the de-correlating sound stimuli is relatively large. Aside from an ADT study, which lasted 30 days (Rodríguez-León et al., 2022), other studies were all considerably longer than ours, lasting from 10 weeks to 12 months. The ADT study showed a non-significant effect on loudness (0.5 on a 10-point scale), following a

daily 20 min active auditory discrimination task. While the current study lasted longer, the effects were somewhat stronger and the listening could be done alongside other activities, thus likely having much greater acceptability and long-term utilisation. The next shortest study was the 10-week trigeminal nerve stimulation experiment (Hamilton and al., 2016), in which an equivalent of 0.62 on a 10-point scale loudness reduction occurred. This is a slightly larger effect on loudness than in the current study but was not measured against a sham/placebo group, and requires frequent visits, placements of electrodes on the tongue, and expensive devices. The 12-week CR neuromodulation study in which participants listened to sounds for a similar amount of time a week to the current study resulted in a non-significant reduction of 0.45 on a 10-point scale, which is less effective than our stimulus. The Levo® system study also lasted 12 weeks, with many hours of listening per night, and did lead to a reduction of 1.00 (absolute reduction, not compared against sham treatment), however this system is also largely inaccessible due to its high price. The TMNMT study lasted 12 months and showed an impressive reduction of 25 % by the end of the experiment. However, it is not certain whether this is reliable, as the study had 8 participants per group. Additionally, a larger cohort study lasting 3 months did not see a significant reduction in loudness, therefore it would be preferable to carry out further longitudinal experiments into this method. Overall, at this stage of testing, our de-correlating stimulus shows similarly, or more, efficacious results than the previous studies, is based on larger numbers and more rigorous control groups than most comparable methods, and is unique in its complete non-reliance on clinician or researcher-involved methods or bespoke hardware, thus giving instant and almost unlimited scale of delivery. With further research, we will aim to increase clinical efficacy of the loudness reduction effects of the de-correlating stimulus sound therapy method.

A minor limitation of the study is that the length of listening each day was not controlled. The amplitude modulation showed the highest amount of listening compared to other types. However, potentially higher amounts of average listening may indicate better tolerability of amplitude modulation compared to phase modulation. Nevertheless, the data indicated that the majority of participants listened for around 1 hour a day. Furthermore, it is important for the sounds to be beneficial at a realistic range of daily listening amounts as this would allow for greater world applicability, due to varying everyday responsibilities and lifestyles.

There was a reasonable retention rate for online studies of sound therapy. This study took 18 weeks overall, with 12 weeks of involving listening for 60 min on average. In previous studies where 6–12 weeks were dedicated to tinnitus therapy, the dropout rate was between 14 %

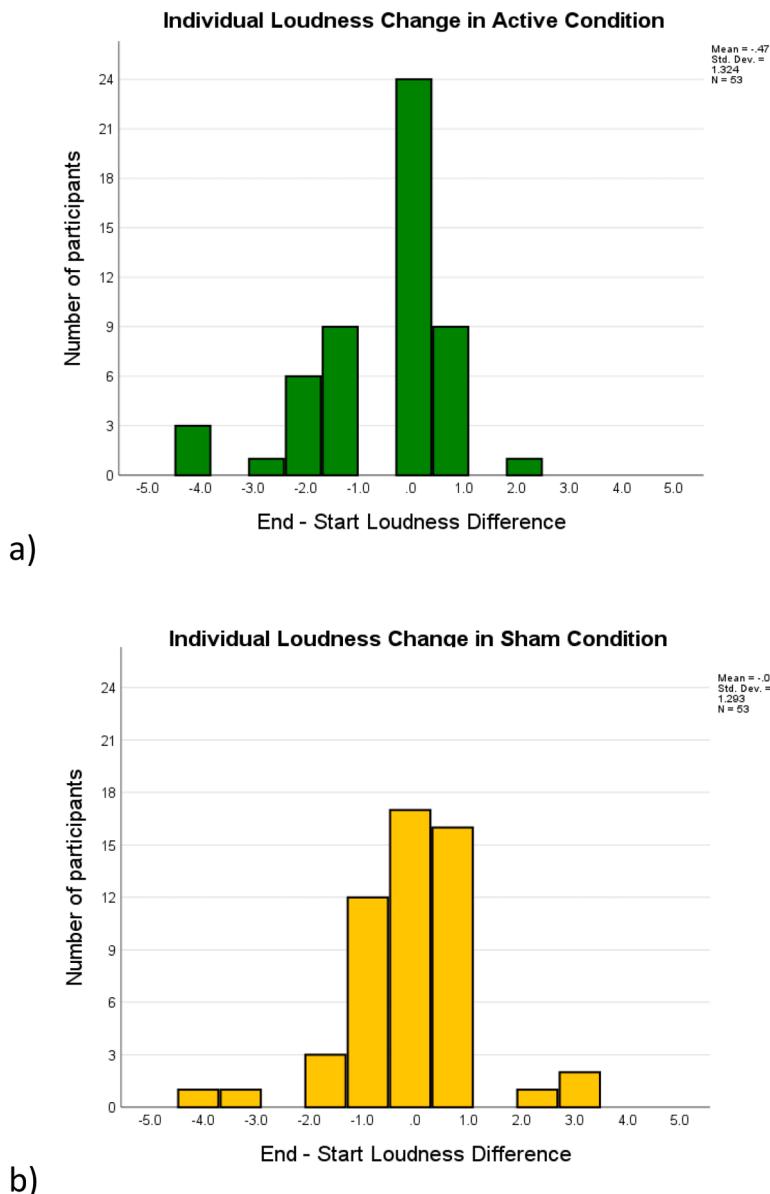


Fig. 6. Individual loudness change in active and sham (amplitude and phase modulation) stimulus conditions. A) represents the difference (end – start = difference) in NRS loudness score of each participant who completed 6 weeks of listening to the active version of amplitude/phase modulation. B) represents the difference in NRS loudness score of each participant who completed 6 weeks of listening to the sham version of the de-correlating stimulus.

and 28 % (Stein et al., 2016; Conlon et al., 2020; Jones et al., 2023). The current study has a slightly higher dropout rate (Fig 2), but the study was completely online whereas in the other 3 examples, participants needed to come in for initial assessments, which potentially motivated them to be more determined to finish the study. In the current study, the majority of dropouts occurred soon after receiving the first sound file. After this, the retention rate was very high.

Our next steps will be to improve tolerability and pleasantness of the sounds, and to investigate how we can maximise the tinnitus loudness reduction. For example, further research is needed to understand how long the effects can last after finishing the listening periods, and what is the optimal length of listening both daily and for the overall treatment course. There is presently no evidence that tinnitus loudness reduction reaches a plateau within the 6 weeks listening period we tested, whilst there is evidence that the effect endures for at least 3 weeks after that. Our results showed that at the end of the three week washout period after a listening period to the active condition of the de-correlating stimulus, the mean NRS loudness score continued to change.

Therefore, it is possible that some carry-over effects were present in the sham condition results when it came second after the active condition. It may therefore be the case that considerably larger reductions naturally occur on prolonged listening to the active de-correlating sound therapy, and for a longer period of time than measured in this study.

Additionally, there are many free parameters of both the carrier sounds as well as the de-correlating modulation itself that can be modified to potentially increase efficacy, and we have tested only one parameter combination so far. These include the range, and rate of change of modulation rates for either type of modulation (amplitude and phase), and also the bandwidth in which the modulation is applied. For instance, as well as tonotopy (organisation by frequency), the central auditory pathway is organised by periodotopy (temporal modulation rate), in which it is sensitive to modulations up to at least 256 Hz (Brewer and Barton, 2016), contrasting with maximal rates of less than 10 Hz we used. Therefore, large proportions of neuronal assemblies in the auditory pathway might be targeted, which our present implementation was not able to recruit. Additionally, if the phase modulation

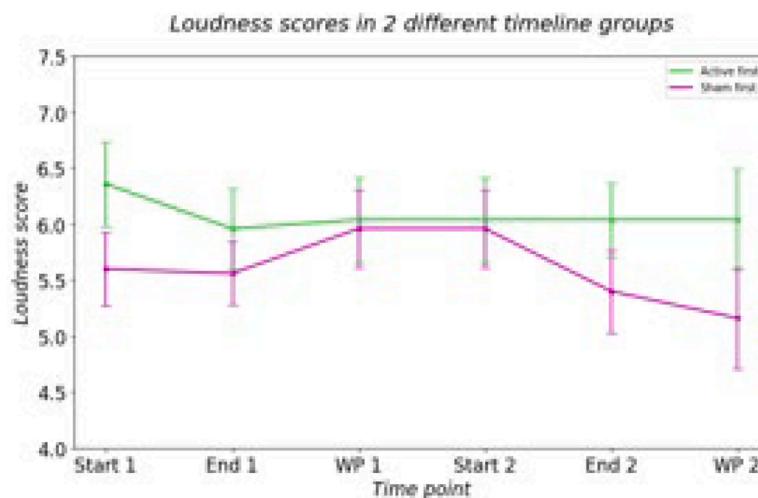


Fig. 7. Raw NRS loudness score change at different timepoints. The mean absolute scores collected from participants who either started with the active condition, or those who started with the sham condition. Error bars indicate standard error of the mean.

Table 5
Tonal vs non-tonal NRS loudness results.

	Tonal (N = 20)	Non-tonal (N = 33)
A_Start	6.15 (1.95)	6.18 (1.88)
A_End	5.55 (1.88)	5.78 (1.90)
A_WP	5.60 (2.19)	5.63 (2.18)
S_Start	5.60 (1.76)	5.97 (1.90)
S_End	5.50 (1.61)	6.00 (1.58)
S_WP	5.75 (1.92)	6.15 (2.20)

In the time point titles, 'Start' refers to the beginning of a listening period, 'End' refers to the end of a listening period, and 'WP' refers to the end of the washout period in which participants did not have any daily listening. The prefix 'A' indicates that the title refers to the active condition, whereas the prefix 'S' refers to the sham condition.

Table 6
Mean and SD of each measure at every time point of the experiment in the noise replacement sample.

	NRS Loudness	THI	HQ	TPI
A_Start	5.50 (2.21)	29.17 (14.65)	15.83 (8.89)	39.35 (20.72)
A_End	5.50 (2.49)	30.67 (16.11)	16.50 (8.77)	39.77 (21.97)
WP_A	5.38 (2.57)	30.17 (16.39)	16.29 (9.41)	40.85 (24.86)
S_Start	5.33 (2.43)	36.42 (20.29)	16.54 (7.71)	43.73 (24.13)
S_End	5.08 (2.67)	30.83 (18.67)	16.17 (8.64)	38.23 (24.51)
WP_S	5.46 (2.64)	29.17 (17.42)	16.13 (8.91)	39.95 (22.53)

In the time point titles, 'Start' refers to the beginning of a listening period, 'End' refers to the end of a listening period, and 'WP' refers to the end of the washout period in which participants did not have any daily listening. The prefix 'A' indicates that the title refers to the active condition, whereas the prefix 'S' refers to the sham condition.

is considered a frequency modulation, then the limit of modulation need not stop at 2π , which constitutes a very small frequency modulation, but could go orders of magnitude higher. Furthermore, amplitude and phase modulations are not mutually exclusive, but could be combined, with either the same modulation ripple, or separate orthogonal ones. Therefore, by systematically exploring these parameters, we may be able to greatly increase the efficacy of our novel stimulus. Neuroimaging studies will likely be necessary to determine the mechanisms through which the de-correlating sound stimulus may influence tinnitus loudness. Iterations of such studies may help determine which parameters are crucial in improving clinical relevance of this sound therapy stimulus.

Furthermore, while synthetic harmonic complex sounds (with little intrinsic listening appeal) were used for this experiment, they do not necessarily need to be the modulation carrier. The modulation could be applied across a range of natural or synthetic sounds that have sufficient high-frequency content. Importantly, the reaction and potential benefit from the sound sequences used in sound therapy can be individualistic, depending on the emotions elicited by the sounds (Searchfield et al., 2017). Therefore, a potential next step could be to apply the modulation to already well-tolerated music/sound sequences that the participants enjoy, thus allowing for an even more personalised approach.

Automated online sound therapy is feasible for longitudinal tinnitus treatment studies. Moreover, our novel cross-frequency de-correlating amplitude and phase-modulated sounds show promise in reducing perceived tinnitus loudness. Once optimal parameters and efficacy are determined, the treatment can be made freely available on an unlimited scale to the tinnitus community, and iteratively improved by the low-cost-low-burden running of large automated online randomised controlled trials.

CRediT authorship contribution statement

E.A. Yukhnovich: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation. **S. Harrison:** Conceptualization. **N. Wray:** Writing – review & editing, Conceptualization. **K. Alter:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation. **W. Sedley:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

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Data availability

Data is available using the following DOI:<https://doi.org/10.25405/data.ncl.27109693>.

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