Sound comparison of seven TMS coils at matched simulation strength

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Abstract

Background: Accurate data on the sound emitted by various transcranial magnetic stimulation (TMS) coils is lacking.

Methods: We recorded the coil sound waveforms of seven coils. We estimated the neural stimulation strength by measuring the induced electric field and applying a strength–duration model to account for different waveforms.

Results: At typical resting motor threshold (RMT), sound pressure level (SPL) at a distance of 25 cm varied 87–111 dB(Z) across coils and the sound duration ranged 1–16 ms. At maximum stimulator output and 5-cm distance, SPL is estimated to be 110–139 dB(Z), and a 10-Hz-train of repetitive TMS (rTMS) would produce a continuous sound level of 87–109 dB(A).

Conclusions: The sound of all tested coils was below, but near, relevant safety limits. The safety standards may be inadequate for risks specific to TMS. Therefore, we recommend hearing protection during TMS.

Highlights

1. Coil click varies by 24 dB(Z) between different TMS coils for matched stimulation.
2. Sound pressure level can exceed 120 dB(Z) even at 25 cm from TMS coil.
3. Close to TMS coil, sound pressure level may reach nearly 140 dB(Z).
4. For rTMS, continuous sound level may reach nearly 110 dB(A).
5. Hearing protection is recommended during TMS, especially rTMS.

Keywords

Transcranial magnetic stimulation, coil click, sound, stimulation strength

Introduction

Transcranial magnetic stimulation (TMS) activates cortical neurons by electromagnetically inducing an electric field (E-field) pulse with a coil placed on the subject's scalp. In addition to the desired E-field stimulation, the pulse causes mechanical vibrations in the coil, producing a brief but very loud sound—often referred to as TMS coil click [Counter & Borg, 1992; Goetz et al., 2015].

The sound pulse can potentially cause hearing loss. This risk can be mitigated with adequate hearing protection [Pasqual-Leone et al., 1992; Tringali et al., 2012; Kukke et al., 2017], but should the hearing protection fail, TMS can cause permanent hearing loss [Zangen et al., 2005]. The sound also evokes unwanted neural activation that deteriorates the specificity of TMS and confounds functional brain imaging data [Nikouline et al., 1999], which can be only partially mitigated with noise masking [Ter Braack et al., 2015].

Due to these side effects, the TMS safety consensus group suggested in 2009 that "the acoustic output of newly developed coils should be evaluated and hearing safety studies should be conducted as indicated by these measures" [Rossi et al., 2009]. Since then, specific stimulator–coil combinations have been evaluated with hearing-safety measurements [Tringali et al., 2012; Kukke et al., 2017], and at least one comparison between coils has been published [Dhamne et al., 2014]. To address methodological limitations of the latter, namely sound level measurements intended only for non-impulsive sounds based on IEC 61672 [Goetz et al., 2015], and expand the range of compared devices, we conducted measurements of the coil click in a total of seven coils for three stimulators and normalized the stimulation strength across the various configurations. Moreover, we interpret the results for single pulses as well as for repetitive TMS (rTMS) in the context of various hearing safety standards.

Material and methods

TMS devices

We tested three stimulators with seven different figure-of-eight coils. The model information of the tested stimulators and coils is provided in Table 1.

Sound recording

The microphone was pointed at the center of the head-side of each coil at a distance of 25 cm (see Supplementary Fig. S1B). We sampled 10 pulses per intensity at 10% to 100% of maximum stimulator output (MSO) in 10% steps. The pulses at each intensity were separated by an interstimulus interval between 2–3 s. To isolate the coil click from sound originating from the stimulator, the coils were placed inside a soundproof chamber (Model 402.a; Industrial Acoustic Company, USA). To suppress echoes in the recordings, the relevant chamber interior walls were covered with 50-mm thick open cell foam pads. The sound was captured with an omnidirectional pressure microphone (Earthworks M50, Earthworks Audio, USA), which had a flat frequency response from 3 Hz to 50 kHz, connected to a high-input-level-capacity preamplifier (RNP8380, FMR Audio, USA) and an audio interface with a sample rate of 192 kHz (Behringer U-Phoria UMC404HD, Behringer, Germany). To convert the digital signal into pascals, we calibrated the system with a 1-Pa reference sound pressure source (Extech Instruments 407722, Extech, USA).

Sound processing

In processing the raw audio, the first pulse at each intensity was excluded as an outlier, since it deviated from the subsequent pulses for all devices especially at low stimulator outputs. The signal was low-pass filtered at 60 kHz to remove high-frequency readout noise, and high-pass filtered at 60 Hz to remove low-frequency

sounds which mostly originated from the air conditioning. The cut-off frequency for the latter filter was selected post-hoc, as none of the coils produced sound that deviated from the background noise at any frequency below 100 Hz. The high- and low-pass filters were fourth-order Butterworth type applied in both forward and reverse time, resulting in flat response frequency response (within 1 dB) from 80 Hz to 50 kHz. For these data, we computed the peak-to-peak sound pressure level (SPL) in a 0.2 s window around the pulse, the duration of the sound impulse defined as the period for which the sound pressure was within 20 dB of its peak value, and 1/3-octave spectra with `poctave` function (Matlab R2018a, Mathworks, USA). In addition, to estimate the non-impulsive sound level due to rTMS, we synthesized 10 seconds of rTMS sound as a superposition of individual pulses and computed the A-weighted (slow time weighted) sound level with `splMeter` from the Audio Toolbox (Matlab R2018a, Mathworks, USA).

Estimation of stimulation strength

To compare the sound between different coils, which provided different stimulation waveforms and MSO, we normalized their stimulation strengths as follows. First, we measured the induced electric field (E-field) in an 85-mm spherical head model [Deng et al., 2013] with a triangle-loop probe [Ilmoniemi, 2009; Nieminen et al., 2015]. The E-field was sampled at 100 MHz with an oscilloscope (Tektronix MDO3054, Tektronix, USA). To obtain the effective stimulation strength, the E-field waveform was digitally low-pass filtered with a time constant of 200 µs, corresponding to the approximate strength–duration time constant in primary motor cortex [Barker et al., 1991; Peterchev et al., 2013; Goetz et al., 2014]. The stimulation strength, defined as the absolute peak of the filtered waveform, was then scaled relative to the average resting motor threshold (RMT) by denoting 100% RMT to correspond to 50.3% MSO for the Magstim 70mm Double Coil driven by a Magstim Rapid biphasic stimulator [Kammer et al., 2001]. Based on the variance of RMT across individuals, for about 95% of subjects, the individual RMT should lie between 75–125% of this value [Kammer et al., 2001].

Sound spectrum weighting and safety limits

Choosing an appropriate safety limit for TMS sound is not straightforward: In addition to the common limit of 115 dB(A) time-averaged steady-state sound level for short daily exposure [OSHA1; OSHA2; OSHA3; ACGIH], we must also consider the impulsive nature of the sound, which is similar to a small explosion, e.g., shooting a firearm, in terms of duration and peak intensity [Peterchev et al., 2015]. Consequently, measurement protocols for such sounds should provide good reference for the measurement protocol of TMS sound. Several safety standards give an instantaneous SPL limit of 140 dB, but with either unspecified frequency weighing [OSHA1; OSHA2], A-weighting [OSHA3], C-weighted [ACGIH], or Z-weighting [MIL] (for frequency weightings, see Supplementary Fig. S4). The A- and C-weighing only limits the sound in the hearing range (as they are defined only up to 20 kHz). With these, the limits for potential near-ultrasound content has to be considered separately. However, the relevant standards do not contain such separate impulsive limits, but only limits for continuous sounds of various durations, varying between 75–110 dB at 20 kHz and 110–115 dB at 25 kHz or above [Duck, 2007]. To avoid the need for two separate metrics, we use the Z-weighted 140 dB peak SPL from MIL STD 1474E [MIL], which also imposes a constraint on the impulsive near-ultrasound content.

Results

Coil electric field and stimulation strength

The peak E-field at 100%-MSO varied between 140–260 V/m across the tested coils, and it had nearly linear relationship to the stimulator output setting for all coils (Fig. 1A). The pulse durations varied between 176–353 µs and were largely stable across the output range of the devices except for the NeuroStar iron-core coil,

which had about 19% longer pulse at 10%-MSO than at 100%-MSO (Fig. 1B). Consequently, for all but the iron-core coil, the devices showed an approximately linear relationship between the output setting and the estimated stimulation strength (Fig. 1C).

Coil sound characteristics

At a distance of 25 cm, the seven coils had a wide range of peak SPL, 96–125 dB(Z) at 100% MSO and 90–114 dB(Z) at the estimated 120% RMT, with the MagVenture MRi-B91 being the quietest and the MagVenture C-B60 being the loudest (Fig. 1D). The peak SPL varied approximately proportionally to the energy of the TMS pulse (Supplementary Fig. S2). There were three distinct click types: very brief and sharp (1–2 ms) from conventional MagVenture coils; medium length (6–7 ms) from NeuroStar coil and Magstim 70mm Double Coil, and long (> 10 ms) from the MagVenture MRi-B91 coil and Magstim AirFilm Coil which have double casing (Fig. 1E). For most coils, the sound duration was comparable across stimulation strengths. For Magstim AirFilm Coil, the pulse duration decreased from 35 ms to 9 ms when the stimulator output was increased from 20% MSO to 100% MSO. All coils produced broad sound spectra with their loudest peak varying between 1–8 kHz and spectrum extending up to 30 kHz (Fig. 2).

The non-impulsive sound for simulated 10-Hz rTMS at 120% RMT ranged 68–88 dB(A), with NeuroStar being the loudest and MagVenture MRi-B91 remaining the quietest but with a much smaller margin than in peak SPL data (Table 2). Due to the observed scaling law for SPL and brevity of the coil clicks: increasing the stimulation strength by 20% or doubling the repetition rate increases the sound level by approximately 3 dB. We validated the latter for frequencies up to 100 Hz, where the sound levels are 10 dB higher than the values shown in the table.

Discussion

Our measurement setup mostly followed the suggested measurement procedures in MIL STD 1474E [MIL], which considers impulse sounds, such as from explosions, which are similar in their characteristics to the coil click. We measured the far field sound, at a distance larger than the characteristic dimensions of the TMS coil. Our microphone was placed at 25 cm away from the center of the coil, compared to the typical coil–ear distance of about 10 cm. We chose this distance to avoid either (1) having to sample the spatial distribution of the sound or (2) underestimating the SPL due to measuring near a nodal point of a standing wave pattern in the near field [Goetz et al., 2014; Goetz et al., 2015]. The sound pressure from TMS coils decays approximately inversely to the distance down to 5 cm [Starck et al. 1996], which suggests that the typical SPL at 5 cm and 10 cm from the coils is respectively about 14 dB and 8 dB higher than the SPL measured at 25 cm. Thus, the peak SPL of the seven coils can be estimated to range from about 98 to 122 dB(Z) at 120%-RMT at 10 cm from the coils. The 24-dB difference between the coils is preserved with this scaling; it is comparable to the typical attenuation obtained with simple hearing protection, even if we do not consider that the hearing protection does not reduce the bone conduction of the sound. Considering the extreme cases we can estimate, single pulses at 100%-MSO and 5 cm from the coils produce SPL of 110–139 dB(Z).

As with the sound of single TMS pulses, there were large differences in the time-averaged steady-state sound levels of pulse trains for rTMS. Extrapolating to a 10 cm distance, a 10 Hz rTMS train has a sound level of 76–96 dB(A) at 120% RMT. At 5 cm distance and 100% MSO, the sound level would reach 87–109 dB(A). The OSHA limit for non-impulsive sound level is 115 dB(A) for short durations (< 15 min) and degrades to 85 dB(A) for longer exposure (up to 8 hours) [OSHA1; OSHA2]. Our estimated sound levels are below the OSHA limit for short-duration non-impulsive sound (with the possible exception of very high repetition rates, e.g. 100 Hz used

in magnetic seizure therapy), but may exceed the longer duration limits, relevant for either longer rTMS trains or multiple rTMS session within one day. Moreover, the rTMS sound is not a non-impulsive sound; therefore, these limits have to be interpreted with caution.

In this dataset of commercial stimulators and coils, all coils had most of their sound in the hearing range. All coils, however, also had considerable amounts of sound in the 20–30 kHz range. To fully capture the sound, we recommend measuring the sound to at least 30 kHz, which is much higher than the 8 kHz or 16 kHz bandwidth available in common sound level meters compliant with Class II or Class I of IEC 61672 (even if the meter supports measurement of peak SPL in addition to the time-averaged steady-state sound level of said standard).

The previous comparison between TMS devices used a sound level meter with a slow temporal response and a measurement bandwidth of only 8 kHz [Dhamne et al., 2014], which is not sufficient for impulsive sounds. In contrast, we obtained much higher sound pressure levels, and, for the three coils common in these two studies, a different order. At 100% MSO and 25 cm distance in our study, the Magstim 70 mm Double Coil, MagVenture Cool-B65, and NeuroStar coils registered at 107, 112, and 116 dB(Z), respectively, whereas these coils produced only 90.2, 78.3, and 82.7 dB(A), respectively, in the prior study despite the smaller measurement distance of 10 cm [Dhamne et al., 2014]. Specifically, the Magstim and MagVenture coils were respectively 17.2 dB and 34.0 dB louder with the wide-bandwidth impulse sound measurement at 25 cm, and these numbers are estimated to rise to 25.2 dB and 42.0 dB extrapolating the loudness at a matched distance of 10 cm.

On the other hand, compared to the previous peak SPL measurement using a head phantom [Kukke et al., 2017], we obtained lower SPLs for the same coil (Magstim 70mm Double Coil, 107 dB(Z) in free field versus 127.6 dB(C) in the ear canal). This difference is only partially explained by the smaller distance between the ear and the coil. We believe that the main factor is the ear canal model itself, which mimics the fact that the pressure levels in the ear are higher than the free field pressure levels [Shaw, 1974], which their GRAS RA0045 microphone attempts to mimic between 0 and 10,000 Hz (and has a narrow +32 dB resonant peak outside that measurement range at 13.5 kHz) [GRAS]. The 140 dB limits, however, are defined for free field SPL.

Given our measurements and previous measurements [Kukke et al., 2017], the impulsive sound levels from a single TMS pulse should have limited risk to hearing, even without hearing protection. However, at extreme settings, the sound of single pulses can come close to the safety limits. Further, conventional acoustic measurements of TMS coils do not address the sound conducted through the skull. Moreover, even a simple mapping of the motor cortex contains several hundred pulses—more than many other impulsive sound sources. rTMS exacerbates these issues by delivering high-frequency pulse trains. rTMS does not fully fit into the description of impulsive sounds, defined as, for example, at most one impulse per second [OSHA3]. Regardless, rTMS can come close to both continuous and impulsive sound limits. Further, the maximum-allowed-exposure limits [OSHA1; OSHA2; AGCIH] are only a guide to safe exposures, and not a well-defined limit to guarantee safety [AGCIH] (i.e., one should reduce exposure well below the maximum limit, if possible). Finally, rTMS has caused permanent hearing loss [Zangen et al., 2005]. Considering all this, we recommend hearing protection for persons near operating TMS coils, and we consider this essential for the TMS subject.

Conclusion

The commonly used TMS devices have large differences in their sound levels at matched stimulation strength. The sound of all tested coils was below, but near, relevant safety limits. The safety standards may be inadequate for risks specific to TMS. Therefore, we recommend hearing protection during TMS.

Conflict of Interest

L. M. Koponen, S. M. Goetz, and A. V. Peterchev are inventors on patents and patent applications on TMS technology including technology for quiet TMS. S. M. Goetz has received research funding from Magstim Inc. A. V. Peterchev has received research and travel support as well as patent royalties from Rogue Research; research and travel support, consulting fees, as well as equipment donation from Tal Medical / Neurex; patent application and research support from Magstim; as well as equipment loans from MagVenture, all related to TMS technology.

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Tables and figures

Table 1. The tested TMS stimulators and coils from Magstim (UK), MagVenture (Denmark), and Neuronetics (USA): Our Magstim 70mm Double Coil had the old type Magstim connector and was connected to the stimulator with Magstim adapter (P/N 3110-00). We used the "standard biphasic" pulse of the MagVenture MagPro X100 incl. MagOption.

Stimulator	**Coil**
Magstim Rapid2 (P/N 3013-US)	70mm Double Coil (P/N 9925-00)
	AirFilm Coil (P/N 3910-00)
MagVenture MagPro X100 incl. MagOption (P/N 9016E0731)	Coil C-B60 (P/N 9016E0482)
	Coil Cool-B65 (P/N 9016E0491)
	Coil MC-B70 (P/N 9016E0564)
	Coil MRi-B91 (P/N 9016E0661)
Neuronetics NeuroStar TMS Therapy System (P/N 81-00315-000)	NeuroStar (P/N 81-00900-000)

Table 2. Sound level for 10 Hz rTMS at 25 cm from the coil.

Coil	**Sound level at 120%-RMT (dB(A))**	**Sound level at 100%-MSO (dB(A))**
Magstim 70mm Double Coil	72	81
Magstim AirFilm Coil	82	87
MagVenture C-B60	84	95
MagVenture Cool-B65	75	83
MagVenture MC-B70	76	94
MagVenture MRi-B91	68	73
NeuroStar	88	93

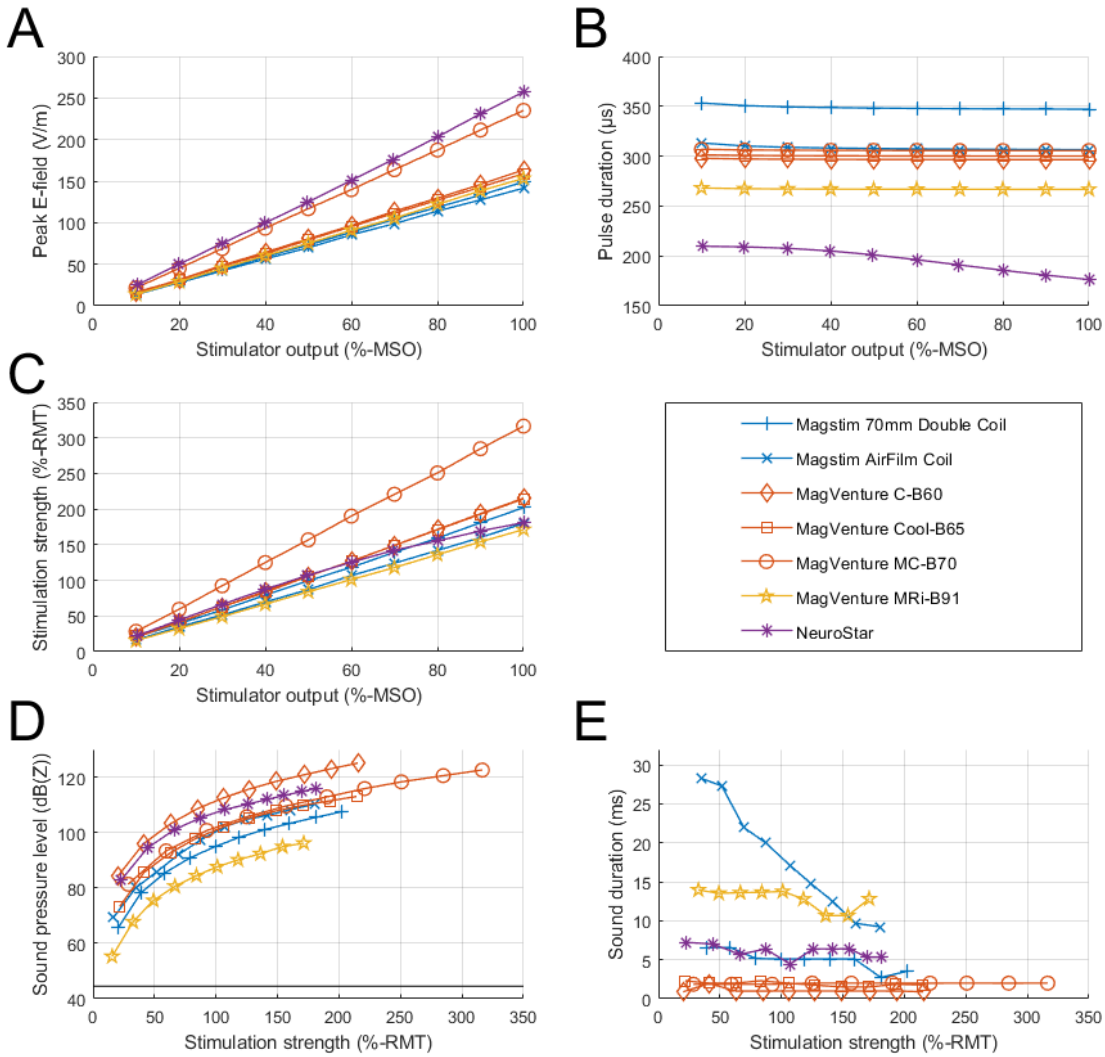

Figure 1. E-field and sound characteristics of various measured coils. (A) Peak E-field value has approximately linear relationship with stimulator output. (B) Pulse durations of air-core coils are approximately constant, whereas pulse duration of NeuroStar iron-core coil starts to drop after about 30%-MSO. (C) Stimulation strength estimated with neural model, where 50.3%-MSO of Magstim 70 mm Double Coil is set to correspond to 100%-RMT. (D) Peak sound pressure level (SPL) with Z-weighting, i.e., a flat response curve, here from 60 Hz to 50,000 Hz. The black line depicts the peak SPL of the recording chamber. (E) Duration for which sound is within 20 dB of peak value.

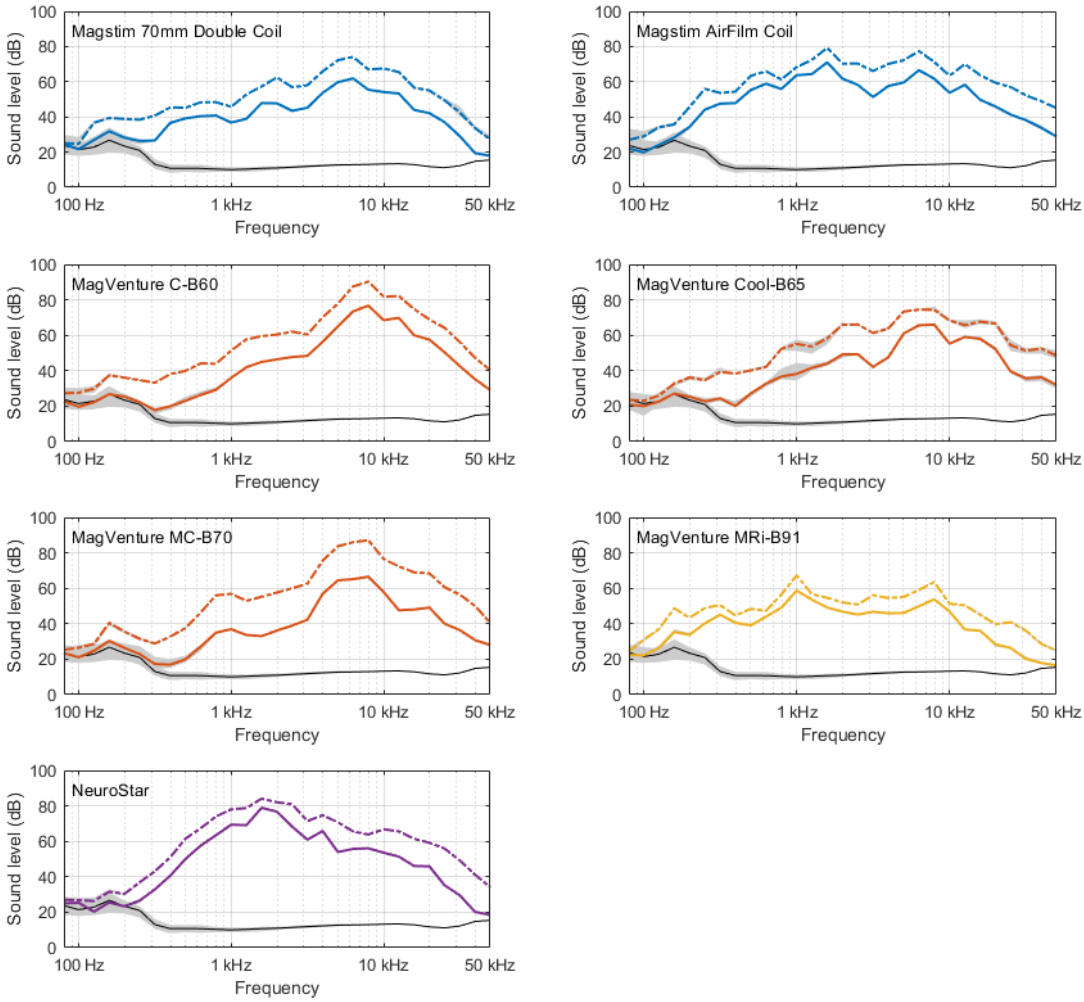

Figure 2. The 1/3-octave spectrums of the tested coils at estimated 100% RMT (solid line) and at 100% MSO (dash-dotted line). A solid black line shows the ambient sound spectrum. The Magstim AirFilm Coil has notably higher ambient noise level, manifesting in larger pulse-to-pulse variability below 100 Hz, most likely due to the integrated air-cooling fan in the coil. For all coils, the peak sound level is in the hearing range. The spectrum at 100%-RMT has been produced from the closest measured intensity by assuming that the sound waveform is proportional to the pulse energy.

Supplementary material

Sound recordings

Based on our preliminary measurement of Tonica MagPro MST (MagVenture, Denmark), the impulsive sound from TMS pulse sources can also be relatively loud. In the preliminary measurements, using the same 25 and 100 cm distances from coil to microphones as in the final measurement dataset, an impulsive sound source with a peak SPL of 104 dB(Z) at 1.7 meters away from the farther microphone was identified. This distance corresponded with the distance to the stimulator. This sound was just 9 dB less than the sound from the tested coil at 1.0 m, i.e., only about 6 dB less if both sound sources would be at equal distances.

To measure the full waveform of the coil sound, we had to isolate it from the impulsive sound from the stimulator. We achieved this isolation by measuring the coils inside a soundproof chamber with the pulse source outside. If one is interested only in the peak SPL and measures from a reasonably close distance to the coil, a soundproof chamber will not be needed. However, in such case, one might want to use at least two microphones (and beamforming) to identify and, if needed, to reject the sound not originating from the direction of the coil (the supplementary sound recording dataset contains a second microphone at 100 cm from the coil, but due to the soundproof chamber data from this microphone was not needed in the analysis). For the placement of microphones and the acoustic foam, see Fig. S1B.

The ambient sound level in the soundproof chamber was 21.2 dB(A) with slow time weighting, and the peak SPL in the coil-click relevant window of 0.2 s was 44.5 dB(Z) (95% confidence interval (CI) of 43.1–46.0 dB(Z)), where the Z-weighting refers to flat frequency weighting from about 80 Hz to 50,000 Hz (see Methods section for filter specification). Consequently, we could measure the pulse durations for pulses down to 65 dB(Z), i.e., down to 20% of the MSO for the three quietest coils and all the way down to 10% of the MSO for other coils.

To assess the scaling law between the peak SPL and the stimulator output, we plotted these two in a logarithmic plot. For all air-core coils, the peak SPL varied approximately proportionally to the energy of the TMS pulse (Fig. S2). This could be expected from first principles, as the magnetic field and coil current are both proportional to the stimulator output voltage. The result is somewhat visible in some of the sound spectra (Fig. 2), which have a peak at about twice the frequency to that of the coil current or E-field traces.

There is one related supplementary file: The full set of sound recordings, band-pass filtered from 60 to 60,000 Hz as described in the methods and compressed to contain data from –50 ms to 150 ms relative to each pulse, is provided as one MAT-file. In this file, the originally 24-bit sound recording data have already been converted to Pascals and are stored as 32-bit floating point variables (which halves the size of the file, at a cost of potentially losing the least significant bit of the recordings). In addition to the coil sounds, to assess the background noise level, there are also 100 events in which no pulse was delivered.

Electric field measurements

To compare the coil click across different TMS stimulators with different TMS coils, we had to first characterize the stimulation strength from each such combination. We did this with our new simplified triangle phantom, which, to maximize the accuracy of the E-field recordings, used a printed-circuit-board based triangular pickup loop, a 3d-printed holder, and a laser-cut alignment tool for mounting the holder on the coils (Fig. S1A). The E-field measurements were estimated to have < 2 mm positional, < 2° angular, and < 2% uncertainty.

The stimulation strength was computed from the E-field recordings as

$$\Delta V = \max_t \left| \int_0^t E(t') \exp\left(-\frac{t-t'}{\tau}\right) \mathrm{d}t' \right| , \tag{1}$$

where ΔV is the stimulation strength, E is the E-field, and τ is the strength–duration time constant, here 200 µs. This resulted in us obtaining calibration tables for the tested stimulators (as there was only one stimulator of each kind, one should not consider these to be generalizable to other Magstim, MagVenture, or NeuroStar devices). For all air-core coils, this stimulator output has highly linear relationship with the estimated stimulation strength of the neural model, resulting in less than ±3% error in the range from about 50% RMT to 100% MSO for all but the coil providing the strongest stimulation strength (MagVenture MC-B70) (Fig. S3).

There are two related file supplements to the E-field measurements:

1. The full E-field measurement dataset as one MAT-file (including the pulse waveforms, with one pulse per coil per intensity, sampled at 100 MHz).
2. To facilitate E-field measurements for other TMS users we provide the technical drawings of the measurement probe as a ZIP-file. This file contains the Gerber files for the two-layer printed-circuit-board probe, an STL file for the 3d-printed probe holder, and a PDF drawing of the laser-cut alignment plate. Assuming a pre-existing data-acquisition system, the total cost of building such a probe should be below $50 even if all components are sourced externally.

Supplementary figures

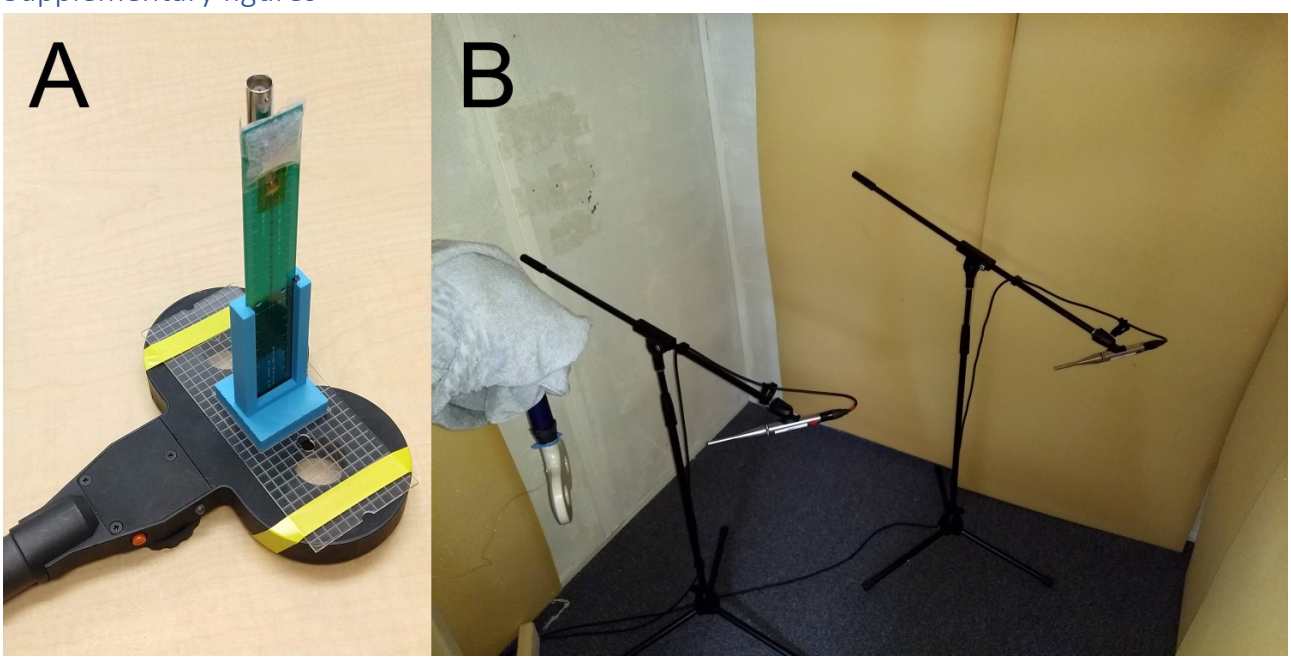

Figure S1. (A) Triangular E-field probe in 3d-printed holder on laser-cut alignment plate. (B) Sound-recording setup: two microphones are directed at coil face at respective distance of 25 cm and 100 cm measured from microphone capsule. As soundproof chamber provided adequate attenuation of external sound sources, only data from closer microphone was ultimately needed for analysis. Corners behind coil and microphones were covered with 50 mm thick open-cell foam to suppress echoes.

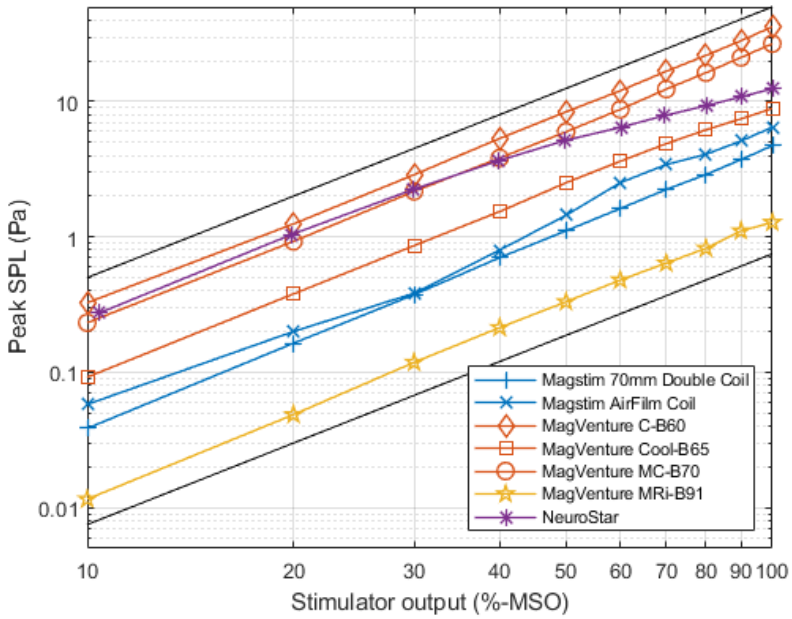

Figure S2. A logarithmic plot of the stimulator output versus peak SPL for different coils. The two black lines surrounding the measured sound pressures show a quadratic growth, i.e., a coil whose peak SPL is proportional to the pulse energy. Except for the NeuroStar iron-core coil, all coils closely follow such a scaling law.

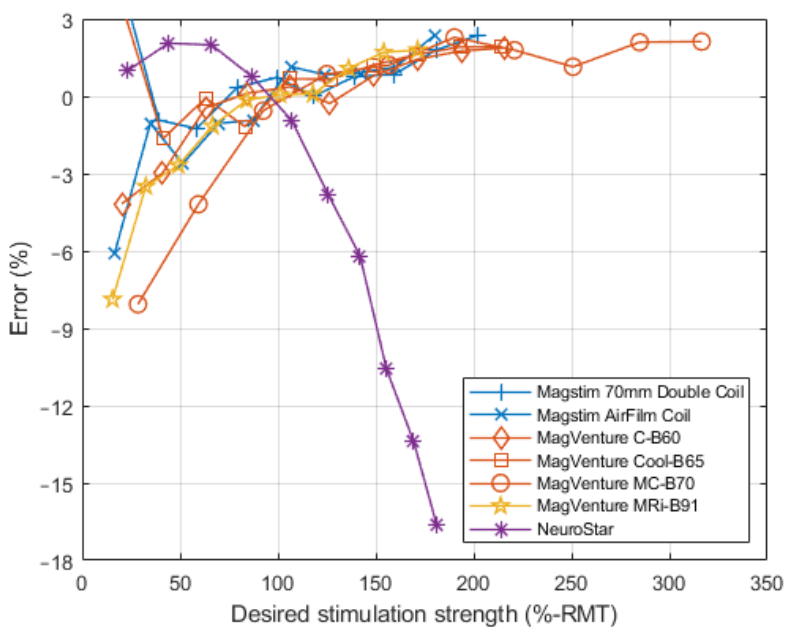

Figure S3. The nonlinearity in the relationship between stimulator output and stimulation strength. For Magstim and MagVenture stimulators, the relative errors are amplified at very low stimulator outputs. For NeuroStar, the error grows with increasing stimulator output.

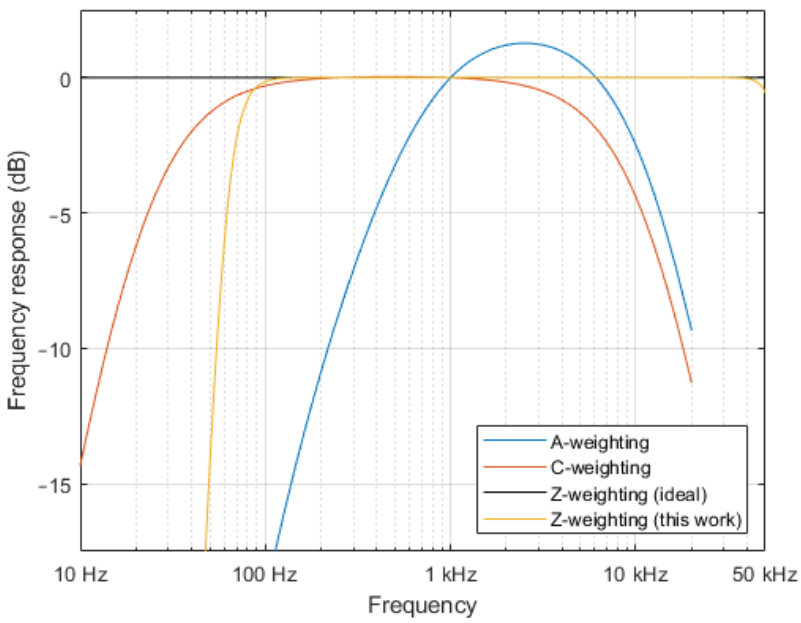

Figure S4. Frequency weightings used in hearing safety standards. A-weighting roughly mimics the perceived loudness curve for barely audible sounds, whereas C-weighting mimics that of loud sounds. The ideal Z-weighting corresponds to no weighting at all. In this work, our Z-weighting filter had a passband from 80 to 50,000 Hz, where the sharp low-frequency cut-off was selected to reduce the noise from non-TMS-coil sources. In practice, a Class II sound-level meter may omit anything above 8 kHz, and a Class I sound-level meter—anything above 16 kHz.