Concurrent TMS-fMRI: An international consensus and functional guide for current and future researchers

Woolgar, A.[1*], Feredoes, E.[2*], Assem, M.[1], Bassil, Y.[3], Bergmann, T.O.[4], Beynel, L.[5], Burke, M.[6], Cash, R.F.H.[7], Comeau, R.M.[8], Correia, M.M.[1], Genc, E.[9], Hartwigsen, G.[10], Jackson, J.B.[1], Kienle, M.[11], Kunz, P.[12], Leticevscaia, O.[2], Luber, B.[5], Lueckel, M.[4], Mathiesen, C.[11], Michael, E.[1], Numssen, O.[13], Oathes, D.J.[14], Rosen, A.C. [15], Schuhmann, T.[16], Schuler, A.-L.[13], Scrivener, C.L.[17], Thielscher, A.[18], Tik, M.[19], Todorov, Y.[11], Vasileiadi, M.[19], Windischberger, C.[19], Hermiller, M.S.[20^], and Sack, A.T.[16^]

[1] University of Cambridge, United Kingdom; [2] University of Reading, United Kingdom; [3] Emory University, USA; [4] Neuroimaging Center (NIC), Focus Program Translational Neuroscience (FTN), Johannes Gutenberg University Medical Center Mainz, Germany, and Leibniz Institute for Resilience Research (LIR) Mainz, Germany; [5] National Institute of Health, USA; [6] Leibniz Research Center for Working Environment and Human Factors, Germany; [7] University of Melbourne, Australia; [8] Rogue Research Inc., Canada; [9] Technical University of Dortmund, Germany; [10] Cognitive and Biological Psychology, Wilhelm Wundt Institute for Psychology, Leipzig University & Max Planck Institute for Human Cognitive and Brain Sciences, Germany; [11] MagVenture, Inc., Denmark; [12] Localite GmbH, Germany; [13] Max Planck Institute for Human Cognitive and Brain Sciences, Germany; [14] University of Pennsylvania, USA; [15] Stanford University School of Medicine, USA; [16] Maastricht University, The Netherlands; [17] University of Edinburgh, United Kingdom; [18] Technical University of Denmark, Denmark; [19] Medical University of Vienna, Austria; [20] Florida State University, USA. * equal contribution (joint first author), ^ equal contribution (joint senior author)

Abstract

Concurrent TMS-fMRI provides a step-change in the toolkit of neuroscience research. Using non-invasive perturbation of ongoing human brain activity and simultaneous read-out of its effects across the brain, it permits causal inference into human brain-behaviour relationships with important implications for both fundamental research and clinical application. Many of the practical barriers to implementation have now been solved and the community is rapidly growing. Here we present an international consensus and discussion, from researchers at all levels and across the fields of cognitive and applied human neuroscience, on the experimental design and practical considerations of this exciting technique.

Introduction

The simultaneous combination of transcranial magnetic stimulation (TMS) and functional magnetic resonance imaging (fMRI) is a cutting-edge approach that non-invasively perturbs ongoing neural activity while simultaneously “reading out” the consequence of this perturbation across the brain. It can identify the whole brain network response to focal neuromodulation, map the spread of induced neural activity changes within and across dynamic networks, and reveal the causal contribution of these network dynamics to cognitive and clinically relevant functions in actively engaged human participants. TMS is an extremely powerful tool for both fundamental brain research and clinical practice, allowing us to noninvasively disrupt or enhance ongoing brain activity, to entrain oscillatory brain rhythms, and to even induce lasting neuroplastic network connectivity changes. However, only by combining TMS with concurrent neuroimaging can we directly examine these immediately induced whole brain activity changes.

Concurrent TMS-fMRI therefore represents a breakthrough in our ability to study human neural processes in both fundamental and applied settings. It can reveal the brain-wide consequences of interfering with or enhancing ongoing activity, introduce a temporally and spatially precise ‘signal’ in a predetermined cortical region and reveal how this signal is propagated through the brain, and target deep structures via functional and/or anatomical connectivity. It can also reveal how these functional interactions are affected by cognitive tasks, enabling unique and powerful inference

into brain mechanisms, network communication, and causal structure-function relationships. It thus provides a non-invasive complement to perturb-and-measure invasive approaches in animal models. It also has important potential to uncover the neural basis by which TMS achieves its cognitive and clinical effects, revealing the cascade of neural changes caused by various stimulation parameters and brain targets and how these vary across individuals.

Concurrent TMS-fMRI has previously been regarded as a niche field with enormous potential but near-insurmountable hurdles for implementation. Today, however, many of the challenges have been solved; not only is it now technically feasible and implemented in dozens of labs worldwide, but the community is growing rapidly and revealing exciting insights into the mechanisms of fundamental cognitive processes, principles of network communication, and remediation in clinical disorders. This paper evolves from a series of consensus meetings held at an international workshop of the TMS-fMRI community. Representing a consensus among more than 30 fundamental and clinical researchers from across the world, we present a guide to conceptual considerations and practical implementation of TMS-fMRI (**Figure 1**), including details of the available setups, best practice in experimental design, and possibilities and limits on inference. Our aim is to complement existing systematic reviews and in-depth technical guides by providing an overview of and functional guide to the current possibilities and considerations with this emerging technique, as well as the technical challenges and solutions that constrain them.

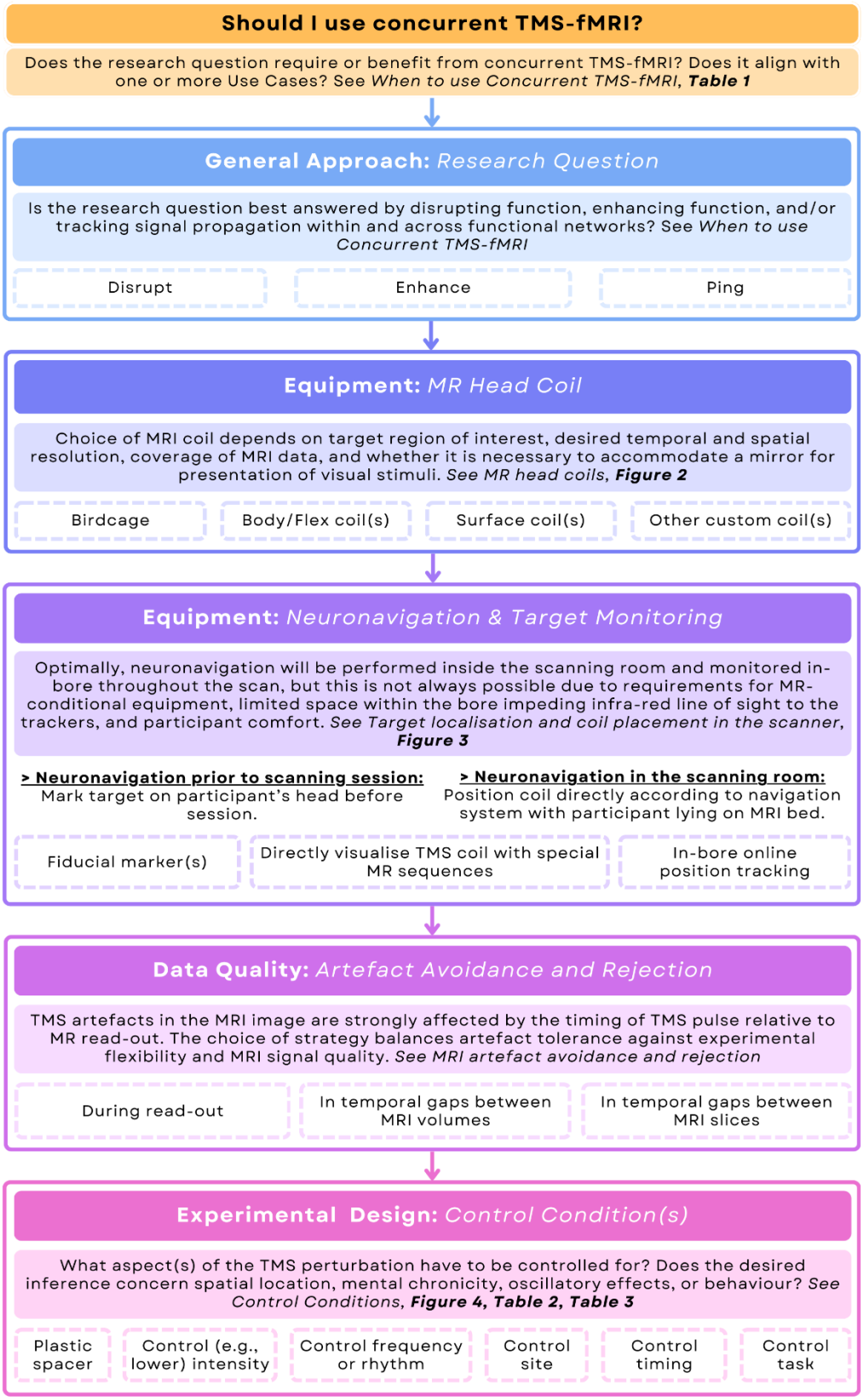

Should I use concurrent TMS-fMRI?
Does the research question require or benefit from concurrent TMS-fMRI? Does it align with one or more Use Cases? See When to use Concurrent TMS-fMRI, Table 1
General Approach: Research Question
Is the research question best answered by disrupting function, enhancing function, and/or tracking signal propagation within and across functional networks? See When to use Concurrent TMS-fMRI
Disrupt
Enhance
Ping
Equipment: MR Head Coil
Choice of MRI coil depends on target region of interest, desired temporal and spatial resolution, coverage of MRI data, and whether it is necessary to accommodate a mirror for presentation of visual stimuli. See MR head coils, Figure 2
Birdcage
Body/Flex coil(s)
Surface coil(s)
Other custom coil(s)
Equipment: Neuronavigation & Target Monitoring
Optimally, neuronavigation will be performed inside the scanning room and monitored in-bore throughout the scan, but this is not always possible due to requirements for MR-conditional equipment, limited space within the bore impeding infra-red line of sight to the trackers, and participant comfort. See Target localisation and coil placement in the scanner, Figure 3
> Neuronavigation prior to scanning session: Mark target on participant's head before session.
> Neuronavigation in the scanning room: Position coil directly according to navigation system with participant lying on MRI bed.
Fiducial marker(s)
Directly visualise TMS coil with special MR sequences
In-bore online position tracking
Data Quality: Artefact Avoidance and Rejection
TMS artefacts in the MRI image are strongly affected by the timing of TMS pulse relative to MR read-out. The choice of strategy balances artefact tolerance against experimental flexibility and MRI signal quality. See MRI artefact avoidance and rejection
During read-out
In temporal gaps between MRI volumes
In temporal gaps between MRI slices
Experimental Design: Control Condition(s)
What aspect(s) of the TMS perturbation have to be controlled for? Does the desired inference concern spatial location, mental chronicity, oscillatory effects, or behaviour? See Control Conditions, Figure 4, Table 2, Table 3
Plastic spacer
Control (e.g., lower) intensity
Control frequency or rhythm
Control site
Control timing
Control task

Figure 1. Overview of design considerations for concurrent TMS-fMRI

When to use Concurrent TMS-fMRI

The first experimental consideration is whether the use of concurrent TMS-fMRI is warranted by the research question. fMRI is at the heart of the cognitive neuroscience toolkit: it allows us to non-invasively observe the human brain in action and has revolutionised our understanding of the biological basis for cognition and action. However, like all neuroimaging, insight from fMRI alone is fundamentally limited because the technique is inherently correlational: it cannot yield inference about the causal role of brain activity for a given perceptual or cognitive function. For example, if a particular brain region is active when a stimulus is shown, the neural activity may be necessary for perception of that stimulus (i.e., the task could not be done without it), or it may just reflect activation not critical for the processes of interest.

TMS, on the other hand, is a well-established technique which temporarily perturbs activity in a local area of cortex to assess the causal role of that brain area, for example, by showing that performance on a certain task is modulated by stimulation to a certain brain area. However, insight from TMS alone is also critically limited because it does not reveal the local and remote effects of stimulation on brain function necessary to interpret the neural basis for its effect.

Combining the two techniques overcomes these limitations. With concurrent TMS-fMRI, we perturb activity in one brain region, then use fMRI to examine the effect of this perturbation across the brain (**Figure 2**, e.g., [1]). This offers the possibility of linking activity in a targeted brain region with activity across the rest of the brain, with cognition, and with behaviour, in a causal framework (e.g., [2]).

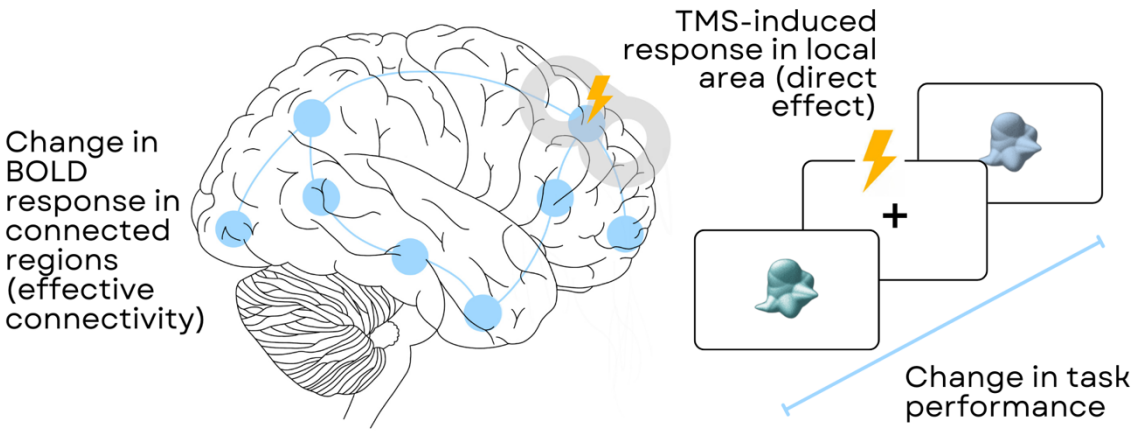


Figure 2. Schematic showing the effect of applying TMS to a target cortical site, propagating throughout a set of brain regions functionally connected at the time of stimulation. The effect of TMS on behavioural task performance can also be measured concurrently, linking network-level effects to behaviour.

Much research using both TMS and fMRI employs them sequentially, either collecting fMRI data and using this to guide subsequent TMS application[3-9], and/or by applying TMS outside of the scanner room, and then collecting fMRI shortly after[10-19]. The latter, "sequential TMS-fMRI", approach is well-suited to study the after-effects of repetitive TMS (rTMS) on neural activity, and avoids the technical challenges associated with performing TMS and fMRI concurrently. However, there is typically a delay of several minutes between the application of TMS and the fMRI measurement, meaning the immediate effects of neural perturbation are not measured. Accordingly, sequential approaches require TMS protocols that induce a persistent effect (e.g., 20-Hz rTMS, theta burst stimulation (TBS), with effects reported up to 20-60 minutes post-stimulation[20-22]). By contrast, performing TMS and fMRI concurrently affords the opportunity to use a much greater range of TMS protocols allowing for different insights.

In the following section, we outline specific situations or "Use Cases" (**Table 1**) in which concurrent TMS-fMRI allows for important experimental flexibility, scientific insight, and clinical promise, which would not otherwise be possible. This is not intended to be a systematic review of all previous work, but rather to lay out the situations in which concurrent TMS-fMRI may allow uniquely powerful insights, illustrated by examples.

A Use Case is a desired insight that is permitted by, or draws on, one or more of the advantages of the concurrent TMS-fMRI approach. Use Cases may overlap in the advantages they draw on and may involve related experimental approaches, and a single research paper may draw on multiple Use Cases; we delineate them here to show the range of insights that concurrent TMS-fMRI makes possible. These cases justify the significant investment of time and resources required to implement this technically challenging but inferentially powerful technique.

Use Case	**Advantage of concurrent TMS-fMRI over sequential TMS-fMRI**	**Example References**
1. Study immediate and/or transient effects of neural perturbation	Only the concurrent approach is sensitive to immediate and transient effects of TMS	23,24
2. Experimental situations requiring trial-wise manipulations	Only the concurrent approach allows for trial-wise application of TMS (due to its transient effect), allowing, for example, for trial-wise manipulation of cognitive variables, TMS parameters, etc.	24-28
3. Validate modulation of intended regions/networks	Sensitive to immediate and transient, local and remote, effects of TMS	23,25,28-31
4. Circuit-mapping (pinging)	Sensitive to immediate and transient remote effects. Avoids neuroplasticity effects and resulting rapid network reorganisation effects induced by repetitive TMS protocols	24,25,27,32-36
5. Study mental chronicity	Not possible with sequential approaches as requires intervention at different timepoints in a trial	24,37,38
6. Modulate neural activity at different frequencies	Not possible with sequential approaches as putative entrainment effects are short lived	25
7. Study state-dependency	Concurrent TMS-fMRI allows for TMS delivery timed to coincide with different temporary neural/cognitive states. Possibility of future close-loop approaches.	24-28,37
8. To establish the appropriate TMS dose (e.g., stimulation intensity)	Quantification of the immediate and transient effect of different TMS parameters (e.g., stimulation intensity and target site)	39

9. Compare short- and long-term effects of rTMS	Sensitivity to immediate and transient effects which may relate to and help predict longer term effects	[34]
10. Predict individual responsiveness to treatment (personalised medicine)	Immediate effects can be used to personalise TMS delivery and predict individual treatment response	[36,40,41]
11. Guide selection of treatment strategy (e.g., cortical target) for therapeutic effect	Test network engagement, modulation of clinically relevant deep brain structures, and symptom relevance of a candidate TMS target in a brief protocol (e.g., before investing in clinical trial)	[36,42,43]

Table 1. Use Cases in which concurrent TMS-fMRI is advantageous or required. Each Use Case allows for an insight, research question, or application that is permitted by, or draws on, one or more of the specific advantages of the concurrent TMS-fMRI approach relative to the sequential TMS-fMRI approach. Use Cases may involve related experimental approaches and overlap in the advantages they draw on. A single research paper commonly draws on multiple Use Cases.

Use Cases 1-6: Uncovering causal pathways in the human brain (Fundamental Science)

Concurrent TMS-fMRI is typically used either to interfere with ongoing neural activity (e.g., with a high intensity single pulse or short train of pulses), to enhance (e.g., entrain, with rhythmic TMS pulses) ongoing neural activity, or to introduce a functionally neutral signal to track its propagation through networks (‘pinging’, e.g., single TMS pulses). In the first two approaches, TMS is used to disrupt or enhance processing, with high spatial and temporal precision, while reading out the immediate consequence across the brain. This is similar to the logic of sequential TMS-fMRI approaches which use rTMS to disrupt or enhance activity for a sustained period of time during which MRI is acquired. In the “pinging” approach, by contrast, TMS is not intended to disrupt or enhance neural function, but to inject a signal that can be tracked as it propagates through the brain.

In all three approaches, concurrent TMS-fMRI presents two advantages over sequential TMS-fMRI. First, only concurrent TMS-fMRI is sensitive to immediate and

transient effects of perturbation. Therefore, the first broad use case (**Use Case 1, Table 1**) is any experimental situation in which the effect of interest is transient. Second, the concurrent approach allows for more flexible experimental design (**Use Case 2, Table 1**). In particular, concurrent TMS can be delivered trial-wise, allowing for single-trial analysis of, e.g., events that are unexpected, situation-dependent, or subject to learning or adaptation. Moreover, it usually means that it is possible to collect data for longer than in sequential designs. The upper limit on a concurrent TMS-fMRI acquisition time is given by safety[44,45] and psychological considerations and is not constrained by the duration of an rTMS effect. This may be important in situations where many trials are needed, for example if there are multiple task variables being compared.

A third key use case is to validate the immediate engagement of (only) the targeted network(s) of interest (**Use Case 3, Table 1**). In particular, concurrent TMS-fMRI can be used to validate modulation of the local cortical target [e.g., [34,39], although it is not always possible to see univariate effects immediately under the coil [46,47] and engagement of relevant downstream cortical and subcortical regions [2]. It may also identify engagement of additional cognitive circuits that confound a behavioural task or cognitive processes of interest due to propagation of TMS effects to non-target regions[48]. This also paves the way for testing individualization strategies in TMS research and clinical applications. For example, TMS-fMRI can be used to experimentally test and validate the assumption that stimulating individually derived cortical sites that are more strongly connected to deep brain regions, results in a stronger transsynaptic modulation of – and thus a stronger remote BOLD response in – these deep target regions. A systematic quantification of these individualised network effects could determine whether such level of individualization is warranted in the context of the spatial resolution of TMS, with important implications for both fundamental research and clinical application.

In addition to these general Use Cases, there are a number of specific situations in which concurrent TMS-fMRI is required. The “pinging” approach, in which a transient injection of energy is tracked as it propagates through the system, is only possible within the concurrent paradigm. This approach provides causal evidence for effective connectivity (**Use Case 4, Table 1**), and the possibility of associated insight into how

connectivity changes under manipulations of interest, without intentionally disrupting brain function. Concurrent TMS-fMRI is well suited to this application, with many studies confirming that TMS activity propagates across brain regions and networks, including to deeper structures such as the subgenual anterior cingulate cortex (sgACC, through TMS to dorsolateral prefrontal cortex (dlPFC), e.g., [33,35-37]), amygdala (through TMS to ventrolateral PFC, e.g., [33,49]), and hippocampus (through TMS to lateral parietal cortex e.g., [25]), as well as between cortical regions e.g., [32,50]. This opens a range of applications, such as understanding how circuit-level connectivity changes with a cognitive task, disruption, or intervention, and how circuit-level effects link to behaviour. The "pinging" approach avoids the mechanistic limitations associated with measuring persistent after-effects of stimulation, as in sequential TMS-fMRI, and the potential interference of associated neuroplasticity mechanisms with high individual variability[51-53]. Moreover, only concurrent approaches are able to track immediate and temporary circuit connectivity which may change in important ways from trial to trial.

A fifth Use Case draws on the superior temporal resolution of concurrent (over sequential) TMS-fMRI to study mental chronometry, examining brain processes at specific points in time, such as at a specific point in a trial (**Use Case 5, Table 1**). For example, Hawco et al., (2017) delivered stimulation to the dlPFC either 200, 600, or 1000ms post-stimulus onset during an associative memory task to assess temporal dynamics during higher level cognitive processing[38]. Relatedly, Feredoes et al., (2011) used concurrent TMS-fMRI to test the effect of frontal TMS during the delay period of a working memory task and delineated a specific role for prefrontal regions in supporting working memory for target items (rather than suppression of distractors) at that timepoint[28] (see also[37]).

A sixth Use Case is to study the spatial effects of entraining neural activity at particular frequencies (**Use Case 6, Table 1**). This is important since neural oscillations are widely thought to modulate the flow of information through whole-brain networks[54], but the relationships are complex and not well understood[55-57]. Here the concurrent TMS-fMRI approach is required because entrainment effects are typically short lived, lasting only hundreds of milliseconds, and not visible in sequential TMS-fMRI. fMRI cannot directly measure oscillatory responses to stimulation (for this, TMS-EEG or the three-way combination of TMS-EEG-fMRI would be required) but can reveal the spatial

extent of putative oscillatory modulation. For example, Hermiller and colleagues demonstrated that theta (but not beta) burst patterned TMS (mimicking theoretical endogenous hippocampal theta-gamma nested rhythms related to memory) engaged the hippocampal-cortical network to enhance memory formation[25]. Relatedly, Dunlop and Nestor used concurrent TMS-fMRI to reveal differential effects of stimulating the same region at different frequencies[58].

Use Cases 7-9: Examining the neural consequences of TMS itself

Another key Use Case for concurrent TMS-fMRI is to better understand the mechanisms of action of TMS itself. This is critical both for fundamental research and for clinical application. It is widely accepted that the outcomes of TMS currently vary widely and unpredictably between individuals [52,59-61]. TMS-fMRI makes it possible to examine the neural changes induced by TMS in real time, garnering resolution on the cascade of neural consequences. This opens important possibilities for personalising TMS to produce physiologically sophisticated, informative, and reliable effects across individuals.

One known source of variability is that TMS responses vary according to neural state, a phenomenon known as state-dependency. Studying this is another Use Case (**Use Case 7, Table 1**) for which concurrent TMS-fMRI is required, as it allows us to measure the effect of TMS under different, transient states. For example, concurrent TMS-fMRI has revealed that TMS to dlPFC will engage sgACC differentially at different phases of a cognitive task [37]. Similar TMS-fMRI results obtain for many different brain systems including, for example, the premotor cortex, TMS to which produces distinct effects in remote regions during rest as compared to during voluntary muscle contraction [62] and in different visuomotor selection tasks [63]; the intraparietal sulcus (IPS), which shows different TMS-induced network effects at rest as compared to an active cognitive state [27], and differential TMS effects on activity in visual regions in the presence versus absence of visual stimuli[26,64], or when attending to one side or other of space [65]; and frontal eye fields which shows attention-dependent propagation of TMS to visual regions [29]. Moreover, spontaneous fluctuations of oscillatory parameters such as power and phase at the moment of TMS application determine TMS-induced BOLD response in local and remote brain regions[24]. State-dependency can also

dramatically influence the directionality and strength of rTMS effects at the behavioural level[66]. These findings highlight the dynamic nature of the brain's response to stimulation, reflecting the state of the stimulated network. These relationships are only known thanks to concurrent TMS-fMRI, and it will be necessary for describing and predicting state dependency more fully. In addition to fundamental insight, understanding this could have important clinical implications, for example for understanding variability in response to TMS combined with adjunct therapies [67-70].

Another key question in the TMS field is how to dose TMS appropriately for each individual. One challenge is that outside of the motor and visual cortex, there are hardly any behavioural measures indicating which stimulation intensity is sufficient to modulate neural activity. Concurrent TMS-fMRI provides a much-needed dependent variable - BOLD signal - which can be measured at any brain region (**Use Case 8, Table 1**). For example, concurrent TMS-fMRI allows us to quantify individual cortical excitation thresholds through dose-response BOLD curves[39], potentially improving on region-specific physiological proxies such as motor threshold. This approach might be used in pinpointing individual stimulation thresholds for a targeted functional domain or specific (r)TMS protocols and may be useful for understanding the relationship of modelled electric fields (E-fields) and BOLD responses for different stimulation intensities[71].

Finally, the concurrent approach also opens the possibility of understanding the relationship between immediate/short-term effects with clinically relevant long-lasting effects of repetitive stimulation (**Use Case 9, Table 1**). This is important because inhibitory and excitatory rTMS show dissociable after-effects on functional connectivity within and between networks[13,14,72], but no consistent pattern has emerged. Comparing the immediate local and global with long-term impacts of perturbation [34]may help us to understand the mechanisms of long-term effects and their variability between participants.

Use Cases 10-12: Clinically inspired research and clinical application

An exciting application of TMS is its potential to intervene on pathological brain function, including deep structures via functional connectivity. In this arena, concurrent

TMS-fMRI again has unique benefits. Two particularly strong use cases leverage concurrent TMS-fMRI to determine an individual patient's responsiveness to TMS, and to guide therapeutic targeting strategies.

First, TMS-fMRI can predict or explain individual differences in clinical responsiveness (**Use Case 10, Table 1**) by revealing how TMS-induced neural activity propagates through circuits and changes circuit communication. For example, two recent depression studies demonstrated that acute TMS-fMRI responses predict reduction in depressive symptoms with subsequent rTMS [36,40]. Oathes et al., used the concurrent TMS-fMRI "pinging" approach in depressed patients to validate engagement of subgenual anterior cingulate (sgACC) engagement before a brief 3-day iTBS rTMS intervention[36]. They found evidence that an individual's pre-intervention circuit response to TMS predicted depression improvement with intervention, over and above the prediction based solely on resting functional connectivity. Circuit integrity as indexed by TMS-fMRI has also been linked to psychotherapy outcome in PTSD[41].

Second, TMS-fMRI can help guide selection of TMS protcols for maximal therapeutic effect (**Use Case 11, Table 1**). For example, in any given patient, there may be multiple TMS-accessible (i.e., cortical surface) nodes of a network at the individual level that have roughly equivalent imaging properties (functional connectivity, tractography, etc.) to the clinically relevant target site. Drawing on Use Case 4, and the observation that immediate and lasting rTMS effects are intimately related[34], concurrent TMS-fMRI allows us to stimulate each of the potential nodes, measure network engagement, and select the strongest candidate for subsequent treatment[42]. Similarly, there may be individual differences in the pattern of spatial propagation of rTMS of different frequencies[58]. Preselecting individualised TMS protocols using concurrent TMS-fMRI may be especially valuable in the context of clinical trials, where novel image-guided stimulation targets can, potentially, be efficiently validated with brief interventions[36] before investing in a full trial.

Technical requirements and practical implementation

A significant barrier to conducting concurrent TMS-fMRI is the necessary hardware, its installation in the MR environment, and the technical demands for its

implementation. Since the earliest TMS-fMRI studies[73-75] employing bespoke infrastructure and problem-solving, researchers make an active contribution to the technical side of TMS-fMRI, both through innovations in hardware, such as dedicated MR surface coils that can integrate a TMS coil[76], and software for synchronising TMS and MR timing[77]. In this section, we describe different aspects of concurrent TMS-fMRI setups that are currently in use, and show a plethora of solutions, many of which the TMS-fMRI community has developed, and shared, through open communication and collaboration. We also present a simple set of minimal requirements for researchers looking to take up the approach. This section complements in-depth concurrent TMS-fMRI guides[2,78,79], which readers can refer to for specific details, as well as providing some updates on latest innovations.

MR-compatible TMS coils and stimulators

A typical setup will have the stimulator outside the magnet room, in close proximity to a waveguide through which the TMS coil cable is passed. Between the stimulator and the waveguide is a specialised in-line low-pass filter to prevent radiofrequency (RF) noise passing through the TMS cable to the magnet room[80]. The length of the cable from stimulator to the coil depends on the location of the magnet relative to the waveguide, with cable lengths of up to 10m possible such that stimulators need to be sufficiently powerful to compensate for the energy loss due to the long cable lengths. There is currently only one manufacturer, MagVenture (Farum, Denmark), that provides a dedicated MR-compatible TMS system which includes strengthened TMS coils to withstand the Lorenz forces from the static MR magnetic field/minimise vibration and movement during stimulation, leakage current cancellation [81], and longer coil cables with modification to minimise power loss, and is free from non-MR compatible electronic components.

MR head coils

An important ongoing challenge is the necessity to co-accommodate TMS and RF coils within a confined space near the head. This constraint forces compromise on full head coverage, number of RF channels, and/or proximity of RF coils to the head, meaning that TMS-fMRI setups do not always achieve the highest levels of resolution available in conventional fMRI. Examples of existing solutions are shown in **Figure 3**

and include accommodating the TMS coil within a large coil (e.g., birdcage), or between two or more flexible RF receive coils that are kept in place with custom holders[82]. If visual presentation of stimuli is not required, one solution involves wrapping the whole head, including the eyes, with an ultrathin "sheet" of GE Air Coils[83]. Alternatively, an ultrathin surface coil with 7 RF channels can be accommodated between the TMS coil and head which allows for good signal at the site of stimulation and expanded coverage when supplemented with a second (or third) surface coil[76]. However, this solution compromises on signal homogeneity (lower signal and sensitivity away from the arrays) and difficulty matching RF coil placement (and therefore signal) across participants[76,84]. The choice of RF coil affects the choice of imaging sequences e.g., coils with fewer RF channels may need to increase voxel sizes to achieve acceptable signal-to-noise ratio (SNR), and may not be suitable for multi-band sequences, limiting temporal resolution. Direct comparisons between some of these options have been reported[37,76,82,84], but to our knowledge, no comprehensive evaluations of all the emerging alternatives exists. Conducting such an analysis would be a valuable focus for future research. Meanwhile, future development of whole head RF coil designs that can accommodate TMS (e.g., see [85] for a 28 channel setup under development) may facilitate robust high-resolution data.

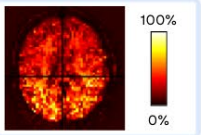
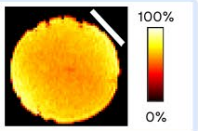
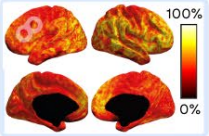
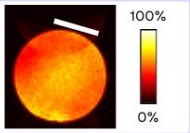
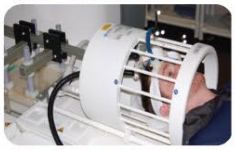
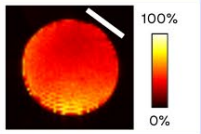
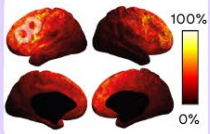
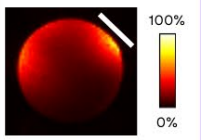
MR Coil *(# of channels)*	Example Configurations		tSNR Maps *(if available)*
Flexible coils			
Siemens Flex *(4 channels)*		Positioned above head, in combination with lower section of Siemens head array (e.g., 20-channel) [86]	
Siemens Body *(18*2 channels)*		Custom 'Sushi' arrangement combining two Siemens 18-channel body coils [87]	
Siemens Flex + Body *(4+18 channels)*		Custom 'Taco' arrangement combining 4-channel flex coil (top) and 18-channel body coil (bottom), wrapped around head and TMS coil [82]	
Head array coils			
Siemens TxRx *(1 channel)*		Single channel head coil as used in e.g., Jackson et al. (2021) [23]	
RAPID BioMedical Birdcage *(1 channel)*		From Riddle et al. (2022) [78]	
RAPID BioMedical Head Array *(8 or 12 channels)*		12-channel RAPID with MagVenture TMS coil holder	
Magnetica 8-channel RX Head Coil *(8 channels)*		Large diameter 8-channel head coil [84]	
Surface array coils			
ALSIX Surface Coil Array *(7 channels per coil array, up to 3 coil arrays per setup)*		TMS coil and attached ALSIX array secured with MagVenture TMS coil holder. Second ALSIX array held with custom flexible arms secured to same holder [84]	
		Two ALSIX 7-channel surface coils secured with MagVenture TMS coil holder and vacuum padding	
Additional TMS coil holder solutions			
			
TMS coil holder from Lee et al. (2023) [88]	Rear view of custom TMS coil holder mounted onto head coil	Original head coil and TMS coil holder from Bohning et al. (1998) [75]	

Figure 3. Example arrangements of TMS and RF head coils in the scanner. Specific solutions are detailed separately for flexible coils, and head and surface array coils, together with a range of coil holder solutions. We also include illustrative tSNR maps for several setups with a white line/figure of 8 indicating the approximate position of the TMS coil. Note that tSNR will depend not only on hardware but also scanner sequence (including image resolution, TR, number of volumes collected, etc) as well as data preprocessing and cleaning, and so tSNR values shown here are only comparable within volume and not between setups. Here, tSNR values are expressed as % of the maximum tSNR achieved for each setup, so do not reflect the possible differences in tSNR scale between setups, but do illustrate the spatial distribution of tSNR within each arrangement. For direct comparisons of tSNR between different setups see [37,76,82,84]. Elements of this figure have been reproduced under CC BY 4.0 licence from [78,84] and under CC-BY-NC-ND 4.0 licence from[86].

Target localisation and coil placement in the scanner

For all TMS applications, identifying cortical targets is crucial. Target site selection based on individualised functional, behavioural, or physiological localizers have been shown to be superior to the use of generalised group or meta-analysis data[2]. Selection of the scalp location follows the same procedure as for non-TMS studies with the gold standard being MR-guided neuronavigation based on a previously-acquired structural scan of a participant [4]. Ideally this structural scan would have been acquired with a standard 32 or 64 channel MR head coil, without the TMS coil in place, for best image quality. If such a scan does not already exist for the participant, it is often most convenient to acquire it in a preliminary MR session, on a different day, so that the researchers have time to transfer the scan to the neuronavigation computer and select the TMS target. Subsequently, the TMS coil must be accurately positioned. Coil placement can be further improved by incorporating E-field modelling, maximising exposure of the cortical target volume to the effective E-field [89-91] while minimising off-target stimulation [92-94]. Additionally, E-field simulations allow performing dose-response analyses for the BOLD response. Concurrent TMS-fMRI specific considerations include spatial constraints imposed by the MR coil and supine position of the participant, and whether and how to track the coil location throughout the scanning session.

Once a scalp location has been identified, the TMS coil must be fixed during MRI scanning. Currently, a commercially available holder only exists for Siemens scanners, although many groups, particularly those using other scanners, produce their own solutions (**Figure 3**) and there are promising new designs (e.g., [88]). Developing a universal, user-friendly concurrent TMS-fMRI coil holder remains a priority for the field.

Supine positioning of the participant in the MRI makes posterior and inferior stimulation targets more challenging to reach. This requires a degree of ingenuity, for example by raising the participant on the bed so that they can lie on top of the TMS coil [95]. There are also issues targeting areas (e.g., prefrontal cortex) in which the coil or holder block viewing of a back-projection mirror. Similarly, targeting lateral areas may require the participant to rotate their head, which may impede viewing visual stimuli.

In addition to scalp position, the angle of the coil is an important parameter to specify in order to maximise the effect of stimulation. The optimal coil angle for a particular target can be estimated using E-field modelling, which takes individual anatomy under the stimulating coil into account. The precise angle can also have significant effects on the network engaged by TMS (e.g.,[96,97]). However, for some individuals, target locations, and TMS-fMRI setups, particularly those setups in which the available space is constrained by the MRI coil (e.g., birdcage head coil setups), a specific coil angle might not be possible to achieve in practice. This also means it may be difficult to keep coil angle consistent across a sample. Moreover, different coil angles may also induce different peripheral co-stimulation confounds, eg., via the excitation of cranial nerves and muscles[98], which adds an additional source of variance across experimental conditions and participants that may need to be controlled for. To mitigate, researchers may like to specify limits on how far they allow coil angles to deviate from the desired orientation. In the future, it may also be possible to use real-time E-field modelling in conjunction with MR-compatible neuronavigation to help determine the optimal coil angle that is possible in practice in the scanner. In the meantime, researchers are encouraged to report the coil angles that were desired and those actually used, highlighting the reason for deviation (e.g., because restrictions imposed by the head coil) and if possible, report any individual differences that may have arisen as a result. Transparency in this regard will help reviewers and readers understand and interpret

the potential issue of achieving a specific TMS coil angle in the scanner environment, along with the possible impact of coil angle differences on BOLD signal effects.

There are several approaches for monitoring and verifying the TMS coil position in the scanner. The most basic approach is to place fiducial markers (e.g., vitamin E capsules [86,99] or mustard sachets [12]) on the coil and triangulate the location off-line after scanning (e.g., [99]) (**Figure 4**). This requires structural scans with a field-of-view to accommodate both the participant head and the TMS coil. There are also MR sequences with ultra-short echo times (e.g., PETRA [100]) that can visualise the TMS coil without fiducial markers. Several short structural scans can be inserted throughout a scanning session to show the position of the TMS coil across the scanning session, but this does add additional time to a scan session. The key limitation here is that if the participant has moved a significant distance from the fixed coil position, this will only be detected after scanning has finished.

A more sophisticated, albeit costly, approach is MR-compatible neuronavigation. Optical infra-red frameless stereotaxy is recognised as the most precise way to localise the TMS coil over a target [101], and requires a dedicated system, with several manufacturers providing this possibility (e.g., Localite, Bonn, Germany; Rogue Research, Montreal, Canada). MR-compatible fiducial markers can be placed on both the participant and the TMS coil, as per non-MR TMS neuronavigation, with navigation then able to take place immediately before the participant is moved into the bore of the magnet, as well as at the end of the scanning session to verify coil location (in a similar approach as described above). Online neuronavigation can also take place continuously throughout scanning with a fully compatible system, opening the possibility of providing real-time feedback to participants to improve positioning [102], or making adjustments between blocks. In-bore tracking is not always practical, however, because the line of sight from camera to the trackers may be impeded by the TMS or head coil, mirror, or participant anatomy. In this regard, installing and utilising in-bore neuronavigation successfully may require a bespoke approach to integrate with an existing scanner and control room setup, as well as MR head coils, and TMS coil holders. Additionally, the precise implementation of in-bore neuronavigation may change according to the targeted brain region. It can also be challenging in practice to achieve stable participant tracking, as participant trackers typically need to be elevated

to be visible, and can be prone to movement if not securely affixed to the participant. Mitigations include performing participant registration with the participant already supine, mounting the tracker on a headband rather than affixing it to skin, or attaching the tracker to participant teeth using a mouthguard. Researchers will often need to work closely with neuronavigation manufacturers to optimise as many of the components as possible, and in-house solutions may be required to solve setup-specific challenges.

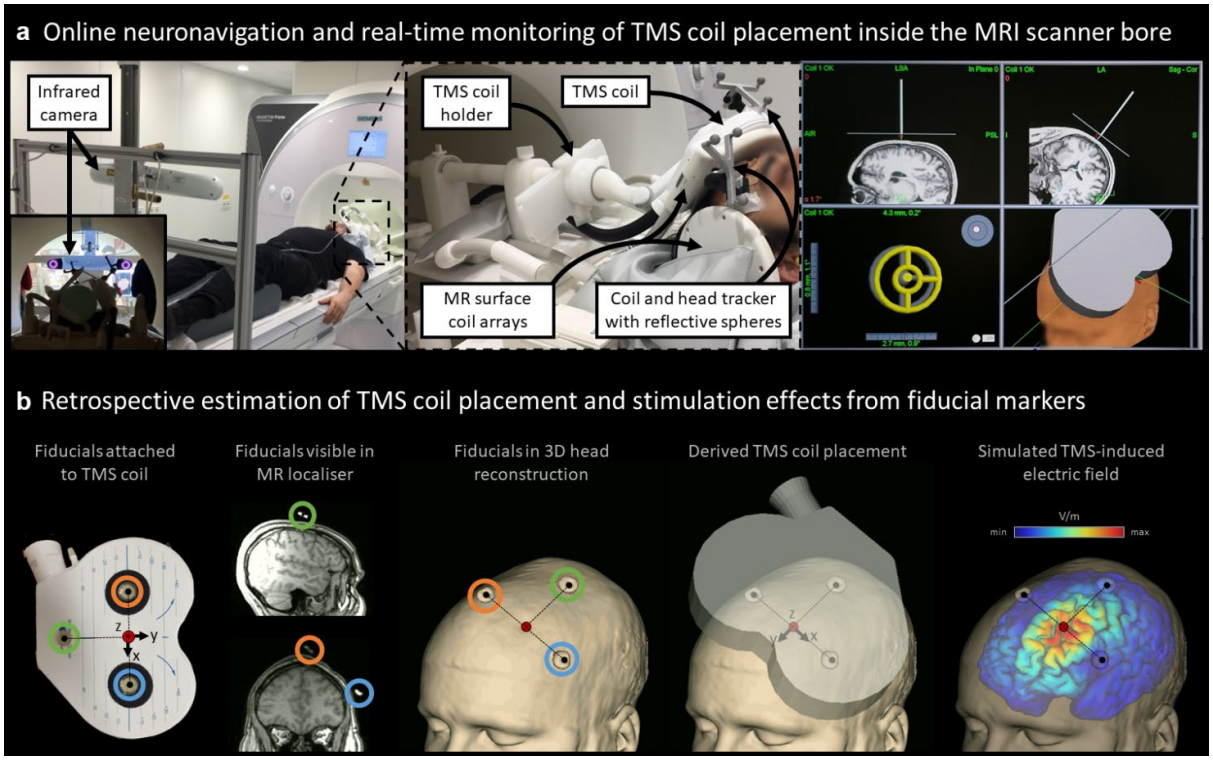


Figure 4. Monitoring of TMS coil placement during concurrent TMS-fMRI. **a**) Exemplary setup for online neuronavigation inside the MRI scanner room, using a MR-conditional infrared camera (plus frame; left) as well as trackers with reflective spheres attached to both the TMS coil and participant's head (middle). This setup also allows continuous real-time monitoring and recording of the TMS coil position inside the scanner bore throughout the concurrent TMS-fMRI measurement (with neuronavigation software; right). **b**) Retrospective localisation of the TMS coil using fiducial markers placed on the coil (encircled in orange, green, and blue). This approach can be used in the absence of in-bore neuronavigation and requires manual identification of the fiducials in a MR localiser image to reconstruct the TMS coil placement at the time of image acquisition. Based on both approaches, it is possible to retrospectively estimate the realised cortical stimulation (e.g., using E-field simulations; B, right), which can then be accounted for during later analyses. (Note: Red dot and x, y, and z arrows represent the coil centre coordinates and x, y, and z vectors, respectively, that comprise the affine 4x4 matrix typically used in neuronavigation or simulation software (e.g., SimNIBS; www.simnibs.org) to describe the TMS coil position within the image coordinate system).

Minimum technical requirements

To assist researchers entering the concurrent TMS-fMRI field, we now describe the minimum technical setup to successfully undertake a study:

(i) MR-compatible TMS coil holder to secure coil over target brain area during scanning. A commercial coil holder (MagVenture, Farum, Denmark), as well as in-house designs are currently in use by the field (**Figure 3**).
(ii) Head coil that can accommodate a TMS coil. Major MRI manufacturers (e.g., Siemens, GE) supply single-channel birdcage coils which are suitable for this purpose. Flexible RF coils are also offered by major manufacturers and are often readily available at research and clinical MR scanners.
(iii) Method for identifying cortical targets in the scanner. The most basic approach is the use of fiducial markers on the TMS coil, and appropriate structural scans should be acquired before, during, and at the end of a scanning session (**Figure 4**). Coil location can then be computed off-line to verify the location that had received stimulation.
(iv) Dedicated components to either an existing TMS setup, or through a commercially available TMS-fMRI system, which includes MR-compatible TMS coil and holder, leakage current cancellation, and RF noise filtering.
(v) A methodology to synchronise TMS pulses with MR image acquisition (see below for specific approaches). This will require receiving an MR volume or slice trigger pulses from the scanner and using it, for example via a direct connection to the stimulator, to trigger TMS delivery (e.g., with a desired delay set at the stimulator to accommodate interleaving with image acquisition). Alternatively, a PC or microcontroller controlling the experiment can receive scanner trigger pulses, and then deliver TTL pulses to the TMS machine at the appropriate time in the task and/or scanning sequence (**Figure 5**).
(vi) Data quality check of acquired data to ensure identification of artefacts (e.g., independent component analysis [103]).

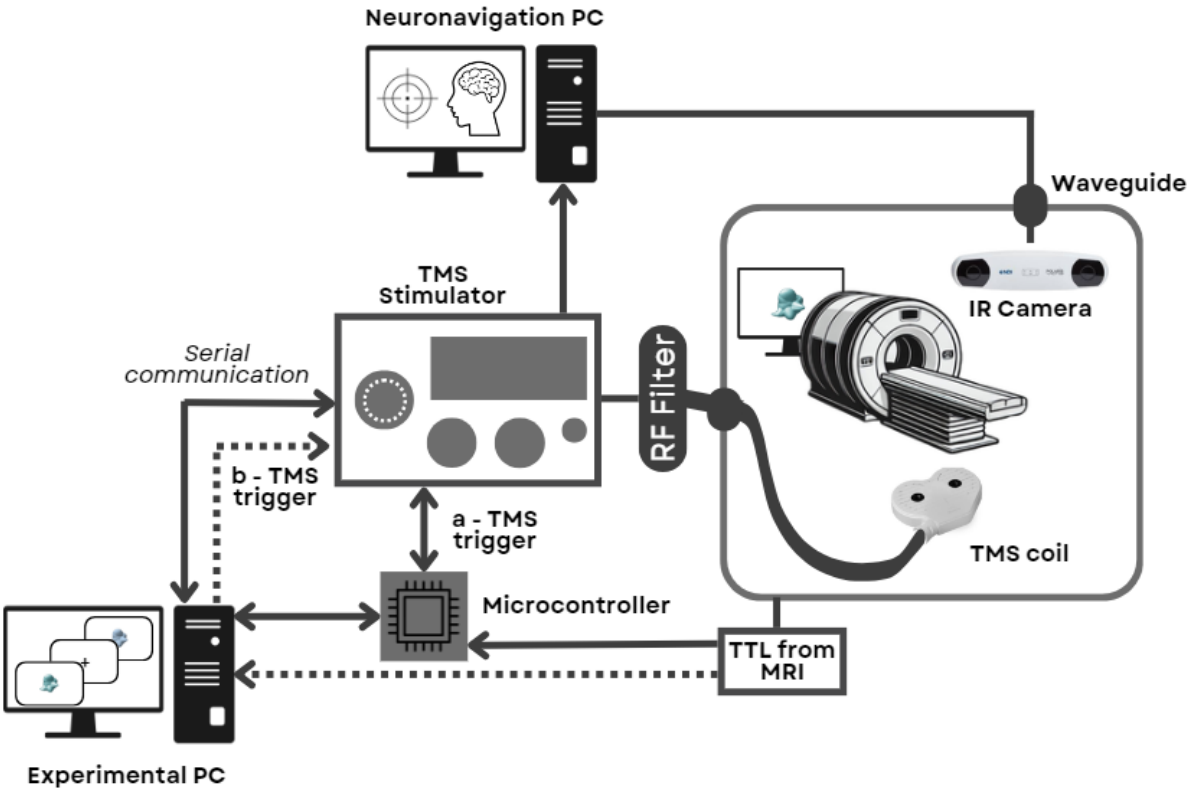


Figure 5. Example circuit diagram for arrangement of hardware for concurrent TMS-fMRI. Timing of the experimental paradigm, MR acquisition and TMS delivery can be synchronised via a microcontroller (solid lines), or directly by an Experimental PC (dotted lines). MR pulses (TTL) are either received by the microcontroller (**a**) or by the Experimental PC (**b**), which in turn trigger the TMS stimulator. When triggering the TMS stimulator at the appropriate point in the scanning and experimental sequence, temporal lags need to be accounted for precisely. A neuronavigation setup can also be included, with the tracking camera located inside the scanner room, connected to the neuronavigation PC in the control room through a waveguide.

MRI artefact avoidance and rejection

The delivery of TMS pulses during EPI acquisition can produce artefacts in the MRI data that are dependent on their timing within the sequence[74,104]. TMS applied during crusher gradients and the RF pulse can cause persistent disruption that may not be obvious during visual inspection [78,105]. In comparison, pulses delivered during k-space

readout will de-phase the transverse magnetisation and cause visible signal loss in the current slice [2]. The nature of the artefacts depends on a range of factors, including the angle of the TMS coil relative to the B0 field, the angle of slice acquisition, acquisition sequence, and distance from the TMS coil to the acquired slice [73,74]. One approach to concurrent TMS-fMRI is to deliver TMS during the readout of specific slices which are later replaced via temporal interpolation [23,28,78]. It is recommended that all slices are disrupted equally often, and that interslice gaps are used to avoid the disruption of adjacent slices [106].

Another approach is to avoid artefacts by delivering TMS during temporal gaps between MR volumes. These are typically up to 1s in duration with at least 50-100ms between the TMS pulse and the onset of the subsequent time to repetition (TR) [26,74,107]. While this leaves the MRI data intact, interleaving TMS between volumes reduces the temporal resolution of the MR data and experimental flexibility. TMS and MR volume onsets cannot be randomly jittered, meaning that the BOLD response to TMS cannot be sampled evenly across slices (although this may be less of a concern for faster multiband acquisitions). This approach also limits the frequency of the TMS protocol, which is determined by either the time between volumes or the number of pulses delivered during the volume gap. Interleaved slice acquisition MR protocols should be avoided with this approach, due to spin-history considerations.

A third approach is to deliver TMS during temporal gaps between slices in the MRI sequence. This method avoids artefacts while providing a larger range of possible stimulus onset asynchronies, but may increase the TR more than the minimum inter-volume gaps, requiring multiband acquisition for acceptable TRs. The timing of TMS is constrained by the MR parameters, particularly the time taken to acquire a single slice and the length of the gap. However, adjusting the duration of the temporal gaps between slices allows for flexibility in the stimulation patterns that can be delivered, allowing scans to be tailored to accommodate a variety of rTMS pulse patterns that may be relevant to the research question. Artefacts can be avoided with as little as 40ms between TMS and subsequent slice [108] and this approach has been used with repetitive TMS protocols such as theta burst volleys [25], 2-Hz [108,109], 4-Hz [74], and 10-Hz Hz [108,109] stimulation. The choice of TMS stimulation protocol (e.g., frequency) is of

course dependent on the research question being studied (see When to use Concurrent TMS-fMRI, and reviews in [9,110]).

To achieve precise timing of pulses relative to the scanning sequence, accurate communication between the stimulator, MR scanner, and an experimenter's software/PC is necessary. The specific setup of this communication pathway will vary based on each scanning unit's setup, but an example arrangement is shown in Figure 5. Solutions include controlling stimulator settings such as stimulation intensity over serial port communication [111], while using temporally precise TTL pulses to trigger TMS. The BEST toolbox [77] gives one example of a physical setup plan, involving an Arduino microcontroller to coordinate slice or volume pulses coming from the scanner, with a TTL pulse delivery to a connected TMS machine at a specified following time. Connection to the experimenter's PC can be included to time TMS pulse delivery relative to a point in a behavioural task of interest. Timing fidelity can be validated using an oscilloscope.

TMS artefacts are mostly due to leakage currents and vibrations from coil discharge[71]. The former is an area noted by TMS-fMRI system manufacturers to address in future system iterations, with some leakage current prevention already in place in the MagVenture system. The latter is more dependent on coil orientation relative to B0, which is, in turn, determined by the targeted brain area, and the associated physical properties with placing the coil over the area. For new coil types, coil positions, or new coil holder solutions, the temporal gap between the pulse and the subsequent MR acquisition would need to be determined to avoid image artefacts while keeping the length of the gap short to improve temporal SNR [74,108]. Coil vibration can also be dampened to some extent by the TMS coil holder, as well as TMS coil design adjustments. Notably, there are also other sources of TMS coil movement, such as spontaneous head movements or TMS-triggered scalp muscle twitches underlying the coil, that may or may not be time-locked to the stimulation, and that will cause similar inhomogeneity artefacts as coil vibrations.

Dosing

It is considered best practice to individualise TMS intensity for each individual [112]. Most commonly, intensity individualization is based on cortical excitability assessed via motor threshold (MT) [113] . This value can then be adjusted for different brain regions based on target depth [114] or E-field modelling [115,116]. For this, the same stimulation setup should be used for MT assessment and in-scanner stimulation phases. Currently, TMS-fMRI hardware limitations sometimes prevent stimulation at certain intensities due to coil heating or power limitations. When these cases cannot be avoided, it is critical to report the realised stimulation intensity.

Sample size

As in all fMRI studies, statistical calculation of the optimal sample size requires an appropriate estimate of the expected effect size. This prerequisite is difficult to meet in most concurrent TMS-fMRI studies, as effect sizes will depend on many factors including the specific task/contrast, stimulation parameters (e.g., single pulse/burst/train, intensity, and frequency), stimulation site, site of interest for BOLD signal evaluation, MR coil setup, imaging sequence, etc. While the field is still young, the exact influence of these different parameters is yet unknown, and this often makes it essentially impossible to obtain robust *a priori* estimates of effect sizes for any particular combination of parameters. In practice, a wide range of sample sizes have been used in concurrent TMS-fMRI studies, ranging from N = 1 to N = 49, with sample sizes tending to increase slightly over the years[2]. Moreover, there are often significant practical barriers to acquiring very large numbers of subjects with this methodology One option to address this challenge is to focus on acquiring more high-quality data from each individual, since reproducibility markedly improves with more scans at the individual-level[117]. This approach has been useful, feasible, and effective for concurrent TMS-fMRI where often hundreds of trials are acquired across multiple runs within one participant. Accordingly, concurrent TMS-fMRI has demonstrated good within-subject reliability, as long as the number of trials is sufficient [118]. At this point it is not possible to make general recommendations about an optimal sample size in concurrent TMS-fMRI. Instead, there is recognition that statistical power has to be balanced against practical constraints, and that a range of sample sizes can be scientifically meaningful, including both small N studies where the focus is on in-depth

analyses of individual subjects using many trials, runs, and sessions (e.g., [24-27,64,65,119]) and larger group samples (>30 participants) that test generalizability and/or compare different populations.

Control Conditions

One of the most challenging aspects of experimental design for TMS-fMRI is the selection of suitable controls. This issue has been discussed extensively in the wider TMS literature, citing auditory and tactile effects of TMS on brain activity and cognition (e.g., [2,118,120-122]). Therefore, combining various control conditions tailored to the research question may be warranted, if possible and pragmatic for the experimental design. Control conditions in concurrent TMS-fMRI include delivering TMS at a subthreshold intensity [23,28,123] or placing a solid spacer between the TMS coil and the participant's head [124]. Active control conditions are also encouraged, such as delivering stimulation at a different location, delivering stimulation at different time(s) within task trials or cognitive processes, or using different stimulation frequencies or patterns (**Figure 6**). Each of the available control options controls for different aspects of the TMS-effect (**Table 2, Table 3**), and, as in TMS in general, no single option controls for everything. It is also important to consider that the most scientifically preferred control option(s) may not always be feasible in practice. In particular, the choice of control condition may impact experimental timing and subject burden. For example, using a solid spacer or a different stimulation target will require repositioning the subject in the scanner (and thus, acquiring additional localizers), which will add to the amount of time a participant is required to lie in the scanner. By contrast, a low intensity control can be programmed into the TMS delivery routines without requiring additional time spent on participant setup. Thus, the choice of appropriate control depends heavily on the research question and aims of the study, as well as pragmatic considerations in the context of concurrent MRI.

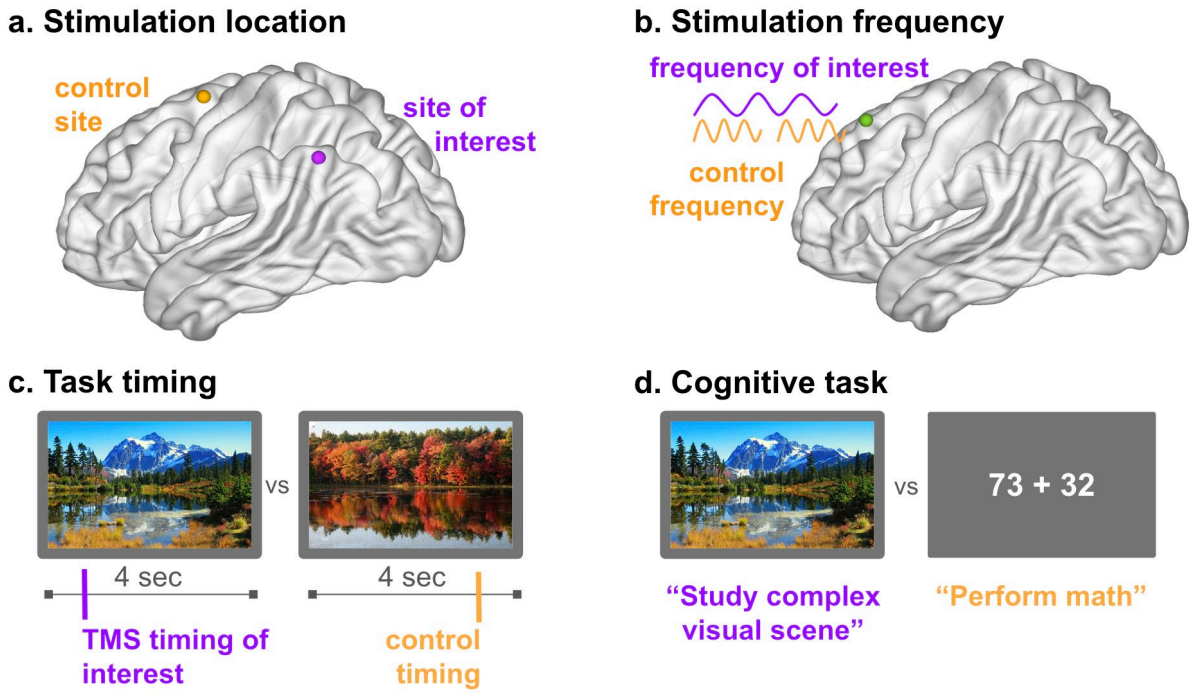


Figure 6. Examples of active control conditions. **a**) Stimulation is delivered to two different target locations, the site of interest (purple) and the control site, using the same stimulation frequency and intensity. **b**) Stimulation is delivered to the same location at the same intensity, but with two different frequencies/patterns, a condition of interest (purple) and a control condition (yellow). **c**) Stimulation is delivered to the same location with the same pattern and intensity but targeting specific times during cognitive task or during stimulus presentation (purple) for some trials, and at another time for other trials (yellow). **d**) The same stimulation location, frequency/pattern, and intensity is used, but a different task is used to engage different cognitive processes and brain networks.

	Auditory (e.g., clicks)	**Muscle/nerve stimulation**	**Mechanical forces (e.g., coil vibrations)**
Plastic spacer	s	Somewhat	s
Sub-threshold intensity control	Somewhat	Somewhat	Somewhat
Control site	(s)	(s)	s
TMS Timing (relative to task)	s	s	s

Control frequency/rhythm	(s)	(s)	(s)
Control task/brain state	s	s	s

Table 2. Non-transcranial peripheral co-stimulation effects and how they may be controlled for. ✓ effectively controlled; (✓) controlled under some circumstances (see text); "somewhat" partially controlled.

Control condition	**Insight gained**	**Limitations**
Sham stimulation (spacer)	Baseline/ low-stimulation comparison	"Realistic" sham conditions hard to establish, may be possible to subjectively distinguish from active stimulation, low spatial specificity of inference
Sub-threshold intensity control	low-stimulation comparison	Often easy to subjectively distinguish from active stimulation intensity, low spatial specificity of inference
Active Control site	Spatial specificity	Interconnecting brain tissue may result in unexpected interactions, potential modulation of other relevant cognitive support processes by "control" region
TMS timing (e.g., relative to task)	Temporal specificity	Potential expectation or priming behaviours due to non-stimulation effects
Control task/ brain state	Task, cognitive process, or brain state specificity	Potentially difficult to match, e.g., in terms of cognitive load and support processes involved
Control frequency or pattern	Frequency or pattern specificity	Potential side effects that modulate task-relevant processes, potentially necessary to adjust MR sequence for the control pattern thereby lowering comparability

Table 3. Summary of potential control conditions.

Sub-threshold and sham stimulation

Currently, there are no MRI-compatible TMS placebo coils available on the market. Instead, stimulation may be delivered using the active TMS coil but with stimulation at sub-threshold (i.e., below motor threshold) intensity. This will mimic some of the auditory noise and somatosensory experience of active stimulation and is the only control option that can easily be interleaved trial-wise with active TMS. Alternatively, researchers may opt to secure an MRI-safe solid spacer between the TMS coil and skull [124]. This will mimic the auditory noise and much of the tactile vibrations while also

providing a lower intensity TMS effect on the brain. A spacer can work well in particular for scalp positions where active stimulation does not lead to muscle coactivation. However, using a spacer will take up more room in an already crowded setup and cannot be interleaved with active TMS trials. In both cases, care should be taken, as even subthreshold intensities can cause downstream effects [32,125].

To address the concern that subjects can differentiate these (and other) controls from active TMS, researchers may consider assessing subjective stimulation-related sensations (e.g., see questionnaire reported in [126]), either to optimise the experimental design or to inform interpretation of TMS effects.

Control sites

An active control at a different stimulation location allows researchers to test whether the effects of TMS are specific to a particular site/network, rather than due to the mere presence of stimulation. A suitable control location should be 1) distinct from the location of interest, 2) accessible within the scanner, 3) hypothesised to have a differential or null effect on the cognitive or neural processes of interest, and 4) ideally, have a similar auditory and somatosensory profile to the site of interest. However, stimulating cortical nodes of brain networks can cause downstream, distributed effects [32,64,127] which may have unintentional consequences [128,129]. Piloting - including offline measures of seed-based functional connectivity, network-precision connectivity, tractography, and/or task-based activations - may inform potential locations. Control sites in the literature include the vertex [26,130], analogous regions in the opposite hemisphere [27], out-of-network locations (e.g., dlPFC versus M1 stimulation effects on the sgACC [35]); parietal versus SMA stimulation effects on hippocampal modulation [25]), and direct comparison between active sites (e.g., occipital versus parietal stimulation on lower versus higher order visual processing [131]).

Task Timing

Another possible control condition is the timing of TMS within a cognitive task. Small variations in TMS delivery within a trial can be almost indistinguishable to participants, but have different effects [38,132] revealing temporally precise information about neural mechanisms. However, change in timing itself may induce behavioural changes for

example due to temporal expectancy. This control condition is therefore best suited to studies in which there is a temporal dependency of the mechanism of interest, and the task and/or TMS paradigm permits application of TMS at different times across a trial.

Task specificity

Task or cognitive process-specificity can be tested by including a control task that is hypothesised to engage different brain regions or neural mechanisms (also see [133]), and should therefore be unaffected by the active TMS condition of interest. This control allows stimulation parameters to be exactly matched across the two tasks (e.g., same target, same pattern, same intensity, same timing). It relies on careful consideration of the brain regions and networks that support the task-of interest and the control task, and a good degree of confidence that they rely on distinct brain regions and/or dynamics that can be differently targeted with TMS. One approach is to use two different trial types which engage different cognitive processes and brain regions. For example, Hermiller et al., [25] compared the effects of hippocampal-cortical memory network-targeted stimulation on intentional memory forming trials (visual outdoor scene stimuli; evokes strong hippocampal BOLD signal) to odd/even number judgement trials (which do not evoke hippocampal BOLD activity). Another approach is to implement a control task manipulation within the same trial. Jackson et al.[23] used a task where each trial included task-relevant and distracting information, and showed a specific effect of TMS on task-relevant, and not distracting information (see also [28])

Control frequencies/patterns

Where the active TMS is hypothesised to have an effect at a specific frequency, a suitable control may be to deliver TMS an alternative frequency, or using a matching number of pulses in an arrhythmic manner [134]. When selecting control conditions using different stimulation frequencies/patterns in TMS-fMRI, one must consider the scan sequence(s), as the timing of TMS pulses relative to MR slices affects the artefacts (see above). Care should be taken to ensure that control frequencies/patterned stimulation condition(s) will not introduce differential artefacts or signal loss compared to the condition of interest. In some cases, different scan sequences may be necessary in order to employ different frequencies/patterns. For example, Hermiller et al., [25] developed two different custom scan sequences: one to accommodate theta-burst

patterned TMS, and one to accommodate 12.5-Hz rTMS. However, utilizing control frequencies/patterns may result in unmatched sensory sensations (e.g., different rhythm of auditory clicks).

Controls summary

As with all TMS work, no single option accounts for all possible facets of non-stimulation TMS effects, and researchers will need to prioritise the aspects that they control for based on their research questions. Forming hypotheses that are task-specific, network- (or region-) specific, frequency-/pattern-specific, and/or timing-specific will inform this choice. For example, if the research question investigates region-specific effects, then an active stimulation location may serve as a reasonable control condition. Ideally, control conditions may also serve as 'sanity checks' for data quality, for example to verify activation of auditory cortex activation in response to trials with TMS versus without TMS (for example, see [25]). Given the technical challenges and participant demand particular to concurrent TMS-fMRI, and the fact that more conditions require more time in the scanner, adding to participant burden and study expenses, multiple controls may not always be feasible. One should also be mindful of the statistical analysis approach to be used, as multiple controls will often require correction for multiple comparisons. In some cases, it may be possible to refer to prior results or even to run offline TMS experiments (without fMRI) to test for behavioural effects of multiple controls, to determine which will be appropriate to use in the scanner. Despite these challenges, important benefits of including appropriate control conditions in concurrent TMS-fMRI experiments include richer datasets which allow insight into the control conditions themselves, as the fMRI allows visualisation of the consequences of experimental manipulations. In sum, there is no one single perfect control condition; rather, the pros and cons of each (**Tables 3,4**) need to be considered with a pragmatic approach to address the research question and goals of the study when utilising concurrent TMS-MRI.

Summary

In summary, researchers navigating TMS-fMRI have to consider multiple interrelated conceptual and practical aspects (**Figure 1**) which can constrain or make possible new scientific insight. They first must consider whether the use of this technically

demanding technique is justified by the research question, for example through alignment to one or more of the Use Cases in which concurrent TMS-fMRI allows for important experimental flexibility, scientific insight, and clinical promise, which would not otherwise be possible (see **Table 1**). They must consider what general approach will answer their question, including whether the most powerful insight would come from disrupting function, enhancing function, and/or tracking signal propagation, and the specific TMS parameters and experimental design that will allow them to do so. Accordingly, they must also consider what aspects of the TMS perturbation are most important to control for according to their desired inference, and weigh this against the practical considerations of the different options laid out here (see Control Conditions). They should then tailor, as far as possible, the practical implementation. They will want to select a head coil that best enables them to answer their research question (e.g., do they want to study direct effects under the coil, or do they need a set up with sufficient whole brain signal to track downstream effects?), and will need to meet the minimum technical requirements for TMS delivery, coil placement and target monitoring. Finally they will need to choose a scheme for artefact avoidance and rejection that balances artefact tolerance against the experimental flexibility and MRI signal quality required for the research question.

Limitations and Future Outlook

Concurrent TMS-fMRI represents a step-change in our ability to noninvasively study human neural processes in vivo and unravel causal brain-cognition relationships with unparalleled methodological rigour. It allows us to develop and test new theories on fundamental brain function, as well as to validate and personalise clinical neuromodulation protocols. Nonetheless, the technique still suffers from various shortcomings that require further research and development. One of the limiting factors relates to the main purpose of this consensus article: the critical mass of labs actively contributing to concurrent TMS-fMRI research. Although concurrent TMS-fMRI is no longer a niche field and significant technical challenges have been solved in recent years, many TMS and/or fMRI colleagues still shy away from implementing the concurrent TMS-fMRI approach, likely due to a lack of clear guidelines, protocols and best practice. We hope the current article will help to overcome this hurdle and increase the number of researchers conducting concurrent TMS-fMRI studies; as well

as accelerating our knowledge, skill sharing, and technical development, this will open the possibility of larger e.g., multi centre studies with harmonised protocols and parameters to validate generalizability and replicability, and for potentially conducting population comparison studies.

As we have shown, concurrent TMS-fMRI allows for new insight that is not otherwise possible. However, there are still important limitations on inference. First, concurrent TMS-fMRI is subject to many of the general limitations of fMRI, including limits on temporal and spatial resolution, and limits on interpretation of the BOLD signal [135]. Second, some of the general limitations of TMS, including uncertainty about its physiological mechanism [136] and the large potential TMS parameter space, present corresponding challenges for experimental design and interpretation of TMS-fMRI data. Inference will become easier as knowledge of physiological effects grows in the TMS field broadly, and as we have shown, concurrent TMS-fMRI can contribute to this endeavour in several ways. In the future, progress may come from converging evidence across techniques and species, by triangulating with other MR indices of structure and function (e.g., diffusion weighted imaging, magnetic resonance spectroscopy), and/or by incorporating computational modelling to capture and formally relate TMS, BOLD and behaviour [137].

Epistemologically, the term causality remains tricky even for concurrent TMS-fMRI studies. Stimulating a particular cortical target region with TMS inside the MR scanner during the execution of a cognitive task may reveal network effects in several brain regions as well as performance changes. The question of how these observations are related remains uncertain, and - outside of the directly targeted region - is based on a correlation between neural and performance changes. One approach may be to target TMS to the identified remote regions directly, to assess the respective neural network changes as well as behavioural effects of those sites, but this may not always be possible, particularly if those regions are located deeper in the brain. To complicate things further, the behavioural change itself (induced by stimulating a brain region) may be a cause for some of the observed neural activity changes. While some of these limitations may be addressed by clever experimental designs and control comparisons, it is important to remember that concurrent TMS-fMRI data need to be interpreted carefully, since causal chains can be long (e.g., [48]).

Technically, as for the entire field of non-invasive neuromodulation, concurrent TMS-fMRI setups will benefit from engineering advances. In particular, development of a range of MR compatible TMS coils to improve specificity of effects, or to tailor focality and depth of penetration, would be welcome, as would development of a convincing placebo coil. Future advances will also come from development of MR head coils that can accommodate the TMS coil while allowing for best practice MRI acquisition and analysis approaches, for example to enhance SNR, respect cortical geometry, and minimise smoothing (e.g., [138,139]). In addition, an unrealised potential benefit of the concurrent approach is the possibility of adjusting TMS stimulation online according to the induced BOLD response (e.g., closed loop), for which the technology is not currently available (but see [85] or a promising step in this direction).

Finally, from concurrent TMS-fMRI research it has become clear that TMS has both local and remote effects and that these network effects depend on stimulation target, dose, timing, and brain state. One area that TMS-fMRI has not yet made as much progress is in studying oscillatory states - yet neural oscillations represent the temporal domain by which network communication is structured in the brain, in which regions phase-lock, couple and uncouple, within specific oscillatory frequency bands. Therefore, adding EEG to the concurrent TMS-fMRI approach may allow for important new insight by indexing the oscillatory brain state at the time of TMS application. Peters et al (2020) recently pioneered a concurrent EEG-TMS-fMRI setup demonstrating TMS-induced oscillatory-state-dependent network effects [24]. This has implications for fundamental cognitive neuroscience to test theories on oscillation-network coupling in human cognition, and for future clinical applications such as state-dependent closed loop neuromodulation. The lessons we learn, including dose- and state-dependency, may also be applied to and validated using other forms of non-invasive brain stimulation, such as electrical and ultrasound stimulation, which can also be applied with concurrent fMRI following the principles and guidelines outlined in this article.

In summary, concurrent TMS-fMRI is now technically achievable and offers unique opportunities for insight into causal brain processes. The aim of this consensus and guide is to bring to fruition the work of teams of concurrent TMS-fMRI researchers from around the world who have driven this most challenging of techniques forward since it

was first published as a research approach in 1998 [107]. Our ambition is that concurrent TMS-fMRI enters into the mainstream as an invaluable contributor to the collective pursuit of understanding the human brain.

Funding Sources

This work was funded by a wide range of sources including salary and project support to the authors. These include UKRI MRC intramural funding (SUAG/093/G116768) and a UKRI BBSRC grant (BB/S019170/1) to A.W., a UKRI MRC Promote Units as National Assets Award (MC_PC_20046), an NWO-OC grant (406.20.GO.004) from the Dutch Research Council (NWO) to A.T.S., research grants by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation. No. 525127358 and No. 525176435) to T.O.B.; HA 6314/4-2 and HA 6314/10-1 to G.H., and the European Research Council (ERC-2021-COG 101043747) to G.H.; National Institutes of Health grants (R61 MH135428; R01 MH120811) and funding from the Hart Fund in Cognitive Neuroscience and New Venture Fund/The Foundation for OCD Research) to D.J.O.; Lise Meitner Excellence Funding by the Max Planck Society to G.H; an Early Career Research Award from Centre for Integrative Neuroscience Discovery, University of Cambridge to M.A.; Austrian Science Fund (P33180), Austrian Ministry for Science and Education (103HSK02), and European Commission (612022) to C.W.; the Federal Ministry of Education and Research (BMBF, grant no. 01GQ2201) to O.N.; NIMH Intramural Research Program (ZIAMH002955) supporting L.B. and B.L.; and the Lundbeck Foundation (grants R313-2019-622 and R244-2017-196) and the Innovation Fund Denmark (Grand Solutions grant 9068-00025B) supporting A.T. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

Author Contributions

This work arises from a series of consensus discussion meetings held at an international workshop on TMS-fMRI organised by E.F., A.W., C.W., and M.T, in Greece, May 2023. The writing of this consensus paper was led by A.W., E.F., M.S.H., and A.T.S. Authors contributed as follows. A.W.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing, Visualisation, Supervision, Project Administration; E.F.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing, Visualisation, Supervision; M.A.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing, Visualisation; Y.B.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing, Visualisation; T.O.B.: Writing -

Reviewing and Editing; L.B.: Writing - Original Draft; M.B.: Conceptualisation, Writing - Reviewing and Editing, Visualisation; R.F.H.C: Conceptualisation, Writing - Reviewing and Editing; R.M.C: Conceptualisation, Writing - Original Draft, M.M.C.: Writing - Reviewing and Editing; R.M.C.: E.G.: Writing - Reviewing and Editing, Visualisation; G.H.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing; J.B.J.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing; M.K.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing; P.K.: Writing - Original Draft; O.L.: Writing - Original Draft; B.L.: Conceptualisation, Writing - Reviewing and Editing; M.L.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing, Visualisation; C.M.: Writing - Original Draft; E.M.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing; O.N.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing; D.J.O.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing, Visualisation; A.C.R: Conceptualisation; T.S.: Conceptualisation; A.L.S.: Writing - Reviewing and Editing; C.L.S.: Conceptualisation, Writing - Original Draft; A.T.: Writing - Reviewing and Editing; M.T.: Writing - Reviewing and Editing; Y.T.: Conceptualisation, Writing - Reviewing and Editing; M.V.: Conceptualisation, Writing - Reviewing and Editing; C.W.: Conceptualisation, Writing - Reviewing and Editing; M.S.H.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing, Visualisation, Supervision; A.T.S.: Conceptualisation, Writing - Original Draft, Writing - Reviewing and Editing, Supervision.

Competing Interests

A.T.S. is chief scientific advisor of PlatoScience Medical and Alpha Brain Technologies, CEO of Neurowear Medical, Director of the Clinical TMS Certification Course (www.tmscourse.eu), and received equipment support from MagVenture, MagStim, and Deymed. C.W. is a member of the scientific advisory board of Brightmind.AI GmbH and a shareholder of ALSIX GmbH, supplier of tailored MR hardware. P.K. is employed by Localite GmbH, manufacturer of TMS neuronavigation devices. M.K., C.M., and Y.T., are employees of MagVenture Inc, suppliers of TMS-fMRI solutions. R.M.C is an employee of Rogue Research Solutions, supplier of TMS neuronavigation devices.

References

1 Driver, J., Blankenburg, F., Bestmann, S., Vanduffel, W. & Ruff, C. C. Concurrent brain-stimulation and neuroimaging for studies of cognition. *Trends Cogn Sci* **13**, 319-327, doi:10.1016/j.tics.2009.04.007 (2009).

2 Bergmann, T. O. *et al.* Concurrent TMS-fMRI for causal network perturbation and proof of target engagement. *Neuroimage* **237**, 118093, doi:10.1016/j.neuroimage.2021.118093 (2021).

3 Feredoes, E., Tononi, G. & Postle, B. R. The neural bases of the short-term storage of verbal information are anatomically variable across individuals. *J Neurosci* **27**, 11003-11008, doi:10.1523/JNEUROSCI.1573-07.2007 (2007).

4 Sack, A. T. *et al.* Optimizing functional accuracy of TMS in cognitive studies: a comparison of methods. *J Cogn Neurosci* **21**, 207-221, doi:10.1162/jocn.2009.21126 (2009).

5 Sack, A. T., Kohler, A., Linden, D. E., Goebel, R. & Muckli, L. The temporal characteristics of motion processing in hMT/V5+: combining fMRI and neuronavigated TMS. *Neuroimage* **29**, 1326-1335, doi:10.1016/j.neuroimage.2005.08.027 (2006).

6 Hebscher, M. & Voss, J. L. Testing network properties of episodic memory using non-invasive brain stimulation. *Curr Opin Behav Sci* **32**, 35-42, doi:10.1016/j.cobeha.2020.01.012 (2020).

7 Wang, J. X. *et al.* Targeted enhancement of cortical-hippocampal brain networks and associative memory. *Science* **345**, 1054-1057, doi:10.1126/science.1252900 (2014).

8 Tambini, A., Nee, D. E. & D'Esposito, M. Hippocampal-targeted Theta-burst Stimulation Enhances Associative Memory Formation. *J Cogn Neurosci* **30**, 1452-1472, doi:10.1162/jocn_a_01300 (2018).

9 Beynel, L. *et al.* Online repetitive transcranial magnetic stimulation during working memory in younger and older adults: A randomized within-subject comparison. *PLoS One* **14**, e0213707, doi:10.1371/journal.pone.0213707 (2019).

10 Dave, S., VanHaerents, S., Bonakdarpour, B., Mesulam, M. M. & Voss, J. L. Stimulation of distinct parietal locations differentiates frontal versus hippocampal network involvement in memory formation. *Curr Res Neurobiol* **3**, 100030, doi:10.1016/j.crneur.2022.100030 (2022).

11 Dave, S., VanHaerents, S. & Voss, J. L. Cerebellar Theta and Beta Noninvasive Stimulation Rhythms Differentially Influence Episodic Memory versus Semantic Prediction. *J Neurosci* **40**, 7300-7310, doi:10.1523/JNEUROSCI.0595-20.2020 (2020).

12 Hermiller, M. S. *et al.* Evidence from theta-burst stimulation that age-related de-differentiation of the hippocampal network is functional for episodic memory. *Neurobiol Aging* **109**, 145-157, doi:10.1016/j.neurobiolaging.2021.09.018 (2022).

13 Hermiller, M. S., VanHaerents, S., Raij, T. & Voss, J. L. Frequency-specific noninvasive modulation of memory retrieval and its relationship with hippocampal network connectivity. *Hippocampus* **29**, 595-609, doi:10.1002/hipo.23054 (2019).

14 Eldaief, M. C., Halko, M. A., Buckner, R. L. & Pascual-Leone, A. Transcranial magnetic stimulation modulates the brain's intrinsic activity in a frequency-

dependent manner. *Proc Natl Acad Sci U S A* **108**, 21229-21234, doi:10.1073/pnas.1113103109 (2011).
15 Gratton, C., Lee, T. G., Nomura, E. M. & D'Esposito, M. The effect of theta-burst TMS on cognitive control networks measured with resting state fMRI. *Front Syst Neurosci* **7**, 124, doi:10.3389/fnsys.2013.00124 (2013).
16 Friehs, M. A. *et al.* No effects of 1 Hz offline TMS on performance in the stop-signal game. *Sci Rep* **13**, 11565, doi:10.1038/s41598-023-38841-z (2023).
17 De Pisapia, N., Barchiesi, G., Jovicich, J. & Cattaneo, L. The role of medial prefrontal cortex in processing emotional self-referential information: a combined TMS/fMRI study. *Brain Imaging Behav* **13**, 603-614, doi:10.1007/s11682-018-9867-3 (2019).
18 Min, Y. S. *et al.* Neuromodulatory effects of offline low-frequency repetitive transcranial magnetic stimulation of the motor cortex: A functional magnetic resonance imaging study. *Sci Rep* **6**, 36058, doi:10.1038/srep36058 (2016).
19 Petitet, P., Noonan, M. P., Bridge, H., O'Reilly, J. X. & O'Shea, J. Testing the inter-hemispheric competition account of visual extinction with combined TMS/fMRI. *Neuropsychologia* **74**, 63-73, doi:10.1016/j.neuropsychologia.2015.04.021 (2015).
20 Hoogendam, J. M., Ramakers, G. M. & Di Lazzaro, V. Physiology of repetitive transcranial magnetic stimulation of the human brain. *Brain Stimul* **3**, 95-118, doi:10.1016/j.brs.2009.10.005 (2010).
21 Huang, Y. Z., Edwards, M. J., Rounis, E., Bhatia, K. P. & Rothwell, J. C. Theta burst stimulation of the human motor cortex. *Neuron* **45**, 201-206, doi:10.1016/j.neuron.2004.12.033 (2005).
22 Wischnewski, M. & Schutter, D. J. Efficacy and Time Course of Theta Burst Stimulation in Healthy Humans. *Brain Stimul* **8**, 685-692, doi:10.1016/j.brs.2015.03.004 (2015).
23 Jackson, J. B., Feredoes, E., Rich, A. N., Lindner, M. & Woolgar, A. Concurrent neuroimaging and neurostimulation reveals a causal role for dlPFC in coding of task-relevant information. *Commun Biol* **4**, 588, doi:10.1038/s42003-021-02109-x (2021).
24 Peters, J. C. *et al.* Concurrent human TMS-EEG-fMRI enables monitoring of oscillatory brain state-dependent gating of cortico-subcortical network activity. *Commun Biol* **3**, 40, doi:10.1038/s42003-020-0764-0 (2020).
25 Hermiller, M. S., Chen, Y. F., Parrish, T. B. & Voss, J. L. Evidence for Immediate Enhancement of Hippocampal Memory Encoding by Network-Targeted Theta-Burst Stimulation during Concurrent fMRI. *J Neurosci* **40**, 7155-7168, doi:10.1523/JNEUROSCI.0486-20.2020 (2020).
26 Ruff, C. C. *et al.* Concurrent TMS-fMRI and psychophysics reveal frontal influences on human retinotopic visual cortex. *Curr Biol* **16**, 1479-1488 (2006).
27 Sack, A. T. *et al.* Imaging the brain activity changes underlying impaired visuospatial judgments: simultaneous FMRI, TMS, and behavioral studies. *Cereb Cortex* **17**, 2841-2852, doi:10.1093/cercor/bhm013 (2007).
28 Feredoes, E., Heinen, K., Weiskopf, N., Ruff, C. & Driver, J. Causal evidence for frontal involvement in memory target maintenance by posterior brain areas during distracter interference of visual working memory. *Proc Natl Acad Sci* **108**, 17510-17515, doi:10.1073/pnas.1106439108 (2011).
29 Heinen, K., Feredoes, E., Weiskopf, N., Ruff, C. C. & Driver, J. Direct evidence for attention-dependent influences of the frontal eye-fields on

feature-responsive visual cortex. *Cereb Cortex* **24**, 2815-2821, doi:10.1093/cercor/bht157 (2014).
30 Hawco, C. *et al.* Spread of activity following TMS is related to intrinsic resting connectivity to the salience network: A concurrent TMS-fMRI study. *Cortex* **108**, 160-172, doi:10.1016/j.cortex.2018.07.010 (2018).
31 Navarro de Lara, L. I. *et al.* High-sensitivity TMS/fMRI of the Human Motor Cortex Using a Dedicated Multichannel MR Coil. *Neuroimage* **150**, 262-269, doi:10.1016/j.neuroimage.2017.02.062 (2017).
32 Bestmann, S., Baudewig, J., Siebner, H. R., Rothwell, J. C. & Frahm, J. Subthreshold high-frequency TMS of human primary motor cortex modulates interconnected frontal motor areas as detected by interleaved fMRI-TMS. *Neuroimage* **20**, 1685-1696, doi:10.1016/j.neuroimage.2003.07.028 (2003).
33 Oathes, D. J. *et al.* Resting fMRI-guided TMS results in subcortical and brain network modulation indexed by interleaved TMS/fMRI. *Exp Brain Res* **239**, 1165-1178, doi:10.1007/s00221-021-06036-5 (2021).
34 Tik, M. *et al.* Acute TMS/fMRI response explains offline TMS network effects - An interleaved TMS-fMRI study. *Neuroimage* **267**, 119833, doi:10.1016/j.neuroimage.2022.119833 (2023).
35 Vink, J. J. T. *et al.* A novel concurrent TMS-fMRI method to reveal propagation patterns of prefrontal magnetic brain stimulation. *Hum Brain Mapp* **39**, 4580-4592, doi:10.1002/hbm.24307 (2018).
36 Oathes, D. J. *et al.* Non-invasively targeting, probing and modulating a deep brain circuit for depression alleviation. *Nature Mental Health* **1**, 1033-1042, doi:10.1038/s44220-023-00165-2 (2023).
37 Grosshagauer, S. *et al.* Chronometric TMS-fMRI of personalized left dorsolateral prefrontal target reveals state-dependency of subgenual anterior cingulate cortex effects. *Mol Psychiatry* **29**, 2678-2688, doi:10.1038/s41380-024-02535-3 (2024).
38 Hawco, C. *et al.* Differing Time of Onset of Concurrent TMS-fMRI during Associative Memory Encoding: A Measure of Dynamic Connectivity. *Front Hum Neurosci* **11**, 404, doi:10.3389/fnhum.2017.00404 (2017).
39 Tik, M. *et al.* Concurrent TMS/fMRI reveals individual DLPFC dose-response pattern. *Neuroimage* **282**, 120394, doi:10.1016/j.neuroimage.2023.120394 (2023).
40 Ge, R. *et al.* Predictive Value of Acute Neuroplastic Response to rTMS in Treatment Outcome in Depression: A Concurrent TMS-fMRI Trial. *Am J Psychiatry* **179**, 500-508, doi:10.1176/appi.ajp.21050541 (2022).
41 Fonzo, G. A. *et al.* Selective Effects of Psychotherapy on Frontopolar Cortical Function in PTSD. *Am J Psychiatry* **174**, 1175-1184, doi:10.1176/appi.ajp.2017.16091073 (2017).
42 Oathes, D. J. *et al.* Combining transcranial magnetic stimulation with functional magnetic resonance imaging for probing and modulating neural circuits relevant to affective disorders. *Wiley Interdiscip Rev Cogn Sci* **12**, e1553, doi:10.1002/wcs.1553 (2021).
43 Chang, K. Y. *et al.* Neural response during prefrontal theta burst stimulation: Interleaved TMS-fMRI of full iTBS protocols. *Neuroimage* **291**, 120596, doi:10.1016/j.neuroimage.2024.120596 (2024).
44 Rossi, S. *et al.* Safety and recommendations for TMS use in healthy subjects and patient populations, with updates on training, ethical and regulatory

issues: Expert Guidelines. *Clin Neurophysiol* **132**, 269-306, doi:10.1016/j.clinph.2020.10.003 (2021).
45 Rossi S, H. M., Rossini PM, Pascual-Leone A; Safety of TMS Consensus Group. Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. *Clin Neurophysiol* **120** (2009).
46 Rafiei, F. & Rahnev, D. TMS Does Not Increase BOLD Activity at the Site of Stimulation: A Review of All Concurrent TMS-fMRI Studies. *eNeuro* **9**, doi:10.1523/ENEURO.0163-22.2022 (2022).
47 Rafiei, F., Safrin, M., Wokke, M. E., Lau, H. & Rahnev, D. Transcranial magnetic stimulation alters multivoxel patterns in the absence of overall activity changes. *Hum Brain Mapp* **42**, 3804-3820, doi:10.1002/hbm.25466 (2021).
48 Bergmann, T. O. & Hartwigsen, G. Inferring Causality from Noninvasive Brain Stimulation in Cognitive Neuroscience. *J Cogn Neurosci* **33**, 195-225, doi:10.1162/jocn_a_01591 (2021).
49 Sydnor, V. J. *et al.* Cortical-subcortical structural connections support transcranial magnetic stimulation engagement of the amygdala. *Sci Adv* **8**, eabn5803, doi:10.1126/sciadv.abn5803 (2022).
50 Goldenkoff, E. R. *et al.* The behavioral and neural effects of parietal theta burst stimulation on the grasp network are stronger during a grasping task than at rest. *Front Neurosci* **17**, 1198222, doi:10.3389/fnins.2023.1198222 (2023).
51 Jannati, A., Oberman, L. M., Rotenberg, A. & Pascual-Leone, A. Assessing the mechanisms of brain plasticity by transcranial magnetic stimulation. *Neuropsychopharmacology* **48**, 191-208, doi:10.1038/s41386-022-01453-8 (2023).
52 Maeda, F., Keenan, J. P., Tormos, J. M., Topka, H. & Pascual-Leone, A. Interindividual variability of the modulatory effects of repetitive transcranial magnetic stimulation on cortical excitability. *Exp Brain Res* **133**, 425-430, doi:10.1007/s002210000432 (2000).
53 Thickbroom, G. W. Transcranial magnetic stimulation and synaptic plasticity: experimental framework and human models. *Exp Brain Res* **180**, 583-593, doi:10.1007/s00221-007-0991-3 (2007).
54 Buzsaki, G. & Draguhn, A. Neuronal oscillations in cortical networks. *Science (New York, N.Y* **304**, 1926-1929, doi:10.1126/science.1099745 (2004).
55 Janssens, S. E. W., Oever, S. T., Sack, A. T. & de Graaf, T. A. "Broadband Alpha Transcranial Alternating Current Stimulation": Exploring a new biologically calibrated brain stimulation protocol. *Neuroimage* **253**, 119109, doi:10.1016/j.neuroimage.2022.119109 (2022).
56 Nelli, S., Itthipuripat, S., Srinivasan, R. & Serences, J. T. Fluctuations in instantaneous frequency predict alpha amplitude during visual perception. *Nat Commun* **8**, 2071, doi:10.1038/s41467-017-02176-x (2017).
57 Vinck, M. *et al.* Principles of large-scale neural interactions. *Neuron* **111**, 987-1002, doi:10.1016/j.neuron.2023.03.015 (2023).
58 Dunlop K, N. S. in *Brain Stimulation: Basic, Translational, and Clinical Research in Neuromodulation.* 178.
59 Wassermann, E. M. in *Oxford Handbook of Transcranial Stimulation* (ed Charles M. Epstein) Ch. 26, 401-408 (2012).

60 Schilberg, L., Schuhmann, T. & Sack, A. T. Interindividual Variability and Intraindividual Reliability of Intermittent Theta Burst Stimulation-induced Neuroplasticity Mechanisms in the Healthy Brain. *J Cogn Neurosci* **29**, 1022-1032, doi:10.1162/jocn_a_01100 (2017).
61 Rocchi, L. *et al.* Variability and Predictors of Response to Continuous Theta Burst Stimulation: A TMS-EEG Study. *Front Neurosci* **12**, 400, doi:10.3389/fnins.2018.00400 (2018).
62 Bestmann, S. *et al.* Mapping causal interregional influences with concurrent TMS-fMRI. *Exp Brain Res* **191**, 383-402, doi:10.1007/s00221-008-1601-8 (2008).
63 Moisa, M., Siebner, H. R., Pohmann, R. & Thielscher, A. Uncovering a context-specific connectional fingerprint of human dorsal premotor cortex. *J Neurosci* **32**, 7244-7252, doi:10.1523/JNEUROSCI.2757-11.2012 (2012).
64 Ruff, C. C. *et al.* Distinct causal influences of parietal versus frontal areas on human visual cortex: evidence from concurrent TMS-fMRI. *Cereb Cortex* **18**, 817-827 (2008).
65 Blankenburg, F. *et al.* Studying the role of human parietal cortex in visuospatial attention with concurrent TMS-fMRI. *Cereb Cortex* **20**, 2702-2711, doi:10.1093/cercor/bhq015 (2010).
66 Silvanto, J. & Pascual-Leone, A. State-dependency of transcranial magnetic stimulation. *Brain Topogr* **21**, 1-10, doi:10.1007/s10548-008-0067-0 (2008).
67 Donse, L., Padberg, F., Sack, A. T., Rush, A. J. & Arns, M. Simultaneous rTMS and psychotherapy in major depressive disorder: Clinical outcomes and predictors from a large naturalistic study. *Brain Stimul* **11**, 337-345, doi:10.1016/j.brs.2017.11.004 (2018).
68 Neacsiu, A. D. *et al.* Enhancing cognitive restructuring with concurrent fMRI-guided neurostimulation for emotional dysregulation-A randomized controlled trial. *J Affect Disord* **301**, 378-389, doi:10.1016/j.jad.2022.01.053 (2022).
69 Neacsiu, A. D. *et al.* Enhancing Cognitive Restructuring with Concurrent Repetitive Transcranial Magnetic Stimulation: A Transdiagnostic Randomized Controlled Trial. *Psychother Psychosom* **91**, 94-106, doi:10.1159/000518957 (2022).
70 Neacsiu, A. D. *et al.* On the Concurrent Use of Self-System Therapy and Functional Magnetic Resonance Imaging-Guided Transcranial Magnetic Stimulation as Treatment for Depression. *J ECT* **34**, 266-273, doi:10.1097/YCT.0000000000000545 (2018).
71 Petrov, P. I. *et al.* Validating models of TMS effects with concurrent TMS/fMRI. *bioRxiv*, doi:10.1101/2023.07.05.547836 (2023).
72 Cocchi, L. *et al.* Dissociable effects of local inhibitory and excitatory theta-burst stimulation on large-scale brain dynamics. *J Neurophysiol* **113**, 3375-3385, doi:10.1152/jn.00850.2014 (2015).
73 Baudewig, J., Paulus, W. & Frahm, J. Artifacts caused by transcranial magnetic stimulation coils and EEG electrodes in T(2)*-weighted echo-planar imaging. *Magn Reson Imaging* **18**, 479-484, doi:10.1016/s0730-725x(00)00122-3 (2000).
74 Bestmann, S., Baudewig, J. & Frahm, J. On the synchronization of transcranial magnetic stimulation and functional echo-planar imaging. *J Magn Reson Imaging* **17**, 309-316, doi:10.1002/jmri.10260 (2003).

75 Bohning, D. E. *et al.* Mapping transcranial magnetic stimulation (TMS) fields in vivo with MRI. *Neuroreport* **8**, 2535-2538, doi:10.1097/00001756-199707280-00023 (1997).
76 Navarro de Lara, L. I. *et al.* A novel coil array for combined TMS/fMRI experiments at 3 T. *Magn Reson Med* **74**, 1492-1501, doi:10.1002/mrm.25535 (2015).
77 Hassan, U., Pillen, S., Zrenner, C. & Bergmann, T. O. The Brain Electrophysiological recording & STimulation (BEST) toolbox. *Brain Stimul* **15**, 109-115, doi:10.1016/j.brs.2021.11.017 (2022).
78 Riddle, J. *et al.* A guide for concurrent TMS-fMRI to investigate functional brain networks. *Front Hum Neurosci* **16**, 1050605, doi:10.3389/fnhum.2022.1050605 (2022).
79 Mizutani-Tiebel, Y. *et al.* Concurrent TMS-fMRI: Technical Challenges, Developments, and Overview of Previous Studies. *Front Psychiatry* **13**, 825205, doi:10.3389/fpsyt.2022.825205 (2022).
80 Bungert, A., Chambers, C. D., Long, E. & Evans, C. J. On the importance of specialized radiofrequency filtering for concurrent TMS/MRI. *J Neurosci Methods* **210**, 202-205, doi:10.1016/j.jneumeth.2012.07.023 (2012).
81 Weiskopf, N. *et al.* Image artifacts in concurrent transcranial magnetic stimulation (TMS) and fMRI caused by leakage currents: modeling and compensation. *J Magn Reson Imaging* **29**, 1211-1217, doi:10.1002/jmri.21749 (2009).
82 Assem, M. M., M.; Eldridge, S.; Woolgar, A. *The Taco setup: A novel TMS-fMRI setup for high resolution whole brain imaging* (in prep).
83 Tik, M. in *2nd International Concurrent TMS-fMRI Workshop presentation.*
84 Jackson, J. B., Scrivener, C. L., Mada, M. & Woolgar, A. Comparison of MR coil options for concurrent TMS-fMRI. *bioRxiv*, doi:10.1101/2024.05.15.594454 (2024).
85 Navarro de Lara, L. I. *et al.* A novel whole-head RF coil design tailored for concurrent multichannel brain stimulation and imaging at 3T. *Brain Stimul* **16**, 1021-1031, doi:10.1016/j.brs.2023.05.025 (2023).
86 Goldstein, S., Rafiei, F. & Rahnev, D. 3D-printed stand, timing interface, and coil localization tools for concurrent TMS-fMRI experiments. *Brain Stimul* **15**, 1290-1291, doi:10.1016/j.brs.2022.08.026 (2022).
87 Burke M., X. Y., Melo L., Takahashi K., Chiappini E., Genc E. in *Proc. ISMRM.*
88 Lee, H. J., Woudsma, K. J., Ishraq, M. F. & Lin, F. H. Design of coil holder for the improved maneuvering in concurrent TMS-MRI. *Brain Stimul* **16**, 966-968, doi:10.1016/j.brs.2023.06.001 (2023).
89 Dannhauer, M. *et al.* TAP: targeting and analysis pipeline for optimization and verification of coil placement in transcranial magnetic stimulation. *J Neural Eng* **19**, doi:10.1088/1741-2552/ac63a4 (2022).
90 Gomez, L. J., Dannhauer, M. & Peterchev, A. V. Fast computational optimization of TMS coil placement for individualized electric field targeting. *Neuroimage* **228**, 117696, doi:10.1016/j.neuroimage.2020.117696 (2021).
91 Numssen, O. *et al.* Efficient high-resolution TMS mapping of the human motor cortex by nonlinear regression. *Neuroimage* **245**, 118654, doi:10.1016/j.neuroimage.2021.118654 (2021).
92 Lueckel, M., Radetz, A., Hassan, U., Yuen, K., Mueller-Dahlhaus, F., Kalisch, R., Bergmann, T.O. in *5th International Brain Stimulation Conference.*

93 Numssen, O., van der Burght, C. L. & Hartwigsen, G. Revisiting the focality of non-invasive brain stimulation - Implications for studies of human cognition. *Neurosci Biobehav Rev* **149**, 105154, doi:10.1016/j.neubiorev.2023.105154 (2023).
94 Lynch, C. J. *et al.* Automated optimization of TMS coil placement for personalized functional network engagement. *Neuron* **110**, 3263-3277 e3264, doi:10.1016/j.neuron.2022.08.012 (2022).
95 Halko, M. A., Eldaief, M. C. & Pascual-Leone, A. Noninvasive brain stimulation in the study of the human visual system. *J Glaucoma* **22 Suppl 5**, S39-41, doi:10.1097/IJG.0b013e3182934b31 (2013).
96 Cerins, A. *et al.* A New Angle on Transcranial Magnetic Stimulation Coil Orientation: A Targeted Narrative Review. *Biol Psychiatry Cogn Neurosci Neuroimaging* **9**, 744-753, doi:10.1016/j.bpsc.2024.04.018 (2024).
97 Opitz, A., Fox, M. D., Craddock, R. C., Colcombe, S. & Milham, M. P. An integrated framework for targeting functional networks via transcranial magnetic stimulation. *Neuroimage* **127**, 86-96, doi:10.1016/j.neuroimage.2015.11.040 (2016).
98 Siebner, H. R. *et al.* Transcranial magnetic stimulation of the brain: What is stimulated? - A consensus and critical position paper. *Clin Neurophysiol* **140**, 59-97, doi:10.1016/j.clinph.2022.04.022 (2022).
99 Sparing, R., Buelte, D., Meister, I. G., Paus, T. & Fink, G. R. Transcranial magnetic stimulation and the challenge of coil placement: a comparison of conventional and stereotaxic neuronavigational strategies. *Hum Brain Mapp* **29**, 82-96, doi:10.1002/hbm.20360 (2008).
100 Grodzki, D. M., Jakob, P. M. & Heismann, B. Ultrashort echo time imaging using pointwise encoding time reduction with radial acquisition (PETRA). *Magn Reson Med* **67**, 510-518, doi:10.1002/mrm.23017 (2012).
101 Herwig, U. *et al.* The navigation of transcranial magnetic stimulation. *Psychiatry Res* **108**, 123-131, doi:10.1016/s0925-4927(01)00121-4 (2001).
102 Windischberger, C. W., M., Grosshagauer, S., Vasileiadi, M., Tik, M. in *5th International Brain Stimulation Conference.*
103 McKeown, M. J., Hansen, L. K. & Sejnowsk, T. J. Independent component analysis of functional MRI: what is signal and what is noise? *Curr Opin Neurobiol* **13**, 620-629, doi:10.1016/j.conb.2003.09.012 (2003).
104 Windischberger, C., Tik, M., Thielscher, A. & Siebner, H. R. in *The Oxford Handbook of Transcranial Stimulation* Ch. 23, 648-674 (2022).
105 Bestmann, S., Ruff, C. C., Driver, J. & Blankenburg, F. in *Oxford Handbook of Transcranial Stimulation* Ch. 36, 569–592 (2008).
106 Bestmann, S. *et al.* Dorsal premotor cortex exerts state-dependent causal influences on activity in contralateral primary motor and dorsal premotor cortex. *Cereb Cortex* **18**, 1281-1291, doi:10.1093/cercor/bhm159 (2008).
107 Bohning, D. E. *et al.* Echoplanar BOLD fMRI of brain activation induced by concurrent transcranial magnetic stimulation. *Invest Radiol* **33**, 336-340, doi:10.1097/00004424-199806000-00004 (1998).
108 Scrivener, C. L., Jackson, J. B., Correia, M. M., Mada, M. & Woolgar, A. Now you see it, now you don't: optimal parameters for interslice stimulation in concurrent TMS-fMRI. *BioRXiv*, doi:10.1101/2021.05.28.446111 (2021).
109 Moisa, M., Pohmann, R., Uludag, K. & Thielscher, A. Interleaved TMS/CASL: Comparison of different rTMS protocols. *Neuroimage* **49**, 612-620, doi:10.1016/j.neuroimage.2009.07.010 (2010).

110 Valero-Cabre, A., Amengual, J. L., Stengel, C., Pascual-Leone, A. & Coubard, O. A. Transcranial magnetic stimulation in basic and clinical neuroscience: A comprehensive review of fundamental principles and novel insights. *Neurosci Biobehav Rev* **83**, 381-404, doi:10.1016/j.neubiorev.2017.10.006 (2017).
111 Habibollahi Saatlou, F. *et al.* MAGIC: An open-source MATLAB toolbox for external control of transcranial magnetic stimulation devices. *Brain Stimul* **11**, 1189-1191, doi:10.1016/j.brs.2018.05.015 (2018).
112 Klooster, D. C. W., Ferguson, M. A., Boon, P. & Baeken, C. Personalizing Repetitive Transcranial Magnetic Stimulation Parameters for Depression Treatment Using Multimodal Neuroimaging. *Biol Psychiatry Cogn Neurosci Neuroimaging* **7**, 536-545, doi:10.1016/j.bpsc.2021.11.004 (2022).
113 Turi, Z., Lenz, M., Paulus, W., Mittner, M. & Vlachos, A. Selecting stimulation intensity in repetitive transcranial magnetic stimulation studies: A systematic review between 1991 and 2020. *Eur J Neurosci* **53**, 3404-3415, doi:10.1111/ejn.15195 (2021).
114 Stokes, M. G. *et al.* Simple metric for scaling motor threshold based on scalp-cortex distance: application to studies using transcranial magnetic stimulation. *J Neurophysiol* **94**, 4520-4527, doi:10.1152/jn.00067.2005 (2005).
115 Caulfield, K. A., Li, X. & George, M. S. Four electric field modeling methods of Dosing Prefrontal Transcranial Magnetic Stimulation (TMS): Introducing APEX MT dosimetry. *Brain Stimul* **14**, 1032-1034, doi:10.1016/j.brs.2021.06.012 (2021).
116 Numssen, O., Kuhnke, P., Weise, K. & Hartwigsen, G. Electric-field-based dosing for TMS. *Imaging Neuroscience* **2**, 1-12, doi:10.1162/imag_a_00106 (2024).
117 Nee, D. E. fMRI replicability depends upon sufficient individual-level data. *Commun Biol* **2**, 130, doi:10.1038/s42003-019-0378-6 (2019).
118 Hawco, C., Steeves, J. K. E., Voineskos, A. N., Blumberger, D. M. & Daskalakis, Z. J. Within-subject reliability of concurrent TMS-fMRI during a single session. *Psychophysiology* **60**, e14252, doi:10.1111/psyp.14252 (2023).
119 Peters, J. C. *et al.* On the feasibility of concurrent human TMS-EEG-fMRI measurements. *J Neurophysiol* **109**, 1214-1227, doi:10.1152/jn.00071.2012 (2013).
120 Duecker, F. & Sack, A. T. Rethinking the role of sham TMS. *Front Psychol* **6**, 210, doi:10.3389/fpsyg.2015.00210 (2015).
121 Duecker, F. & Sack, A. T. Pre-stimulus sham TMS facilitates target detection. *PLoS One* **8**, e57765, doi:10.1371/journal.pone.0057765 (2013).
122 Bergmann, T. O., Karabanov, A., Hartwigsen, G., Thielscher, A. & Siebner, H. R. Combining non-invasive transcranial brain stimulation with neuroimaging and electrophysiology: Current approaches and future perspectives. *Neuroimage* **140**, 4-19, doi:10.1016/j.neuroimage.2016.02.012 (2016).
123 Heinen, K. *et al.* Concurrent TMS-fMRI reveals dynamic interhemispheric influences of the right parietal cortex during exogenously cued visuospatial attention. *Eur J Neurosci* **33**, 991-1000, doi:10.1111/j.1460-9568.2010.07580.x (2011).
124 Leitao, J., Thielscher, A., Tunnerhoff, J. & Noppeney, U. Concurrent TMS-fMRI Reveals Interactions between Dorsal and Ventral Attentional Systems. *J Neurosci* **35**, 11445-11457, doi:10.1523/JNEUROSCI.0939-15.2015 (2015).

125 Schwarzkopf, D. S., Silvanto, J. & Rees, G. Stochastic resonance effects reveal the neural mechanisms of transcranial magnetic stimulation. *J Neurosci* **31**, 3143-3147, doi:10.1523/JNEUROSCI.4863-10.2011 (2011).
126 Giustiniani, A. *et al.* A questionnaire to collect unintended effects of transcranial magnetic stimulation: A consensus based approach. *Clin Neurophysiol* **141**, 101-108, doi:10.1016/j.clinph.2022.06.008 (2022).
127 Bestmann, S., Baudewig, J., Siebner, H. R., Rothwell, J. C. & Frahm, J. BOLD MRI responses to repetitive TMS over human dorsal premotor cortex. *Neuroimage* **28**, 22-29, doi:10.1016/j.neuroimage.2005.05.027 (2005).
128 O'Shea, J., Johansen-Berg, H., Trief, D., Gobel, S. & Rushworth, M. F. Functionally specific reorganization in human premotor cortex. *Neuron* **54**, 479-490, doi:10.1016/j.neuron.2007.04.021 (2007).
129 Hartwigsen, G. *et al.* Rapid short-term reorganization in the language network. *Elife* **6**, doi:10.7554/eLife.25964 (2017).
130 Jung, J., Bungert, A., Bowtell, R. & Jackson, S. R. Vertex Stimulation as a Control Site for Transcranial Magnetic Stimulation: A Concurrent TMS/fMRI Study. *Brain Stimul* **9**, 58-64, doi:10.1016/j.brs.2015.09.008 (2016).
131 Leitao, J., Thielscher, A., Tuennerhoff, J. & Noppeney, U. Comparing TMS perturbations to occipital and parietal cortices in concurrent TMS-fMRI studies-Methodological considerations. *PLoS One* **12**, e0181438, doi:10.1371/journal.pone.0181438 (2017).
132 de Graaf, T. A., Jacobs, C., Roebroeck, A. & Sack, A. T. FMRI effective connectivity and TMS chronometry: complementary accounts of causality in the visuospatial judgment network. *PLoS One* **4**, e8307, doi:10.1371/journal.pone.0008307 (2009).
133 Bradley, C., Nydam, A. S., Dux, P. E. & Mattingley, J. B. State-dependent effects of neural stimulation on brain function and cognition. *Nat Rev Neurosci* **23**, 459-475, doi:10.1038/s41583-022-00598-1 (2022).
134 Terney, D., Chaieb, L., Moliadze, V., Antal, A. & Paulus, W. Increasing human brain excitability by transcranial high-frequency random noise stimulation. *J Neurosci* **28**, 14147-14155, doi:10.1523/JNEUROSCI.4248-08.2008 (2008).
135 Logothetis, N. K. What we can do and what we cannot do with fMRI. *Nature* **453**, 869-878, doi:10.1038/nature06976 (2008).
136 Allen, E. A., Pasley, B. N., Duong, T. & Freeman, R. D. Transcranial magnetic stimulation elicits coupled neural and hemodynamic consequences. *Science* **317**, 1918-1921, doi:10.1126/science.1146426 (2007).
137 Manohar, S., Whyte, C., Feredoes, E., Woolgar, A. in *Conference on Cognitive Computational Neuroscience.*
138 Coalson, T. S., Van Essen, D. C. & Glasser, M. F. The impact of traditional neuroimaging methods on the spatial localization of cortical areas. *Proc Natl Acad Sci U S A* **115**, E6356-E6365, doi:10.1073/pnas.1801582115 (2018).
139 Glasser, M. F. *et al.* A multi-modal parcellation of human cerebral cortex. *Nature* **536**, 171-178, doi:10.1038/nature18933 (2016).