

# Reliability and Validity of Transcranial Magnetic Stimulation–Electroencephalography Biomarkers

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## ABSTRACT

Noninvasive brain stimulation and neuroimaging have revolutionized human neuroscience with a multitude of applications, including diagnostic subtyping, treatment optimization, and relapse prediction. It is therefore particularly relevant to identify robust and clinically valuable brain biomarkers linking symptoms to their underlying neural mechanisms. Brain biomarkers must be reproducible (i.e., have internal reliability) across similar experiments within a laboratory and be generalizable (i.e., have external reliability) across experimental setups, laboratories, brain regions, and disease states. However, reliability (internal and external) is not alone sufficient; biomarkers also must have validity. Validity describes closeness to a true measure of the underlying neural signal or disease state. We propose that these metrics, reliability and validity, should be evaluated and optimized before any biomarker is used to inform treatment decisions. Here, we discuss these metrics with respect to causal brain connectivity biomarkers from coupling transcranial magnetic stimulation (TMS) with electroencephalography (EEG). We discuss controversies around TMS-EEG stemming from the multiple large off-target components (noise) and relatively weak genuine brain responses (signal), as is unfortunately often the case in noninvasive human neuroscience. We review the current state of TMS-EEG recordings, which consist of a mix of reliable noise and unreliable signal. We describe methods for evaluating TMS-EEG biomarkers, including how to assess internal and external reliability across facilities, cognitive states, brain networks, and disorders and how to validate these biomarkers using invasive neural recordings or treatment response. We provide recommendations to increase reliability and validity, discuss lessons learned, and suggest future directions for the field.

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## RELIABILITY AND VALIDITY IN NEUROIMAGING

Noninvasive brain imaging and stimulation have revolutionized human neuroscience over the past 30 years. Many tools exist to image brain activity, including functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and electroencephalography (EEG). Each modality has different limitations in terms of cost and complexity (fMRI, MEG), limited temporal resolution (fMRI, functional near-infrared spectroscopy), and limited spatial resolution (MEG, EEG). Pairing these imaging techniques with noninvasive brain stimulation can enable the causal study of responses to perturbation in focal regions of cortex and connected networks. These causal methods include using transcranial direct and alternating current stimulation and transcranial magnetic stimulation (TMS) and have been critical in accumulating knowledge of and treating neurological and psychiatric disorders. To use noninvasive brain stimulation techniques as part of a biomarker, stimulation responses must be quantified with a metric related to normal neurophysiology, pathophysiology, or responses to an exposure or intervention (1–6). TMS effects on the motor and visual cortices can be captured with corticospinal (electromyography) and visual perception readouts, but TMS to other

regions may be best captured using electrophysiology. The combination of TMS with EEG is particularly promising due to the comparable temporal resolution between TMS and EEG and the possibility of improving EEG's poor spatial specificity using the greater spatial specificity of TMS itself (7).

Given the limitations of each of these noninvasive tools, it is critical that the readouts of stimulation-imaging methods are stable and reproducible (reliability) and measure the underlying neural processes of interest (validity). Reliability refers to the consistency of a biomarker. Internal reliability refers to the ability to reproduce the biomarker within a laboratory and asks the question, “How well in the lab and for this experimental setup can the study be reproduced?” Biomarkers also need to have strong external reliability, answering the question, “How well in other laboratories or clinical environments, with different experimental setups and where operators may be trained differently, can the study yield consistent results?” There are many instances in which a metric can have validity but not internal reliability or external reliability (Figure 1). We propose that it is necessary to critically evaluate and optimize both the reliability and validity of any brain biomarker of interest, particularly prior to implementation in aiding diagnosis or treatment.

All too often, there is an understandable desire to immediately use recently discovered human noninvasive tools rather than to first send them through months of rigorous testing. Testing of a tool is time consuming and often less immediately impactful while applying that novel tool to study a specific brain circuit or disorder can yield high-impact publications, open up future lines of investigation, and be immediately translatable to the clinic. However, if a tool has either low reliability or validity, a clinical application should not proceed until deemed sufficient by the scientific community. Unfortunately, and particularly for tools not regulated by the U.S. Food and Drug Administration, there is no such rigorous statistical barrier to mainstream use. Instead, rigorous testing is often performed after years of application research (8,9). A lack of rigor in biomarker development can, in the end, impede scientific progress and cast doubt on these measurement tools, weakening the scientific community's view on clinical noninvasive human neuroscience over time (10).

We propose that prior to clinical use, measurements derived from noninvasive tools must be rigorously evaluated and deemed to have high reliability and validity. The field of psychometrics is dedicated to the evaluation of scientific metrics of psychological properties but is most often applied to clinical and behavioral assessments and not regularly to novel neuroimaging biomarkers (11,12). Thus, we must develop these psychometric-like rigorous testing algorithms for novel noninvasive brain measurements prior to clinical use. Below, we outline this process for one relatively new noninvasive brain measurement tool, TMS-EEG, and describe how to rigorously assess and optimize TMS-EEG biomarkers. We hope that other research endeavors follow suit in rethinking, re-evaluating, and improving biomarkers from their measurement tool of choice.

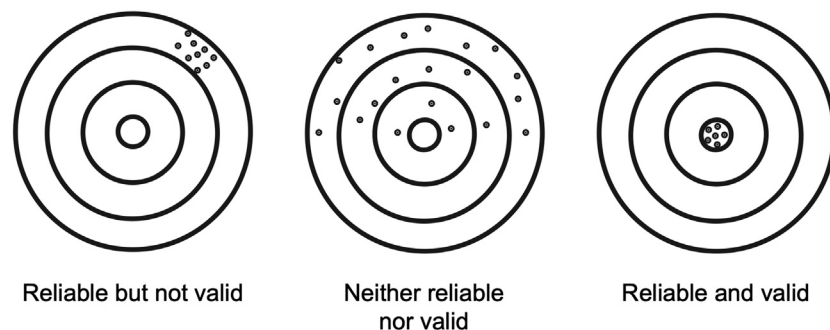
### MOTOR-EVOKED POTENTIALS: A GOLD STANDARD

While noninvasive imaging techniques (fMRI, MEG, EEG) measure various aspects of neural activity, they lack a causal component. Causal techniques such as TMS involve perturbing brain activity and measuring the consequent response. Initial TMS studies focused on stimulation of the primary motor cortex (M1) (1,2,7,8,13), the source of much of our knowledge about the physiological effects of TMS in humans (14–16). Thanks to the somatotopic organization of the M1, a muscle of interest can be activated by applying TMS to a specific portion

of the M1 (17). Suprathreshold single TMS pulses over M1 elicit a strong electromyography response over skeletal muscles, termed the motor-evoked potential (MEP). The MEP is linearly correlated with the number of activated corticospinal neurons (14) and is thus considered valid to track corticospinal excitability. Based on many studies, the MEP has been shown to be highly reliable, stable across time within a laboratory (internal reliability) (18–22), and generalizable across laboratories (external reliability) (11,23–26), partially due to its high signal-to-noise ratio (SNR) (>1000- $\mu$ V responses with low levels of noise). Of course, some theoretical assumptions and approximations are required, but all things considered, the MEP and its features (e.g., latency, amplitude, morphology) have high internal and external reliability as well as high validity to track excitability of the corticospinal tract. As such, it is in widespread use both in research and clinical practice (27–29). Unfortunately, MEPs can only probe the corticospinal tract, and as a result, other tools including TMS-EEG are needed to explore causal relationships in other brain regions.

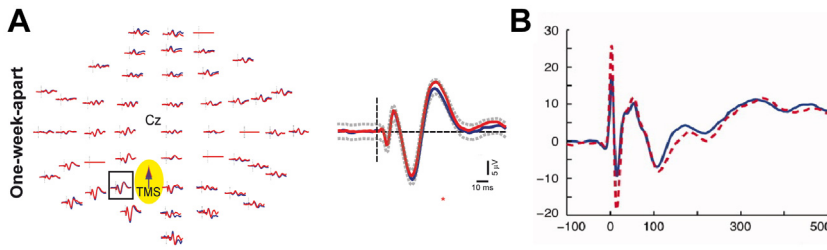
### TMS-EVOKED POTENTIALS

Although relatively new, TMS-EEG is a powerful noninvasive neuroimaging tool with strong internal reliability (also known as reproducibility) (30–32). However, more rigorous external reliability and validity assessment with subsequent optimization is needed. TMS-evoked potentials (TEPs) are a result of coupling single pulses of TMS with scalp EEG recording. TEPs were first described in 1997 (30). Foundational studies in motor cortex physiology, cortical excitability related to movement, and stimulation intensity followed (33,34). TEPs became more relevant as a potential clinical tool when they were used to help understand sleep physiology (35,36). In contrast to MEPs, which probe the entire corticospinal tract, TEPs measure the central nervous system response to single pulses of TMS without requiring a motor readout. TEPs consist of a multiphasic response lasting ~500 ms (31). Initial reports described high internal reliability (Figure 2) [see (30)], demonstrating that TEPs can be repeatable after a week and are sensitive to changes in stimulation amplitude, site, and angle (30). Indeed, although outside the scope of this review, it should be noted that TEPs are also highly sensitive to small but relevant changes in stimulation site, angle, and intensity (30). Subsequently, TEPs were largely viewed as plug-and-play and have since been applied to various cognitive states and connectivity



**Figure 1.** Reliability and validity of neuroimaging biomarkers. A biomarker should be scrutinized for both reliability and validity because it is possible to have high reliability but low validity or high validity but low reliability.

Reliability of TMS-EEG



**Figure 2.** High internal reliability of transcranial magnetic stimulation (TMS)-evoked potentials. In both of these studies (30,31), TMS-evoked potentials after single-pulse TMS to the primary motor cortex were internally consistent across time (1 week between experiments). (A) Adapted with permission from Casarotto *et al.* (30), where blue line represents the first and red line the second recording 1 week later. (B) Adapted with permission from Lioumis *et al.* (31), where the dashed line represents the first and the solid line the second recording 1 week later.

features (37,38), brain disorders (39,40), stimulation sites (41), stimulator devices (42), amplifier types (42), and EEG recording setups (43).

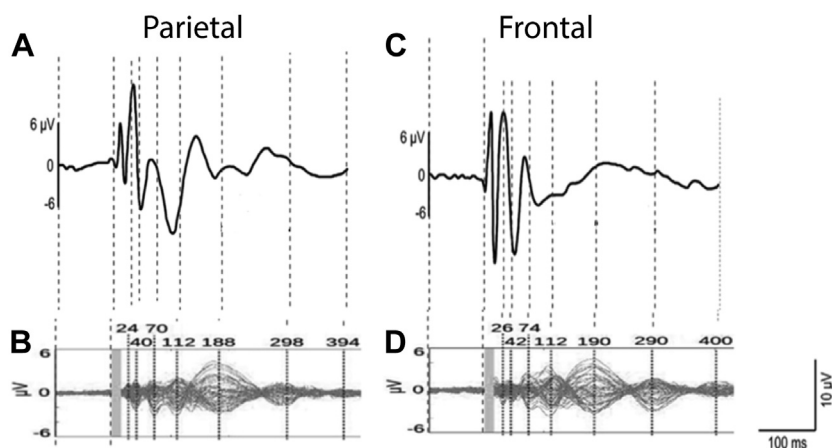
However, shortly after dissemination, the assumed high external reliability began to be questioned. Initial studies were performed by stimulating medial structures with minimal muscle artifacts (30,35,44), which may explain the high reports of internal reliability. It was eventually determined that 1) stimulation to lateral brain regions elicits strong early muscle artifacts that can confound the TEP (45,46) and 2) the sensation and auditory click from a TMS pulse results in nonspecific sensory evoked responses (47). In addition, while sample-and-hold amplifiers in early TEP reports reduced artifacts during and directly following the TMS pulse, due to their high cost, less expensive direct current amplifiers were often purchased by other groups, introducing additional differences across laboratories. Therefore, controversies ensued when TEPs across laboratories reported different levels of internal reliability of the TEP. In recent years, multiple groups have re-evaluated the internal reliability of TEPs (32,48,49). Previously demonstrated substantial internal reliability for later components (>50 ms) of the TEP is now known to consist partially of sensory nonspecific off-target effects (47), and weaker internal reliability for earlier components (<50 ms) of the TEP is thought to reflect more valid components of local cortical excitability (50). Discussion of the reliability and validity of these early and late components of the TEP collided when similar TEP

morphologies were reported after single pulses of sham (placebo) TMS (10) and single pulses of TMS to the shoulder (51). In response, a discussion ensued within the TMS-EEG scientific community, questioning the most appropriate methods for obtaining TEPs with high reliability and validity (Figure 3) (49). This discussion highlighted the need for 1) rigorous assessment with each new TMS coil, location, angle, and intensity probed, as well as 2) standardization across the TMS-EEG community with respect to reliability and validity assessments.

To move toward robust measures of causal brain excitability, particularly for extended use in clinical applications, we evaluate in the sections below the off-target and intended neural signals present in the TEP, discuss these in reference to reliability and validity metrics, and outline methods to assess and enhance these metrics.

**OFF-TARGET COMPONENTS (NOISE) IN THE TEP: RELIABLE BUT NOT VALID**

The largest amplitude components in the TEP are usually reliable but not valid. Because the TEP is the result of single TMS pulses averaged across multiple trials (52,53), it is an aggregate of all electrical signals measurable using EEG. Contributing sources to the TEP have overlapping time courses and are thus susceptible to net displacement effects of individual waves (i.e., constructive and destructive interference). In addition to multiple central neural sources



**Figure 3.** Low external reliability of the transcranial magnetic stimulation-evoked potential (TEP). Comparison of TEPs from different laboratories. Local TEP responses after stimulation of (A, B) the parietal cortex and (C, D) the frontal cortex. (A) and (C) are from Rosanova *et al.* (41) and (B) and (D) are from Conde *et al.* (10). The figure is adapted with permission from Belardinelli *et al.* (49).

(41,54,55), contributions to this aggregate waveform also include nonneural sources (56–60) and peripherally evoked neural sources unrelated to the direct effects of, but time-locked, and in response to TMS (10,50,51,61–63). TMS-evoked central neural sources will be referred to hereafter as signal, and nonneural sources, peripherally evoked neural sources, and off-target neural sources will be referred to as noise.

Myriad sources of noise confound interpretation of the TEP. Nonneural contributions include 1) pulse artifact from current flow through the coil; 2) recharge artifact from the capacitor between discharges; 3) decay artifact from changes in capacitance between the electrodes and gel as well as between the gel and the scalp; 4) electrode noise from poor contact with the scalp or conductive gel drying or leaking; 5) line noise from equipment in the room (60 or 50 Hz); 6) evoked and continuous muscle activity; 7) electrocardiogram; 8) eye blinks, eye movements, microsaccades; and 9) movement of the electrodes (often where the coil is resting on the cap) (56–60). Peripherally evoked contributions to the TEP include 1) somatosensory-evoked potentials from the sensation of the TMS pulse on peripheral nerves and 2) auditory-evoked potentials from the auditory click of the TMS pulse (10,47,50,51,61–63). Off-target central neural sources can also occur due to 1) inhibitory mechanisms, including those associated with visual field changes from eye blinks, eye movements, and microsaccades (64,65); 2) fluctuations in brain state such as awakeness and attention (63,64,66); and 3) pain-related responses (67). Best approaches for handling these many off-target contributions are the topics of numerous other publications and methodological debates (9,59,60,62,68–70). However, it should be emphasized that these non-neural, peripherally evoked, and central off-target components of the TEP are often reliable, with large amplitudes and long durations (68,71), and therefore should be carefully considered and minimized using a combination of techniques during data collection (35,47,50,61,72,73) and during postprocessing (9,51,60,62,71). In summary, there are numerous sources of reliable and easily recognizable large amplitude noise contributions to the TEP that need to be accounted for when designing a study, minimized during data collection, and if needed removed during data analysis to uncover the effective signal of interest.

### TRUE TEP COMPONENTS (SIGNAL): VALID BUT UNRELIABLE

While obtaining the true neural TEP signal is challenging due to the multitude of large magnitude off-target recordings often also present in the TEP (noise) [see [Off-Target Components \(Noise\) in the TEP: Reliable but Not Valid](#)] (46,74), the observation of valid components of the TEP from locally excited brain tissue is possible and can provide important insights into brain physiology and pathology. When TMS is applied to brain regions where off-target noise confounds are minimal, there is strong evidence for the neural basis (validity) of TEPs, especially in the early (<50 ms) components (50). For example, in M1, the MEP correlates with the amplitude of the early 15- to 30-ms response of the TEP (75,76), suggesting that early TEP components reflect

cortical excitability. Moreover, local high-frequency TEPs evoked by M1 stimulation and paired-pulse MEPs (conditioned MEPs) share a similar time course, suggesting that they may index similar types of cortical activity (77). Furthermore, TMS to the prefrontal cortex produces TEP peaks (78) with amplitudes (79) and latencies (31) that correlate with M1 TEP amplitudes. However, TEPs evoked by the prefrontal cortex and M1 stimulation may reflect different underlying neural mechanisms: Early TEP peaks (<50 ms) following the left prefrontal cortex stimulation are insensitive to excitatory NMDA receptor blockade (80), whereas early M1 TEP peaks reflect a balance of GABAergic (gamma-aminobutyric acid) inhibition and glutamatergic excitation (81). Moreover, corticothalamic frequencies evoked by TMS differ depending on the targeted cortical area (41). In addition to TEP peaks, other TMS-EEG metrics such as interhemispheric signal propagation (82) and interhemispheric balance, which reflect interhemispheric dynamics, and paired-pulse TMS metrics such as long-interval cortical inhibition (83) may be useful especially in clinical populations in which MEP measurements are not possible, as in the case of pathological states such as suicidal depression (84). Complexity-based metrics also appear to be promising for biomarker development, including but not limited to the Perturbational Complexity Index (83,85) and the Similarity Index (62,86). TEPs have been examined in various neurological and psychiatric disorders [for review, see (53)], these studies have largely focused on later (>100 ms) components of the TEP, where the peripherally evoked off-target effects are known to be present and have large amplitudes, confounding the validity of these biomarkers. In summary, although there is evidence suggesting validity of the early components of the TEPs, the off-target neural sources and nonneural artifacts surrounding these early components hinder reliability and exploration as potential biomarkers of diagnosis and treatment outcome. Thus, increasing the amplitude of these early TEPs and removing artifacts and other off-target effects is a critical next step to boost both reliability and validity of the TEP.

### EVALUATION OF TEP RELIABILITY

A reliable TMS-EEG biomarker should be stable across time (87,88) when there is no change in the indicated disease process and should be sensitive to change when fundamental parameters, including instrument, recording setup, cortical area stimulated, or intensity of stimulation, are varied (30). Reliability of a biomarker can be evaluated by 1) measuring the same metric over time within a laboratory [minutes (40), hours (87), or weeks (25,26,59) in a test-retest fashion (25,28,64,69)]; 2) repeated quantification across different instruments or in different laboratories (48,51,67); or 3) against different pre-processing and analytic pipelines (9,56,62). As described in more detail below, we find that internal reliability can be high when using certain setups (26) and when applying TMS to medial brain regions with minimal muscle activation. Reliability is reduced with the presence of noise sources, including when more lateral sites with larger muscle activations are stimulated. Methods to remove sources of noise and boost reliability include experimentally minimizing sensory contributions online

## Reliability of TMS-EEG

(62) and offline (56) and should be considered in reference to reliability metrics.

### BOOSTING TEP RELIABILITY DURING DATA COLLECTION

With a thorough understanding of the factors contributing to noise and signal in the TEP, various methodological approaches during assessment can be employed to boost the SNR and improve reliability. EEG amplifiers with specialized features (high sampling rate, high dynamic range, slew-rate limiting, and/or sample-and-hold circuitry) can reduce the effect of the primary electromagnetic pulse artifact on the recorded EEG signals (89–91). Delaying stimulator capacitor recharge until after the TEP time period of interest can prevent recharge-related electrical noise from masking relevant EEG signals (92). Minimizing EEG electrode impedance (<5 k $\Omega$ ) can reduce decay artifact caused by charge buildup at the electrode-gel-skin interface (93). Active electrodes can reduce sensitivity to environmental electrical noise such as 50 or 60 Hz line noise when compared with passive electrodes (94). A thin layer of foam placed between the coil and scalp may reduce artifacts related to bone conduction of the TMS sound (73). Passive noise reduction with earmuffs (47,50) and active noise masking (61,73) minimize auditory sensation and saliency of pulses. In combination with noise reduction and masking, alterations in pulse timing can further reduce off-target EEG components related to sensation and saliency (47). When feasible, rearranging electrode wires can minimize TMS-induced electrical artifact in electrodes near the site of stimulation (43).

Undesirable noise and desirable signal can be highly sensitive to stimulation location, coil angle, and intensity. By quantifying some aspects of noise and signal in real-time, it is feasible to individualize stimulation parameters (location, angle, intensity) to directly maximize the SNR of specific TEP features (30,95). Such real-time individualization approaches hold great promise for improving the reliability of TEP-based biomarkers by minimizing off-target effects and maximizing local brain responses. These approaches may also improve the validity of TEP-based biomarkers by effectively targeting stimulation to more relevant brain circuits with greater fidelity (96).

### EVALUATION OF TEP VALIDITY USING NONINVASIVE TOOLS

As stated above, early components (<50 ms) of the TEP may represent valid metrics of local cortical activation but are currently confounded by multiple sources of noise, which in turn reduces both internal and external reliability. The currently low accuracy of the early TEP with potential for high validity is deeply influenced by SNR, making an otherwise valid biomarker invalid (9). In the TEP, underlying signals of local activation can be masked by noise (97). It is worth noting that off-target sensory responses and true and valid TEP may not be independent and linearly separable phenomena. Thus, standard methods to remove these sensory responses and nonneural artifacts from genuine brain responses (51) as well as statistical comparisons between real and sham TMS (50,66,73,98–100) may be

called into question and reveal the intrinsic challenge about the nature of TEP analysis. These limitations do not necessarily imply that the early TEP cannot be a valid biomarker but rather that it requires further investigation, mechanistic understanding, sharing of data and protocols, and optimization of experimental setup to maximize SNR. Indeed, if we consider that validity describes how well a tool is sampling the desired physiology, in terms of local excitability, data gathered in the last few decades tells a promising while not complete story of the possible validity of early (<50 ms) components of the TEP. Indeed, early TEPs correlate with corticospinal tract excitability (33,76); are reduced in schizophrenia (101,102); mimic characteristic slow waves in non-rapid eye movement sleep, deep sedation, and disorders of consciousness (35,44,103–105); and are modulated in recovery from injury or stroke (106,107). However, intracranial brain recordings show promise to definitively link TEPs to their underlying neural correlates.

### EVALUATION OF TEP VALIDITY USING INVASIVE BRAIN RECORDINGS

To evaluate the validity of a tool, in addition to linking novel neuroimaging metrics with well-known noninvasive measures, it is also important to link to intracranial neurophysiology. Stated another way, using insights gained from intracranial recordings as the “ground truth” may be valuable to inform noninvasive TMS studies and establish the validity of TEP components. Intracranial neurophysiology can be valuable in a number of ways, including 1) TMS-evoked intracranial electrophysiology, 2) electrical stimulation-evoked electrophysiology, and 3) simultaneous invasive and noninvasive brain recordings. First, recent novel work combining TMS with intracranial brain recordings suggests that single pulses of TMS modulate both local and downstream brain circuitry that can be captured in the TMS-evoked intracranial response (108). Second, examining the intracranial neural responses to intracranial electrical stimulation can also provide valuable ground truth information (109–113). As intracranial electrical stimulation is not perceived, the ground truth corticocortical response profile to electrical stimulation without sensory confounds can be compared with the noninvasive localization and morphology of TEPs. In this manner, one can identify and isolate TMS-evoked sensory responses from grounded TMS-evoked neural signals that are consistent with intracranial recordings. Finally, in contrast to the previous non-time-locked evaluations of noninvasive and intracranial measurements, a novel combination of simultaneous intracranial and EEG scalp recording after stimulation (13) can provide a direct assessment of the neural correlates of noninvasive biomarkers. Caveats with this intracranial approach are that the patient population is currently limited to patients undergoing epileptic surgery and that there are physiological and artifactual differences between electrical and magnetic stimulation. In summary, pairing noninvasive and invasive brain stimulation with intracranial recording methods has great potential for improving the validity of TEPs and other novel neuroimaging metrics.

## BOOSTING TEP VALIDITY USING OFFLINE ANALYTIC METHODS

In addition to online optimization during data collection, offline analytical methods can be employed to remove noise and thus boost the SNR and validity of the TEP. There are many preprocessing pipelines that have been developed for this purpose (31,69,70,114), all of which involve a similar set of preprocessing steps: removal of 1) large TMS pulse artifacts, 2) line noise, 3) other known non-neural artifacts such as from eye movement and blinks, and 4) off-target neural sources (62), such as somatosensory and auditory activations. Removal of this noise is approached mainly using a combination of interpolation, filters, and independent component analysis-based methods (57,68). Interpolation is useful for artifacts with known timing and overwhelmingly high amplitude, such as the primary TMS pulse artifact, but inherently causes loss of data in the interpolated time range. This is why this technique is only typically used when the artifact overwhelms the overlapping EEG data. Filters break the signal into its spectral components and remove those outside of the specified range to effectively remove line noise, drift, and high-frequency muscle and environmental electrical noise. Independent component analysis is a blind source separation technique typically used for removal of eye-blink and saccade artifacts and by many groups for removal of other off-target activations. Independent component analysis is used to decompose the EEG data into independent sources of activity that are linearly mixed and is followed by identification of artifactual sources using known spatial and temporal characteristics and removal (68). This process can either be done manually or automatically using machine learning classification algorithms (59,115). In summary, offline removal of known artifacts in the TEP can boost SNR and enhance validity of the TEP.

After removing known noise, several further decisions regarding how to quantify the TEP are necessary, each of which can affect its validity. The TEP waveform is a complex multiphasic response, and quantifying this response is not straightforward. Many decisions are necessary including which peaks to quantify (P30, N45, P60, N100, and/or P200), how to quantify a peak (peak amplitude, peak-to-peak-difference, area under the curve, latency, etc.), which electrodes to analyze (single electrode, multiple electrodes, sensor or source space), and whether to evaluate in time or frequency space (41,76). All of these decisions can greatly influence the validity of the TEP because each metric extracts different information encoded in the TEP signal. For example, in assessing TEP change based on late TEP peaks (N100, P200), see also (66), one might find a more reliable (yet less valid) change because later TEP peaks are significantly composed of auditory-evoked potentials caused by the clicking sound produced by the TMS machine (10). Thus, to ask targeted questions regarding how the brain responds to the TMS probing of targeted neural circuits, it is essential that the metrics used to quantify TEP signals during analysis encode targeted and valid neural responses. Basic statistical techniques comparing the TEP after real and sham repetitive TMS have been utilized to determine whether certain features, such as the late TEP peaks (99), represent valid measures of targeted neural activity. However, myriad features can be extracted from the TEP, and basic statistical techniques

are not ideal for exploratory investigation across many of them. As such, more sophisticated statistical techniques (such as machine learning methods) could be helpful to describe multiple TEP features in a data-driven manner. These data-driven feature exploration approaches can be helpful for future hypothesis generation. In summary, careful consideration of offline analytic decisions and incorporation of more modern data-driven approaches can greatly influence the validity of TEPs.

## RECOMMENDATIONS AND FUTURE DIRECTIONS

In this paper, we evaluate TMS-EEG, a powerful causal neuroimaging tool, to describe and discuss the concepts of reliability and validity of potential biomarkers [see also (116) and (117) for discussions regarding TMS-EEG-related biomarkers]. The TMS field started with a gold standard MEP approach that was highly reliable (both internally and externally) and valid. As the field incorporated TMS-EEG approaches to evaluate corticocortical interactions outside the motor cortex, initial groups reported high internal reliability. However, as TMS-EEG was adopted across labs and translated to different brain regions and experimental setups, external reliability and validity were both reduced. We speculate that the trajectory of investigating neurophysiological responses to TMS, from initial high internal reliability and validity to reduced external reliability and validity, is all too common in noninvasive neuroimaging. We hope that by adopting the recommended approach outlined below, this trajectory can be modified to produce tools with high reliability and validity.

To help guide further research into the reliability and validity of novel and established neuroimaging techniques, we provide some general recommendations:

- Although reliability and validity are related, a biomarker can have high reliability but low validity or high validity but low reliability (Figure 1). We suggest that careful consideration of both are necessary before implementing a biomarker to make diagnostic or treatment decisions.
- Internal reliability can be enhanced by optimizing the SNR during data collection. Hardware optimization, real-time search for optimal stimulation parameters, and closed-loop methodologies can enormously reduce noise and increase signal strength.
- Although initial reports of internal reliability may be high, we recommend immediate or very early assessment of external reliability by collaborating closely with one or more external labs. Further, prompt dissemination and data sharing are of critical importance to ensure consistently high external reliability across groups and experimental setups.
- Validity is difficult to assess using noninvasive neuroimaging methodologies. Intracranial methods (animal models, human intracranial EEG) can provide ground truth assessment to improve evaluation of biomarker validity. Furthermore, simultaneous scalp and intracranial EEG may allow for direct comparisons between noninvasive biomarkers and their neural correlates (13). We strongly recommend that investigators initiate collaborations with labs using these intracranial methods to assess biomarker validity.

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