We introduce here the concept of a transcranial brain atlas (TBA), a new kind of brain atlas specialized for transcranial techniques. A TBA is a probabilistic mapping from scalp space to atlas label space, relating scalp locations to anatomical, functional, network, genetic, or other labels. TBAs offer a new way to integrate and present structural and functional organization of the brain and allow previously subsurface and invisible atlas labels visible on the scalp surface to accurately guide the placement of transcranial devices directly on the scalp surface in a straightforward, visual manner. We present here a framework for building TBAs that includes (i) a new, continuous proportional coordinate system devised for the scalp surface to allow standardized specification of scalp positions; (ii) a high-resolution, large sample–based (114-participant) mapping from scalp space to brain space to accurately and reliably describe human cranio-cortical correspondence; and (iii) a two-step Markov chain to combine the probabilistic scalp-brain mapping with a traditional brain atlas, bringing atlas labels to the scalp surface. We assessed the reproducibility (consistency of TBAs generated from different groups) and predictiveness (prediction accuracy of labels for individuals without brain images) of the TBAs built via our framework. Moreover, we present an application of TBAs to a functional near-infrared spectroscopy finger-tapping experiment, illustrating the utility and benefits of TBAs in transcranial studies. Our results demonstrate that TBAs can support ongoing efforts to map the human brain using transcranial techniques, just as traditional brain atlases have supported magnetic resonance imaging and positron emission tomography studies.

INTRODUCTION

Brain atlases are maps that relate brain locations in standard stereotaxic space [for example, Talairach and Montreal Neurological Institute (MNI)] to specific anatomical (1, 2), functional (3), network (4), and gene expression labels (5). Brain atlases provide a platform to integrate and present our knowledge about the brain and are immensely important, acting as prior knowledge in support of ongoing efforts to map structural and functional organization of the human brain. Noninvasive brain mapping approaches used in these efforts can be divided broadly into two categories. The first category uses three-dimensional (3D) brain imaging techniques, for which information from the 3D brain atlases can be directly incorporated. The second category uses transcranial brain imaging/stimulation techniques, such as functional near-infrared spectroscopy (fNIRS) and transcranial magnetic stimulation (TMS). Because of the nature of these transcranial techniques, information from current brain atlases (in the brain space only) cannot be directly used in these techniques (6, 7).

Noninvasive transcranial brain mapping techniques are growing rapidly given their potential for investigating brain mechanisms and treating brain disorders (8, 9). TMS, for example, can examine causal relationships between specific brain regions and behaviors (10) and has potential treatment efficacy for various neuropsychiatric disorders (11) including treatment-resistant depression (12). On the other hand, fNIRS offers a good balance between temporal and spatial resolution as well as loose constraint on the subject, ease of usage, and low cost compared to functional magnetic resonance imaging (fMRI). Thus, fNIRS can be easily applied in a near-natural environment (13) and used to study special populations such as infants (14), which other imaging modalities find very challenging.

Transcranial brain mapping devices are placed on the visible scalp surface, while the target areas of stimulation or imaging are located inside the brain, invisible from the researcher during placement. This disconnect makes optimal placement of devices given a target brain region (in the invisible brain space) very difficult, and problems in the placement may result in inconsistent experimental results and even conflicting conclusions. The positioning of the TMS coil is one of the major theoretical and practical issues for TMS applications, and practically, inconsistency of TMS coil placement for treating depression could result in divergent treatment outcomes (15). Similarly, the placement of fNIRS probes is critical; improper placement may result in recordings from different parts of cortex, missing the targeted cortical regions of interest (ROIs) (16). Accurate placement of fNIRS probes to cover ROIs and maintain high interparticipant correspondence at multiple channel positions is critical for group-level analysis and remains a pressing challenge (6, 17). The disassociation between the visible device placement space and the invisible target space, where brain atlases are currently located, impedes the direct use of brain atlases to support transcranial brain mapping.

To overcome this fundamental difficulty, we propose a new brain atlas: a transcranial brain atlas (TBA). A TBA is a mapping from the scalp surface to standard brain atlas labels. Once built, it can be used to provide atlas information while requiring only scalp positional information, which can be easily obtained with a magnetic digitizer (18) or an optical-tracking system (19). Moreover, a TBA visualizes the previously subsurface and invisible brain atlas labels on a virtual scalp surface, offering a direct and convenient presentation of atlas information for transcranial studies. TBAs can be combined with online or, in the future, augmented reality navigation systems (20) to guide the positioning of devices to precisely and accurately target ROIs.

Here, we present a framework for building TBAs that includes (i) a new continuous proportional coordinate (CPC) system devised for the scalp surface to allow standardized specification of scalp positions; (ii) a high-resolution, large sample–based (114-participant) mapping from scalp space to brain space to accurately and reliably describe human cranio-cortical correspondence; and (iii) a two-step Markov chain to
combine the probabilistic scalp-brain mapping with a traditional brain atlas, bringing atlas labels to the scalp surface. We then present results on reproducibility (consistency of TBAs generated from different groups) and predictiveness (prediction accuracy of labels for individuals without brain images) of the TBAs built. We also present the results of an fNIRS finger-tapping study to illustrate TBA usage and benefits. The TBA framework is highly extensible and opens a whole new toolbox for transcranial studies.

RESULTS

Brain atlases involve three spaces: brain space B, label space L, and, for transcranial atlases, scalp space S (Fig. 1). A brain atlas is a probabilistic mapping, P(L|B), from brain space to label space, where uncertainties in a population-based atlas are due to individual variation. A TBA is a probabilistic mapping, P(L|S), from scalp space to label space. To achieve this mapping, we need to first mathematically define scalp space S, that is, devise a coordinate system for it. Then, we need to probabilistically map scalp space to brain space, that is, find P(B|S), taking into account individual variation. Last, we need to combine the scalp-brain mapping P(B|S) with the brain-label mapping P(L|B) to obtain a scalp-label mapping P(L|S).

Scalp space: S

We propose a 2D coordinate system defined on individual scalp surfaces, the CPC system (Fig. 2A), and a method for planar visualization of scalp surfaces under this system, the Beijing Normal University (BNU) projection (see Materials and Methods and Fig. 2B). The CPC system has two important features. First, it is a continuous coordinate system in which each point on the scalp surface is mapped one-to-one to a pair of real numbers in \([0, 1] \times [0, 1]\). This permits the quantitative specification of any possible location on an individual’s scalp, which is critical for computer-based guidance and optimization of device placement (18).

Second, the CPC system provides interindividual scalp anatomical correspondence. It inherits this feature from the system on which it is based, the International 10-20 System, which provides well-established interindividua correspondence. The CPC system uses the same four foundational cranial landmarks as the 10-20 system and, like 10-20, is also defined in terms of proportions (though details differ, see Materials and Methods). To illustrate the consistency between CPC and 10-20, we show the 10-20 reference points of 114 participants in CPC space, visualized via BNU projection (see Materials and Methods and Fig. 2C). The tight distributions of the 10-20 reference points suggest that previous findings under the 10-20 system, including anatomical correspondence, are likely to be similar under the CPC system.

One-to-one mapping and interindividual correspondence together provide a standard scalp space in which scalps are spatially registered and comparable across individuals, thus laying the foundation for TBAs. Besides visualizing atlas labels, this standard space allows improved communication of experimental methods, promoting reproducibility, as well as mapping of other scalp-referenced information, for example, scalp-to-cortex distance (Fig. 2D), which may be useful for

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Fig. 1. Overview of brain atlases and TBAs. A brain atlas maps locations in brain space to labels. Because of individual variation, this mapping is probabilistic. A TBA maps locations in scalp space to labels through a probabilistic transcranial mapping from scalp space to brain space.
probabilistic transcranial mapping practitioners. Using CPC space does not require a separate registration step. Once the cranial landmarks are found, the coordinate space is naturally registered, without additional computational expense and operational burden.

**Probabilistic transcranial mapping: P(B|S)**
The underlying cortical location b corresponding to a given scalp CPC location s (Fig. 3A) can be determined in the individual’s native brain space [identified by the individual 3D structural MR image (sMRI)] using existing methods—here, we use the balloon inflation model (Fig. 3B) (21), although other choices can be used for specific applications (see Discussion). For each scalp point s, we repeat this process for all individuals in a data set (114 here) and spatially normalize the brain locations to MNI space (Fig. 3C). The resulting set of coordinates b gives us the empirical probability P(B|s). We then repeat this for all CPC points at the resolution desired to obtain P(B|S), the probabilistic transcranial mapping from scalp space to standard brain space. To evaluate the variability of this transcranial mapping, for each scalp location s, we calculated the SD of its set of corresponding brain locations b (Fig. 3D) using our data set from 114 participants. The mean SD among all locations in CPC space was 5.31 mm. Frontal areas had a relatively lower interindividual SD of about 4 mm. SD increased moving toward the posterior, reaching about 6 mm around the central sulcus and in the parietal areas, and finally reaching about 8 mm in the occipital areas.

**Transcranial brain atlas: P(L|S)**
We use a two-step Markov chain to combine the probabilistic transcranial mapping P(B|S) and a traditional brain atlas P(L|B), projecting atlas labels to the scalp (see Materials and Methods). To demonstrate our framework, we made TBAs from four commonly used brain atlases: (i) the LONI (Laboratory of Neuro Imaging, University of Southern California) Probabilistic Brain Atlas constructed from 40 adult humans (Fig. 4), abbreviated as LPBA40, in which 56 human cortical structures are labeled on the basis of macroscopic anatomical parcelation in MNI space (i); (ii) the 2nd edition Automated Anatomical Labeling Atlas (AAL2), in which 60 macroscopic anatomical volumes of interest in each hemisphere of a single individual are labeled in MNI space (2, 22); (iii) the Talairach atlas, in which 47 Brodmann areas (BAs) are labeled in the space of a single individual (23); and (iv) the Craddock400 atlas, in which 400 brain areas in the whole brain are parcelled on the basis of the resting-state functional connectivity (24). We present results from the TBA built on the LPBA40 atlas (TBA_LPBA) as an example below and give results for TBA_AAL, TBA_BA, and TBA_Craddock400 in the Supplementary Materials.

As our understanding of the brain proceeded historically from coarse to fine, we first examine a TBA for coarse anatomy, showing only the major lobes (TBA114_LPBA_LOBE; Fig. 4, A and B). From the maximum likelihood labeling map (MLLM) in Fig. 4B, the most likely labels at each scalp location, we see that the original spatial topology among the four lobes and properties such as bilateral symmetry can also be found in the BNU projection of the TBA. The maximum probability map (MPM) in Fig. 4A, showing the probability of the most likely label, suggests high labeling consistency among individuals (median, 0.95) over most of the scalp. The areas with lower probability roughly correspond to the prominent sulci or fissures separating the major lobes.

Next, we visualize the 35 label TBA built from the LPBA40 (TBA114_LPBA) via both BNU projection (Fig. 4, C and D) and perspective projections (Fig. 4E) using the original color-coding scheme of the LPBA40. Out of the 56 regions in the original LPBA40, 21 are invisible in the TBA, because they are unreachable under the balloon inflation model. Some large regions in the LPBA40, such as the precuneus, occupy only a small area in the TBA114_LPBA. The MPM of the TBA114_LPBA (Fig. 4C) suggests fairly high labeling consistency among individuals (median, 0.76), with lower consistency near boundaries.

**Reproducibility of TBAs**
For a TBA to be reliable, it must be reproducible; that is, TBAs constructed using data from different groups of individuals should be similar if the individuals were sampled from the same population. To evaluate reproducibility, we randomly divided our 114 participants into two equal groups and used them to separately construct TBA57A and TBA57B. We quantified the similarity of these two TBAs by the region-wise Sørensen-Dice coefficient (DICE; see Materials and Methods), listed in table S1 (median, 0.95).

**Predictiveness of TBAs**
The motivation for making TBAs is to support transcranial studies by providing atlas labels for given locations on an individual scalp only. Thus, the accuracy of label prediction for a previously unseen individual (with no sMRI data) is critical. To evaluate prediction accuracy, we randomly divided the 114 participants into a construction group (92 participants), building TBA92, and a testing group (22 participants). We obtained the ground-truth labeling for each testing group participant using that individual’s sMRI data: We applied the balloon inflation model to obtain an individual-specific transcranial mapping and transferred atlas labels to the scalp using this mapping.
Fig. 3. Probabilistic transcranial mapping. (A) Given one CPC point $s = (0.4, 0.6)$, (B) we identify the corresponding single point on each individual scalp (black dots) using the CPC definition and determine the position of the cortical projection point $b$ (yellow dots) via the balloon inflation model in individual MRI space. We then register these projection points to MNI space. (C) Distribution of the registered projection points is the probabilistic transcranial mapping for $s$. (D) Variability of the probabilistic transcranial mapping built from our data, quantified by the SD of the MNI coordinates $b$ (in millimeters).

Fig. 4. TBA built from the LPBA40. Labels are simplified to the major lobes in the upper panels. (A) MPM of TBA114_LPBA_LOBE, showing the probability of the most likely label via BNU projection. (B) MLLM of TBA114_LPBA_LOBE, showing the label with highest likelihood. (C) MPM of TBA114_LPBA. (D) MLLM of TBA114_LPBA. (E) MLLM of TBA114_LPBA rendered using perspective projection on the scalp of a randomly selected participant.
The discrepancy between the TBA92 labeling (prediction) and the ground truth labeling was the prediction error. TBA92 (Fig. 5A) is very similar to the ground-truth labeling of an example testing group participant (Fig. 5B). The prediction accuracy map (Fig. 5C), showing accuracy as a fraction correct across the 22 testing participants, suggests high prediction accuracy (median, 0.955) over most of the scalp. The areas colored yellow in Fig. 5D are predicted with an accuracy higher than 90%, while red areas, mostly at region boundaries, had an accuracy lower than 90%. To evaluate TBA predictiveness for individuals of a different race (our main data set consisted of Chinese adults), we used data from a group of 24 Caucasian adults (age, 23.43 ± 4.6; 17 males and 7 females) as another independent testing group, resulting in slightly lower prediction accuracy (median, 0.917; fig.S8A).

**TBA application**

We conducted an fNIRS finger-tapping study with seven participants to illustrate TBA usage and its potential benefits. We selected the left precentral gyrus from the AAL2 atlas as the imaging ROI. We developed a TBA-based navigation system that uses a magnetic digitizer for localization (see Materials and Methods) to guide the placement of the fNIRS probe array, here 3 x 5. For comparison, we used the widely accepted International 10-20 System to guide placement: We set the midline of the probe block along the T3-C3-Cz line, with the lower edge of the block at T3 to approximately cover the central sulcus (25, 26). Figure 6A shows the intended location for each approach. We assume each fNIRS channel location to be the midpoint between an emitter and a detector. Radii of red discs in Fig. 6B depict the SDs across participants of the cortical projections of the actual channel locations (calculated using sMRI data), illustrating placement consistency for each approach (top, TBA; bottom, 10-20). The SDs for TBA-guided placement were smaller (5.32 ± 1.3 mm versus 10.19 ± 1.75 mm; \( t_{21} = 13.28; P < 0.001 \), paired two-tailed \( t \) test). The number of channels covering the left precentral gyrus (Fig. 6D, yellow channels) was 26% higher, on average, for the TBA-guided placement. The difference did not reach a statistical significance (Wilcoxon signed-rank test, single-sided \( P = 0.13 \); signed rank = 2), possibly due to the small sample size (\( n = 7 \)). Last, we examined the group-level oxygenated hemoglobin (HbO) activation pattern during finger-tapping (Fig. 6C) for the TBA-guided placement (top) and 10-20-guided placement (bottom). Channel 9, located in the hand knob, was significantly activated [HbO general linear model (GLM) analysis; \( t_{6} = 6.45; P < 0.005 \), two-tailed one-sample Bonferroni-corrected \( t \) test] for data acquired under the TBA guidance, but no channel under the 10-20 guidance passed the corrected threshold. It showed a higher peak activation under the TBA guidance (channel 9, \( t_{6} = 6.45 \)) than under the 10-20 guidance (channel 11, \( t_{6} = 4.79 \)). We compared individual-level activation between the two peak channels, that is, channel 9 of TBA versus channel 11 of 10-20. Across the subjects, a significant difference was found between these two conditions (\( t_{6} = 2.83; P = 0.03 \), paired two-tailed \( t \) test). Further, the activation focality was measured by the difference of the activation strength between the peak-activated channel and the average of the rest channels. The TBA method showed a significantly higher focality than the 10-20 method (\( t_{6} = 2.45; P = 0.049 \), paired two-tailed \( t \) test).

**DISCUSSION**

**CPC system**

The CPC system has important advantages over existing methods. In 3D volume-based coordinate systems (for example, native MRI space), not all coordinates have a corresponding scalp location, due to the inherent mismatch of the 3D system with the 2D nature of the scalp. This makes using these systems cumbersome for specifying scalp locations and complicating registration. The currently accepted scalp reference system, the International 10-20 System (and its derivatives), is enumerative, meaning that not all scalp locations have a corresponding coordinate value, making it impossible to specify most scalp points. Thus, both volume-based and 10-20–based systems, due to the lack of one-to-one mapping, are suboptimal for use as scalp coordinate systems. In contrast, the CPC system provides a one-to-one mapping for all scalp locations.

**Cranio-cortical correspondence**

Identifying a brain location from a scalp location is a critical and challenging step in building a TBA, which requires a fairly consistent scalp-brain mapping, or cranio-cortical correspondence, across individuals. Cranio-cortical correspondence is a fundamental issue for transcranial techniques in general and has been investigated since the 10-20 system was developed. On the basis of this reference system, correspondence has been investigated at multiple spatial scales (for example, in terms of brain regions, gyri, and voxels) using various approaches, such as cadaver examination, x-ray, computed tomography, and MRI [reviewed in (27)]. In a first attempt to quantify cranio-cortical correspondence of the 10-20 system, Okamoto et al. (26) used MRI data from 17 participants, identifying 10-20 reference points and their cortical projection points in MNI-registered volumes. They reported an average SD of 7.9 mm for the spread of each projected 10-20 reference point. A follow-up study repeated the analysis on the same data and reduced the average SD to 6.6 mm by replacing the manual 10-20 reference point localization procedure with Jurcak’s automatic positioning algorithm (28). These 10-20–based studies provide preliminary quantitative evidence for a consistent cranio-cortical correspondence between individuals.
Here, we measured the SD of cortical points projected from a much larger set of scalp locations using our 114-participant data set. This was the first time that all scalp locations (limited by our sampling resolution), not just 10-20 reference points, were mapped to cortical locations. Averaged over all CPC space, the SD of projected point locations was 5.31 ± 1.49 mm. Assuming a 3D Gaussian distribution, about 61% of the projected points will be within this distance from the mean position, and 99% of the projected points will be within 10.62 mm. The map of the SDs (Fig. 3D) shows that the highest variability is mainly located at boundary regions between brain structures, such as the medial longitudinal fissure and lateral fissures; for most of the brain, variability is lower than the 5.31 mm average. This map is, to our knowledge, the first high-resolution, large sample–based quantitative description of cranio-cortical correspondence for humans. Our results strongly suggest that there is a fairly consistent cranio-cortical correspondence between individuals and that transcranial mapping can predict, with limited error, locations in brain space using only scalp coordinates, a fundamental requirement for practical TBAs.

**TBA application**

A TBA, a probabilistic mapping P(L|S), provides two distinct ways to support transcranial brain mapping studies. In the forward direction of this mapping, we can use P(L|S) to obtain a label from a scalp location, informing us of the recording or stimulation target of a placed device. In the backward direction, we can use P(L|S) to estimate the scalp location that best records or stimulates a given target brain region. Our fNIRS finger-tapping experiment demonstrated the improvement in group-level HbO activation pattern (Fig. 6C) that TBA-guided placement can facilitate. The improvement is likely attributable to two factors: better coverage of ROI (Fig. 6D) and better consistency among participants (Fig. 6B).

For some transcranial studies, such as those using instruments with cost and other advantages over MRI, additional sMRI scanning is seldom conducted. TBAs are well suited to support these studies. Our predictiveness validation showed that, in this situation, the median labeling accuracy was higher than 90%, and errors occur mostly near boundaries of label regions. However, for other applications, such as clinical TMS, accuracy is paramount. A TBA is only a summary of the commonality between individuals and does not inform us of an individual’s deviation from the mean, so we advise caution here. In this case, if the individual’s sMRI data are available, an individual-specific TBA can be constructed based on the individual (nonprobabilistic) transcranial mapping computed from sMRI data, providing more assured labeling accuracy. This removes the variability due to transcranial mapping differences among individuals.

**Extensions**

Two areas in which the present work can be extended are the choice of brain atlas and transcranial mapping method. In terms of brain atlas, besides the four brain atlases we examined here, atlases of different data modalities and of different populations are potentially useful to researchers. For data modalities, functional atlases (3), connectivity...
atlases (4), and others will be considered in future work, because atlases need not be limited to discrete labels. Besides traditional label information, scalar, vector-valued, and even more complex data of arbitrary type may be useful for some applications. Examples are cortical thickness maps (scalar), neural activation maps for presenting results (scalar), 3D coordinates of the projection point (vector) to look up information from other sources, and lists of brain areas functionally connected to the covered brain area. The TBA framework can be used to "bring to the surface" any data set originally registered to brain space. Because our TBA construction framework can accommodate any atlas, developments in the field can be readily incorporated.

Besides data modality, using sMRI data from different populations during TBA construction allows TBAs to target specific populations of interest. Because the brain and skull change throughout life, TBAs constructed from young adult brain data may only be valid for young adults, as differences from young adults are significant for youth and senior populations, particularly infants (29). These differences in anatomy will likely result in different cranio-cortical correspondence (30). Accordingly, TBAs can be constructed specifically for infants, children, and elderly people to assist developmental and aging studies. Furthermore, because transcranial mapping techniques have been widely used in various neurological and mental disorders (31), the atypical brain structures sometimes seen in these disorders may merit building specific TBA to assist in imaging and stimulation of these groups. Our TBA construction framework can also be applied to preclinical models—nonhuman primates and rodents—which are widely used to investigate the neuroplasticity induced by TMS stimulation (32). Using sMRI data sets and atlases of animal models, specific animal TBAs can be constructed using the pipeline we presented here.

Limitation
The transcranial mapping is a key technical step in TBA construction and an obvious area for extension. Here we use the balloon inflation model for its simplicity and practical effectiveness (21). These models have been widely adopted in localization algorithms for fNIRS (6, 17) and in current navigation systems for TMS (19). However, depending on the physical mechanism of the transcranial technique, this simplified model may be improved. Recent progress in numerical computing includes models describing how electric fields (33) and optical paths are generated from devices and distorted by tissues (34). Studies also suggest that physics-based cranio-cortical mappings would lead to nontrivial benefit in predicting the efficacy of transcranial imaging (16) and stimulation (35). Therefore, an attractive approach for extending our work is to integrate these more sophisticated transcranial mapping models to produce application-specific TBAs.

CONCLUSIONS
We have proposed the novel concept of a TBA and a probabilistic framework for building such atlases. TBAs allow the visualization of brain region labels on the surface of the scalp, providing anatomical reference and navigational guidance for transcranial research. We devised the novel CPC system for the scalp surface, which enables high-resolution localization and automatic registration and facilitates standardization and reproducibility of placement of transcranial devices on the scalp surface. Our data quantify the reproducibility, predictiveness, and potential benefits of our methods. Moreover, for the first time, we provide a high-resolution map of the variability of cranio-cortical correspondence for humans. The framework is not limited to building transcranial atlases for brain region labels; it can also bring to the scalp surface any data set originally registered to brain space, allowing extensions to suit particular applications.

MATERIALS AND METHODS
CPC system definition
We first introduced five cranial landmarks inherited from the EEG 10-20 system (25): nasion (Nz), a sunken area at the upper end of the nose bridge; inion (Iz), an external occipital protuberance near the middle of occipital bone; left/right preauricular point (AL/AR), an anterior root of the tragus of left/right ear; and Cz, a cranial landmark that separates both the geodesic curve of Nz-Iz and AL-AR. The five landmarks are illustrated (fig. S1A, red dots). Given a scalp surface and the five landmarks on it, we defined the coordinates of a scalp point s (magenta point) in the CPC system as follows. We defined the equator (cyan) as the intersecting curve between the scalp surface and the plane through Nz, Cz, and Iz. We defined the longitude-like curve (green) as the intersection between the scalp surface and the plane through AL, AR, and s. This curve, shaped like a horseshoe headband, intersects the equator at s’ (brown dot). The CPC for s is a pair of nonnegative real numbers (s_e and s_l) consisting of the position of s’ and s along their respective curves expressed as a proportion of the curve length.

\[ s_e = \frac{L_{Nz-s}}{L_e} \] (1)
\[ s_l = \frac{L_{AL-s}}{L_{AL-s-AR}} \] (2)

where \((s_e, s_l) \in [0, 1] \times [0, 1]\). \(L_{Nz-s}’\) is the curve length from Nz to s’ along the equator, and \(L_e\) is the full length of the equator from Nz to Iz; \(L_{AL-s}\) is the curve length from AL to s along the longitude-like curve, whose full length is \(L_{AL-s-AR}\).

BNU projection
To visualize the entire upper scalp surface in a single planar view in a neuroscientist-friendly way, we proposed the following scheme. We constructed the CPC space on a standard hemisphere, where Nz, Iz, AL, and AR lie on the hemisphere’s edge at 90° intervals (fig. S1B), and Cz lies at the apex of the hemisphere. The hemisphere, along with the CPC space defined on it, was flattened using the Hammer-Aitoff equal-area map projection (36), resulting in a planar map of the CPC space (Fig. 2B). We call this two-step process the BNU projection. Any information in the scalp space, including TBAs we constructed, can be presented using the BNU projection, enabling quick visual comparison between different individuals, populations, data sets, and different imaging modalities, using one visualization.

sMRI data
We used an sMRI data set with 114 Chinese young adult participants (age, 18 to 26; 63 females and 51 males) from the SLIM database (37) of the International Neuroimaging Data-sharing Initiative (INDI). The high-resolution 3D T1-weighted structural images were obtained using a magnetization-prepared, rapid acquisition gradient-echo sequence (repetition time/echo time, 1900/2.52 ms; flip angle, 9°; field of view, 256 mm × 256 mm; slices, 176; thickness, 1.0 mm; voxel size, 1 mm × 1 mm × 1 mm).
Brain atlas data
Here, we adopted four brain atlases widely used in the analysis of neuroimaging studies: the LPBA40 atlas, the AAL2 atlas, the Talairach atlas, and the 400-ROI Craddock atlas. Image data of these four brain atlases in the format of NifTI (Neuroimaging Informatics Technology Initiative) file were obtained from the web with authorization.

The image data of LPBA40 were obtained from the website of the LONI laboratory (www.loni.usc.edu/atlastes/Atlas_Download.php). There were several derivatives of LPBA40 according to the spatial normalization procedure applied during the atlas production. The SPM5 edition package of the atlas was selected because of its spatial normalization method; that is, the unified segmentation was consistent with the current study. In the package, the estimated gray matter probability density maps for each tissue, for example, lpba40.spm5.avg152T1_L supérieur_frontal_gyrus.gm.pdf.nii, were directly used in the construction of TBA_LPBA40. The SPM12 version package of AAL2 atlas was downloaded from www.gin.cnrs.fr/en/tools/aal-aal2/.

The NifTI formatted Talairach atlas was obtained from www.talairach.org/. Because the Talairach atlas was constructed in the Talairach space rather than in the MNI space, a Talairach-to-MNI spatial transformation was performed on each labeled voxel with the help of MATLAB script tal2icbm_spm.m provided by Brain-map.org (http://brainmap.org/icbm2tal/).

The 400-ROI Craddock Atlas was downloaded from http://ccraddock.github.io/cluster_roi/atlases.html. Specifically, we took the edition of "cor010_2level_K32," in which the brain atlas was constructed from temporal correlation metrics between voxel-wise time courses and with a two-level clustering scheme performed on group-level functional connectivity data. The parameter K was set to 32, resulting in a whole-brain parcellation of 400 ROIs. The size of the ROIs was 3 ± 0.75 cm³, comparable to the focality of TMS and other brain stimulation techniques (38).

sMRI processing
We segmented each individual sMRI into six tissue images: gray matter, white matter, cerebrospinal fluid (CSF), bone, soft tissue, and air/background in native space, using the unified segmentation protocol (39) in SPM12 (Wellcome Trust Centre for Neuroimaging; www.fil.ion.ucl.ac.uk/spm). The unified segmentation also generated a native-to-MNI transformation field. We generated a brain image (gray matter + white matter) and a head image (gray matter + white matter + CSF + bone + soft tissue), smoothed each with a Gaussian kernel with full width at half maximum of [3,3,3], and binarized the result at a threshold of 0.5. Then, we applied the surface extraction algorithm in SPM12 to extract the scalp surface point cloud (Fig. 3B, pink) and cortical surface point cloud (in gray) for the participant.

We visually identified the four cranial landmarks Nz, AL, AR, and Iz in the individual sMRI using the MRIcon software. We located the 10–20 reference point Cz in the extracted individual scalp surface using the Jurcak’s iterative algorithm (40). We then established the CPC system on the individual scalp surface according to the definition, using custom MATLAB codes. Here, we performed discretization of CPC space by evenly dividing each dimension into 100 segments to obtain a uniform grid, called CPC100, although, in general, the resolution can be set as needed.

Transcranial projection
On each point of the CPC100, the balloon inflation algorithm (21) was used to calculate the projection point in the native brain. The balloon inflation can be briefly described as two stages. The first was the balloon inflation stage, in which a sphere centered at the given cranial point was generated. As the sphere expanded, a set of points on the brain surface interacted with the sphere. The barycenter of the initial set of the intersecting points was used to determine the projection direction in the next stage. The second was the projection stage, in which a straight line extended from the cranial point through the barycenter and finally reached the brain surface. In addition, the intersection point was determined as the cortical projection point. Note that these resultant projection points were represented still in the native space (the subject’s head space); therefore, a spatial normalization process was applied to transform them into the standard MNI space. Here, a spatial normalization was performed with the transformation field estimated in the unified segment procedure.

The balloon inflation algorithm has been described in more detail in a previous study (21), and the MATLAB code of the algorithm can be downloaded from www.jichi.ac.jp/brainlab/tools.html.

TBA construction
We used a two-step Markov chain model to combine the probabilistic transcranial mapping and a traditional brain atlas to obtain the scalp-label mapping. Because one can retrieve the atlas label l from a brain atlas given the brain location b, without requiring the scalp location s [that is, conditional independence: P (L|B, S) = P (L|B)], P (L|S) can be computed from P (B|S) and P (L|B) using the Chapman-Kolmogorov equation.

\[
P(l_i|s_i) = \sum_{j=1}^{N_b} P(l_i|b_j) \cdot P(b_j|s_i)
\]  

(3)

where \( s_i, i = 1, 2, \ldots, N_s \), are locations in discretized CPC space; \( b_j, j = 1, 2, \ldots, N_b \), are locations in discretized MNI space; \( l_i, k = 1, 2, \ldots, N_l \), are labels from the brain atlas. Here, the discretized CPC space was given by the CPC100 grid. Among the 114 participants, the maximal distance between two neighboring points of CPC100 was 4.76 mm, and for 99% of the participants, this value was less than 3.79 mm, giving a spatial resolution that is comparable with most transcranial techniques (38). The discretized brain space was defined by the tissue probability map (TPM), and a template of SPM12 with a spatial resolution of 1.5 mm × 1.5 mm × 1.5 mm was used as the discretized MNI space.

DICE index
We used the maximum likelihood labeling from TBA57A and TBA57B to compute the DICE index

\[
DICE(l) = \frac{2|X_{IA} \cap X_{IB}|}{|X_{IA}| + |X_{IB}|}
\]  

(4)

where \(| |\) gives the area of the regions inside, and \(X_{IA}\) and \(X_{IB}\) are the regions with label l in TBA57A and TBA57B, respectively. DICE index values range from 0 to 1, with larger values indicating higher consistency.

TBA-based navigation system
We developed a TBA-based navigation system that uses a 3D magnetic digitizer (18) for scalp localization. The operational steps for TBA-guided navigation were as follows. First, the cranial landmarks Nz, AL, AR, and Iz were visually identified on the head of the participant, and their locations in real-world coordinates were recorded using the
digitizer (fig. S2A). Then, a sparse set of points were uniformly sampled from the scalp surface using the digitizer to reconstruct the participant’s scalp surface (18). On the basis of the landmarks and reconstructed scalp surface, the CPC100 grid was placed in real-world coordinates. Then, a TBA (here, for example, TBA114_LPBA40) was mapped onto the participant’s CPC100 grid and visualized in real-world coordinates (fig. S2B). During navigation, as the operator moved the stylus of the digitizer on the participant’s scalp in physical space, a black dot, signifying the location of the tip of the stylus (fig. S2B), would move accordingly on the scalp map in the navigation system’s user interface. Thus, an operator could use this scalp map to guide the placement of TMS coils or fNIRS probes, similar to using a GPS (Global Positioning System) navigation system with a digital map. Details of the TBA-based navigation system will be presented in another publication.

**fNIRS finger-tapping data**

We recruited seven right-handed adults (males) for the finger-tapping experiment and recorded fNIRS data with a 3 × 5 probe array and an ETG-4000 optical topography system (Hitachi Medical Company). For each participant, we recorded two sessions of fNIRS data: one for TBA-guided probe placement and the other for traditional 10-20-based placement. The order of the two sessions was counterbalanced across participants. Each session consisted of eight blocks of 20-s finger-tapping and eight blocks of 20-s rest, in alternation.

In the TBA-guided placement session, we placed the middle line of the fNIRS probe block along the narrow strip of the precentral gyrus in TBA114-AAAL for the first participant. After we finished the probe arrangement for the first participant, we recorded the CPC values of the central node and the nearest four neighbor nodes in the probe block, representing the position and orientation of the probe block. For the remaining participants, we placed the probe block using only these five CPC values. In the 10-20-based placement session, we set the midline of the probe block along the T3-C3-Cz line and the bottom edge of the block at T3 in every participant, with the goal of covering the central sulcus (25, 26).

We recorded the resultant scalp locations of the fNIRS channels (midpoint between an emitter and a detector) for each participant and determined the corresponding MNI coordinates (via balloon inflation model) and AAL2 atlas labels using individual sMRI data we acquired from the participants. We quantified ROI coverage by the number of channels located within the left precentral gyrus. For each channel, we calculated the SD across participants of the projected cortical locations to quantify interindividual variation. We performed a GLM analysis (NIRS-SPM toolbox) to detect individual-level HbO responses to finger-tapping for each channel. Then, we performed group-level analysis (two-tailed one-sample Bonferroni-corrected t test) on the resultant beta maps to characterize the group-level response.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/9/eaar6904/DC1

Supplementary Results

- Fig. S1. CPC system definition.
- Fig. S2. TBA-based navigation.
- Fig. S3. TBA built from the AAL2 atlas.
- Fig. S4. TBA built from the Talairach Atlas, showing BAs.
- Fig. S5. TBA built from the Craddock400 atlas.
- Fig. S6. Label prediction performance.
- Fig. S7. ROI-wise DICE map.
- Fig. S8. Accuracy maps of cross-racial prediction.
- Table S1. ROI-wise DICE of TBA_LPBA, TBA_AAAL, and TBA_BA.

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Acknowledgments: We would like to thank J. Qiu and L. Liu for sharing data. Funding: This work was supported by the National Natural Science Foundation of China (grant nos. 61431002, 61273287, and 31521063), the National 973 Program (grant 2014CB846100), the Interdisciplinary Research Funds of BNU, and the Fundamental Research Funds for the Central Universities (2017XTCX04). Y.Y. is supported by the Intramural Research Program of the National Institute on Drug Abuse, the NIH. Author contributions: XX, Y.Y., and C.Z. designed the research. XX and Y.Y. developed the algorithm and software. Y.Y. and Y.Z. conducted the experiment and collected the data. XX, ZZ, YY, and Y.Z. did the analysis. Competing interests: C.Z. is an inventor on four patent applications related to this work (no. 201711322471.4 [date: 12 December 2017]; no. 20171126640.0 [date: 5 December 2017]; no. PCT/2018/083999 [date: 22 April 2018]; and no. PCT/2018/083400 [date: 22 April 2018]). The authors declare no other competing interests. Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. T1 images and brain atlases can be accessed via web links described in Materials and Methods. The results of the constructed TBAs will be available later on our homepage. Additional data related to this paper may be requested from the authors.

Submitted 17 December 2017
Accepted 26 July 2018
Published 5 September 2018
10.1126/sciadv.aar6904

Citation: X. Xiao, X. Yu, Z. Zhang, Y. Zhao, Y. Jiang, Z. Li, Y. Yang, C. Zhu, Transcranial brain atlas. Sci. Adv. 4, eaar6904 (2018).