Jalyssa Smith is a Biomedical Engineering major at the University of Memphis, graduating in the spring of 2024. She has earned Honors in Biomedical Engineering and will continue her education to earn a master's degree. At the University of Memphis, she has been involved in the track program and the National Society of Black Engineers. The past year she has worked under Dr. Amy L. de Jongh Curry to learn more about Transcranial Magnetic Stimulation (TMS) and its ability to improve the lives of those with neurological disorders. In the future, she will be exploring pediatrics and the developing brain to further the understanding of the effects of TMS and efficacy of treatment.

Jalyssa's paper received a *QuaesitUM* outstanding paper award.

**Jalyssa Smith**

# The Identification of the Influence of TMS Parameters on Induced Electric Field and Volume of Activated Cortical Tissue

**Faculty Sponsor**

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## Abstract

Transcranial Magnetic Stimulation (TMS) is a noninvasive procedure that utilizes magnetic fields to study brain function, diagnose, and treat neurological diseases. This study investigates the effect of TMS coil location, type, and orientation on induced E-field and volume of activated tissue. SimNIBS, an open-sourced platform, simulated three coil types and orientations, targeting the primary somatosensory cortex. Within the same hemisphere, E-field and volume of activation differed up to 10% and 35%, respectively. Coil orientation altered E-fields up to 11%, and volume of activation by 30%. An inverse relationship was observed between the volume of activation and magnitude of TMS-induced E-field.

## Introduction

Transcranial Magnetic Stimulation (TMS) is a noninvasive procedure utilizing magnetic fields to induce electric currents in the brain. TMS is used to study brain function through functional mapping and is approved by the Food and Drug Administration (FDA) for treatment of depression and obsessive-compulsive disorder. Ongoing research indicates that TMS may also be a viable treatment method for other neurological disorders, such as strokes and chronic pain.

The magnitude of the induced electric field (E-field) is influenced by the type of stimulation coil, orientation of the coil, and coordinates of coil placement [3]. The brain is comprised of white and grey matter and cerebrospinal fluid, which have different conductive properties. In turn, the different composition affects the resulting E-field distribution to neurons during TMS. The type of coil and orientation also affects the E-field distributions and stimulates different regions of neurons. Based on the coil orientation, the induced E-field may be parallel or perpendicular to the cortical columns, which are a group of neurons and alter the effectiveness of TMS. Moreover, the stimulation, or activation, of neurons is dependent on an appropriate induced E-field intensity.

To better understand the effect of TMS parameters, computational modeling of TMS-induced E-fields may be utilized. As an open-source computational platform, SimNIBS [1], was developed to simulate TMS-induced E-fields in physiologically realistic brain anatomy for a variety of clinically relevant stimulation coil types, coil orientations, and coil locations. SimNIBS allows for clinically relevant coil placements utilizing the Montreal Neurological Institute (MNI) brain coordinates and employs the finite element method (FEM) to simulate applied magnetic fields and resulting E-fields in the brain. In this study, we focused on stimulation of the primary somatosensory cortex (SI). Located in the parietal lobe, body surface receptor signals travel through peripheral nerves to the thalamus and relayed to SI to perceive the body and physical environment [2]. SI has been a target location in current TMS research to assist motor and sensory recovery after strokes [3]. The objective of this study was to determine if the induced E-field intensity and volume of activated cortical tissue varied for (1) homologous coil placements on the right and left hemispheres, (2) different coil placements within the same hemisphere, (3) different coil orientations, or (4) different coil types.

## Methods

### E-Field Modeling and Obtaining Volume of Activated Cortical Tissue

The TMS-induced E-field was computed using the free, open-source simulation platform SimNIBS 4 [1]. The head model used in the study was acquired from the example MRI dataset along with default settings. The platform calculates the E-field using a quasistatic form of Maxwell's equations which are [4]

**Eq. 1**
$$\nabla \cdot \left(\underline{\sigma} \nabla \phi\right) = -\nabla \cdot \left(\underline{\sigma} \frac{\partial \boldsymbol{A}}{\partial t}\right)$$

**Eq. 2**
$$\boldsymbol{E} = -\nabla \phi - \frac{\partial \boldsymbol{A}}{\partial t}$$

For each coil, SimNIBS simulations determine the magnetic vector potential (A) which is dependent on coil shape, position, and current delivered to the coil [4]. Using Eq. 1, the magnetic vector potential is calculated by relating it to the tissue-specific isotropic conductivity (σ) and electric potential (φ). FEM is implemented to calculate the electric potential and E-field (E) in units of volts per meter (V/m) using Eq. 2. SimNIBS also outputs the volume of cortical tissue with an E-field greater than or equal to 50% and 75% of the maximum E-field. In this study, we report the volume of activated cortical tissue using the E-field equal or greater to 75% as it represents the appropriate threshold in therapeutic applications of TMS [5].

### TMS Parameters

Three electrode placements were chosen within the primary somatosensory cortex on both hemispheres. In the left hemisphere, coil placements at C3 and C5, which are MNI coordinates, and a midpoint between the two were selected. In the right hemisphere, coils were placed at C4 and C6, which are homologous location to C3 and C5, respectively, and a midpoint between C4 and C6. **Figure 1** displays the electrode placements in the left hemisphere.

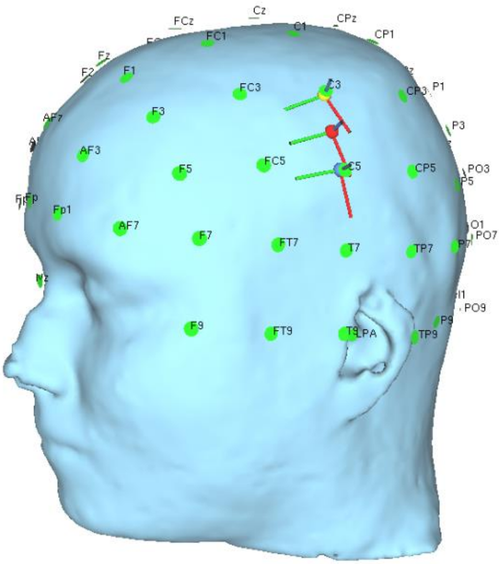

**Figure 1.** Three electrode placements in the left hemisphere, C3 (top), C5 (bottom), and a midpoint between the two. The red and green bars indicate the electrodes x-axis and y-axis, respectively.

At each electrode placement, three different orientations were tested. **Figure 2** displays the orientations, including the coil pointing toward the nose (Nz), occipital (Oz), and vertex (Fcz). Moreover, at each electrode placement and orientation, three coil types were tested including the Magstim 70 mm (Mag70) and Magstim D50 Alpha BI (MagD50), and MagVenture B70 (MagB70). The Mag70 and MagD50 coils are configured in a figure-of-eight shape with a coil diameter of 70 mm and 50 mm, respectively. The MagB70 is configured in a butterfly shape and the two figure-of-eight shaped coils are slightly bent to better conform to the shape of the head. For each simulation, the intensity of the stimulating current delivered to the coil was set to 150 A/μs. The coil was placed 0 mm from the scalp at each location. SimNIBS outputs analyzed were the induced maximum E-field and volume of activated cortical tissue to at least 75% of the maximum E-field. Percent differences were then calculated to identify the effects of coil locations, types, and orientations on the E-field intensity and distribution.

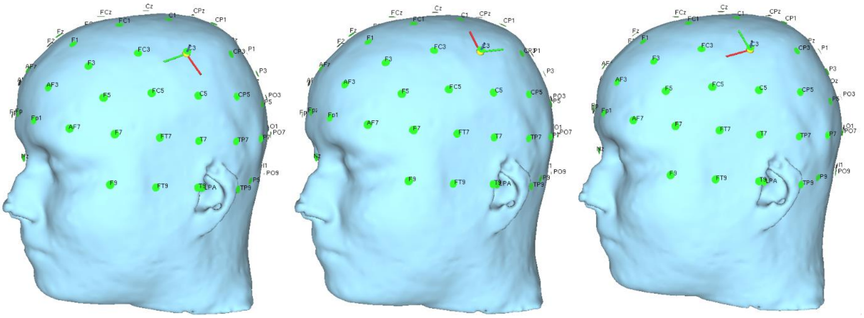

**Figure 2.** Transcranial magnetic simulation coil orientations where the red and green bars represent the x-axis and y-axis, respectively. (A) Current flowing toward the nose (Nz). (B) Coil rotated 180° in the occipital direction (Oz). (C) Coil oriented 60° toward the vertex (Fcz).

# Results

## Difference in Maximum E-Field

We obtained maximum E-Field data for three different electrode placements in the two hemispheres within SI and for different coil types and orientations. An example of the E-field distributions is shown in **Figure 3**. It also demonstrates the different E-field magnitudes and volume of activated tissue with varying coil types.

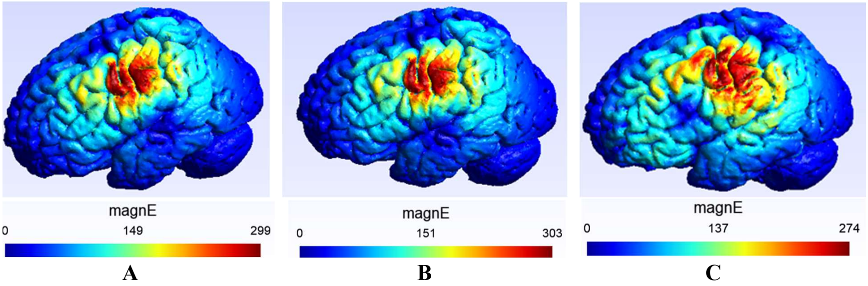

**Figure 3.** E-field magnitudes (V/m) and distributions at C3 using the Mag70 coil pointed toward (A) the nose (Nz), (B) occipital direction (Oz), and (C) the vertex (Fcz).

The maximum E-Field values are shown in **Figure 4** and ranged between approximately 250 to 300 V/m. At homologous regions in the left and right hemisphere, the percent difference between the maximum E-field were between 2–7%. Generally, electrodes C5 and C6 were noted to have the greatest differences compared to the other homologous regions. The differences between coil locations within the same hemisphere, however, was 5–10%. Regarding the coil orientation, the greatest differences were between Fcz and Nz/Oz, with 11% difference in the right hemisphere. In contrast, the difference between Nz and Oz in both hemispheres was only around 1%. Overall, the E-field intensity was greater when pointed toward Nz and Oz versus Fcz. Lastly, the Mag70 coil consistently produced 10% lower E-fields than the MagD50 and MagB70.

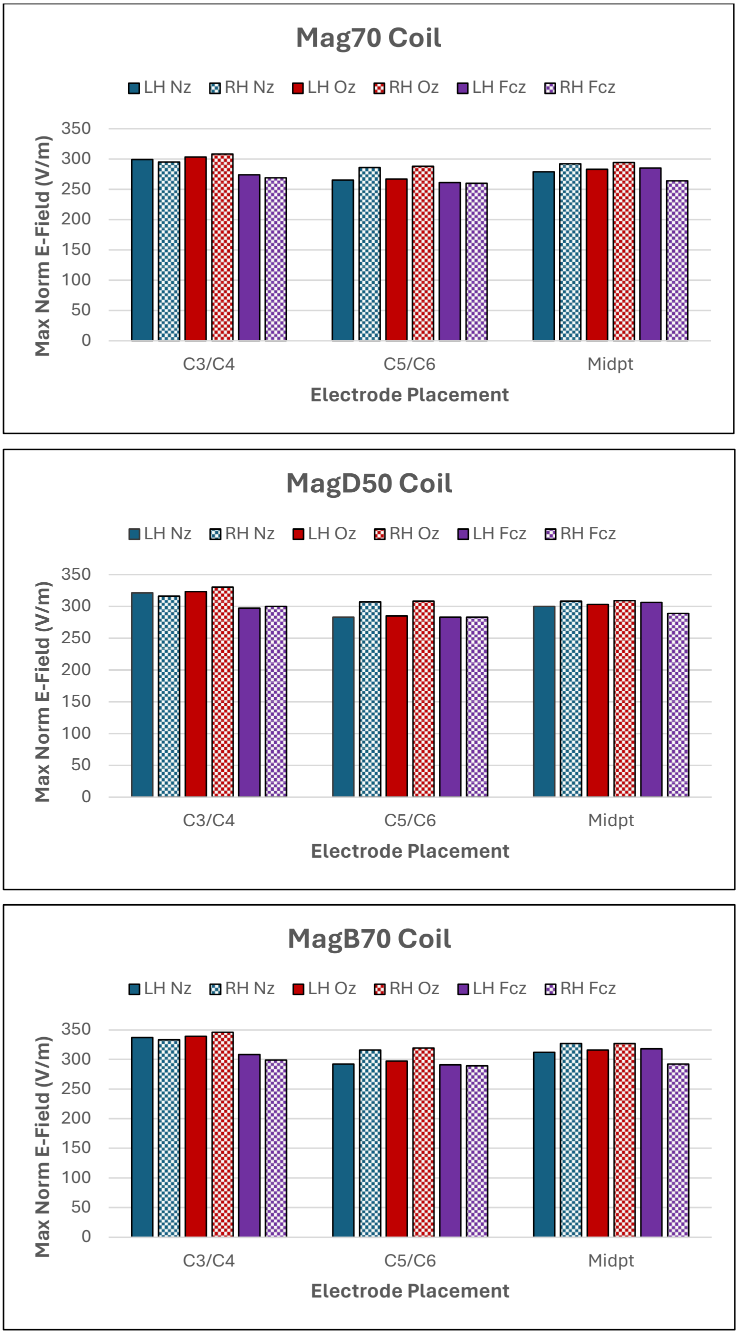

**Figure 4.** The max norm E-field at the electrode placements and orientation for the three different coils, (A) Mag70, (B) MagD50, (C) MagB70.

### Difference in Activated Volume of Cortical Tissue

We determined the activated volume of cortical tissue for homologous electrode placements, and different coil types and orientations. The values for the activated volume of tissue are shown in **Figure 5**. The activated volume of tissue ranged between approximately 3000 to 5000 . There were 3–20% differences at homologues sites, the greater percentage difference between C5 and C6 and C4 (7% difference). Within the same hemisphere, the activated volume of cortical tissue differed significantly. In the left hemisphere the percent difference was 25% compared to the right hemisphere which was more consistent with a percent difference of 11%. The right hemisphere also experienced greater percent differences in orientations. While there were similar values when the coil is pointed toward Nz and Oz, the values were generally about 30% greater when compared to the Fcz direction. Generally, the Fcz direction had the greatest volume of activated cortical tissue as demonstrated in **Figure 3**. Moreover, the Mag70 produced about 8-10% higher than the MagD50 and MagB70.

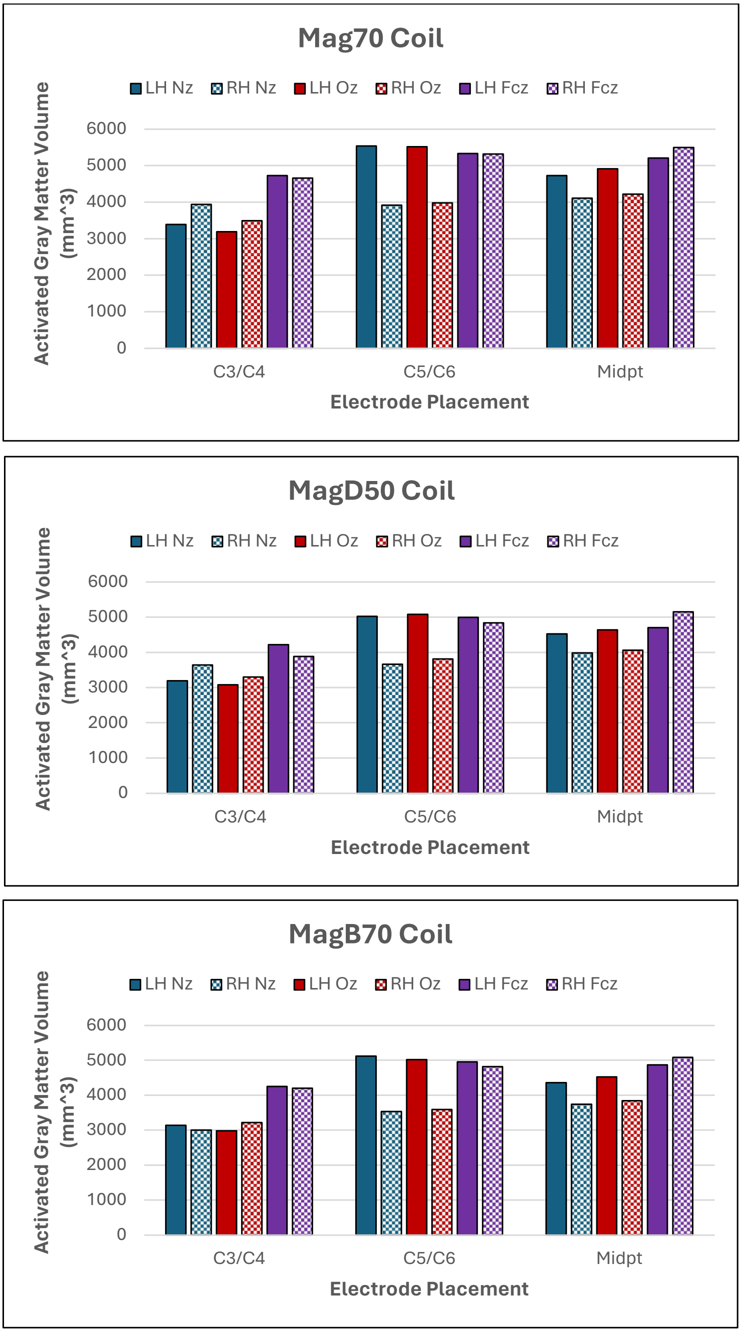

**Figure 5.** The activated gray matter volume at the electrode placements and orientation regarding coils, (A) Mag70, (B) MagD50, (C) MagB70.

## Discussion

The simulations identified that the maximum induced E-field and volume of activated cortical tissue is influenced by the coil's location, orientation, and type. These results were consistent with a previous study [5] that examined the influence of the coil's location on multiple brain areas, including SI, and orientations. Within the same hemisphere, the E-field and volume of activated cortical tissue was more variable than at homologous locations. Due to the difference in tissue conductivity between the gray and white matter and cerebrospinal fluid, the E-field and distribution will be affected. The coil pointed toward Nz and Oz also produced higher E-field, suggesting better alignment with the cortical columns. Thus, further investigation on the alignment of the coil and induced E-field may identify possible relationships. While the Mag70 produced lower E-fields than the MagD50 and MagB70, the volume of activated cortical tissue was higher. This supports the claim that smaller coil diameters and butterfly coils provide more focal magnetic fields but shallower magnetic depths [6].

The difference in induced E-field and volume of activated cortical tissue for coil types also highlights an inverse relationship. Generally, with an increase in induced E-field there is less activated volume in the cortical tissue. The trend was also demonstrated between coil orientations as Fcz produced lower E-fields, but greater activated volume of tissue. Thus, our results indicate there is a tradeoff between the focus and depth of the magnetic fields. In applications such as functional mapping, increased focal fields are desired whereas neurological treatments may require greater magnetic depth.

There were some limitations to the study. The use of isotropic conductivities throughout the brain can affect the resulting E-field distribution and size of the activated volume of cortical tissue. Moreover, due to using one head model, different tissue structures such as tumors cannot be modeled. The model also does not differentiate between neuronal elements, such as interneurons, with a differential response to TMS. Moreover, this study focused on the primary somatosensory cortex and requires additional study on other brain areas to compare and demonstrate the effect of TMS targeting different brain regions. Additional simulations may also support that TMS parameters should be individualized on a patient specific basis.

## Conclusion

Using SimNIBS, we demonstrated the effect of TMS parameters, including coil location, orientation, and type, have on the E-field and volume of activated cortical tissue. We found an inverse relationship between the maximum induced E-field and volume of activated cortical tissue. Thus, it is imperative to understand the TMS application, such as functional mapping and depression treatment, which may require more focal E-field or magnetic depth to optimize TMS diagnosis and treatment.

In future work, we plan to simulate additional head models to identify the influence of TMS parameters on varying model anatomy. Pediatric models of varying ages for TMS simulations will be completed to better understand the effects of anatomical differences in developing brain anatomy on the distribution of TMS-induced E-fields.

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