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Focal Electrically Administered Therapy (FEAT): Device parameter effects on stimulus perception in humans

Jeffrey J. Borckardt, PhD¹, Katie Linder, BS, BA¹, Raffaella Ricci, PhD¹, Xingbao Li, MD¹, Berry Anderson, RN¹, Ashley Arana¹, Ziad Nahas, MD¹, Vahe Amassian, MD, James Long, PhD³, Mark S. George, MD¹, and Harold A. Sackeim, PhD⁴

¹Brain Stimulation Laboratory (BSL), Psychiatry Department, Medical University of South Carolina (MUSC)

²Dept. of Physiology, SUNY-Brooklyn, New York

³James Long Company, New York

⁴Columbia University

Abstract

Background—Focal Electrically-Administered Therapy (FEAT) is a new method of transcranial electrical stimulation capable of focal modulation of cerebral activity. Other than invasive studies in animals and examination of motor output in humans, there are limited possibilities for establishing basic principles about how variation in stimulus parameters impact on patterns of intracortical stimulation. This study used a simpler paradigm, and evaluated the effects of different stimulation parameters on subjective perception of the quality and location of scalp pain.

Methods—In two studies, 19 subjects were randomly stimulated over the left forehead, varying the anode-cathode arrangement, the intensity of stimulation, the electrode size and placement, and whether the current flow was unidirectional or bidirectional. Subjects rated the location of the sensation, and its quality.

Results—The perceived center of stimulation moved toward the cathode, regardless of placement. This shift in subjective sensation was more prominent when the electricity was unidirectional. Additionally, more intense stimulation, as well as stimulation with a smaller electrode, caused greater perceived pain. Unidirectional stimulation was rated more painful when traveling from a large anode to a small cathode and less painful when traveling from a small anode to a large cathode. Finally, participants were more likely to perceive the electrical stimulation as moving towards a specific direction when the intensity was high than when it was low.

Conclusions—The intensity and location of sensations can be manipulated by varying the intensity, current direction, or geometry of electrodes.

Keywords

Focal Electrically Administered Therapy; ECT; TMS; tDCS

Introduction

There is a growing interest in alternative methods to achieve focal brain stimulation. Invasive techniques, such as deep brain stimulation (DBS) and vagus nerve stimulation (VNS), involve the delivery of a unidirectional current through implanted electrodes. With these techniques, focality is thought to be enhanced by the use of unidirectional, as opposed to bidirectional, current flow and by positioning the cathode proximal to the site of intended maximal

stimulation. With noninvasive, transcranial magnetic techniques, imposing a time-varying magnetic field on the scalp has been the principal method for producing focal stimulation in underlying neural tissue.^{1, 2} Transcranial magnetic stimulation (TMS) relies on the principle of magnetic induction, whereby a time-varying magnetic field induces current flow when in contact with a conductive medium, such as neural tissue. Since the scalp and skull are transparent to the magnetic field, the focality of TMS is principally determined by the geometry and orientation of the magnetic coil.³⁻⁵

Despite its non-invasiveness, TMS has important limitations as a focal stimulation method. The intensity of the magnetic field falls considerably with distance from the coil.⁶ With standard methods, depolarizing stimulation is limited to a depth from the cortical surface of approximately 2 cm, corresponding roughly to the gray-white matter junction.⁷ Second, the energy transfer is extremely inefficient when converting from the time-varying current in the magnetic coil to the orthogonally-oriented magnetic field, and then to the induced electrical field in brain.¹ The amperage of the current in the coil (e.g., 10,000 A) is profoundly greater than the peak amperage in brain. Third, the physical limitations of most magnetic coils restrict their capacity to withstand repetitive, high intensity electrical stimuli before heating excessively or otherwise failing. This limitation in coil design effectively caps the maximal intensity of the induced electrical field.⁸ Fourth, the shape of the electrical waveform induced in brain is a function of the rate of change (first derivative) of the imposed magnetic field. The induced electrical waveform produced by standard magnetic stimulators is complex with multiple positive- and negative-going peaks. Unlike the rectangular pulse traditionally used with electrical stimulation, the peak-induced current with TMS is expressed only instantaneously, and there is uncertainty about the components of the complex waveform that are responsible for its neurobiological effects.

The development of magnetic seizure therapy (MST) illustrates these limitations. In electroconvulsive therapy (ECT), seizures are readily produced with a single train of transcranial electrical pulses delivered by an electrical stimulator. The evidence that electrical dosage and electrode placement strongly impact on the efficacy and cognitive effects of this intervention justified the development of forms of stimulation that offered greater control over intracerebral current paths and current density. Sackeim (1994) originally proposed that this might be accomplished with high intensity magnetic stimulation.^{9, 10} After 15 years of intensive engineering efforts, it has been shown that MST is capable of reliably eliciting generalized seizures from motor cortex.¹¹⁻¹³ As yet this technique has not demonstrated the capacity to deliver both focal and substantially suprathreshold stimuli to any brain region.

A number of the limitations of TMS can be overcome through use of repetitive transcranial electrical stimulation (rTES). The shape or waveform of electrical stimuli can be easily manipulated and optimized for efficiency in producing specific neurobiological effects. The intensity or amplitude of the electrical stimulus is easily controlled and, in principle, virtually unlimited in magnitude. The capacity to deliver high intensity stimuli means that rTES is capable of producing depolarization in deep brain structures. Furthermore, electrical stimulators have been designed to deliver pulse trains in which the voltage or current of each pulse or the energy delivered over a pulse train is held constant (called constant current stimulation). TES is a form of constant voltage stimulation and current flow in brain is a function of the voltage of the electrical field and local tissue impedance (called constant voltage stimulation). Charge density and charge density per phase are the key determinants of the neurobiological effects of electrical stimulation¹⁴. Thus it is advantageous that stimulation techniques follow constant current, rather than constant voltage, principles.

Despite these advantages, the use of rTES as either a research tool or treatment intervention has largely been limited to ECT. One reason for this is that the scalp, CSF, and brain have low

impedance, while the impedance of the skull is both high and heterogeneous. Under ordinary circumstances, the skull acts as an insulator and, for example, the bulk of externally applied ECT current is shunted through the scalp and does not enter brain^{15–19}. To achieve adequate current density in brain many potential applications of rTES would require sufficiently high charge density in peripheral scalp tissue that the stimulation would be painful. However, this limitation of rTES may be overcome by use of general anesthesia for applications involving seizure induction and local anesthesia for non-convulsive rTES.

Of greater concern is the notion that the smearing of the electrical stimulus is unavoidable given the shunting resulting from the high skull impedance, and this undercuts any possibility of achieving focality. However, Amassian and colleagues (1987) demonstrated that rTES could achieve a focality comparable in spatial resolution to rTMS, depending on the directionality of current flow, electrode geometry and electrode positioning^{20–22}. Specifically, one could achieve focality with rTES by using unidirectional as opposed to bidirectional stimulation, and an asymmetric electrode geometry with the anode considerably larger than the cathode, thereby concentrating current density near the exiting cathode. If a similar stimulation paradigm is used, focal electrically-administered seizure therapy (FEAST) and focal electrically-administered therapy (FEAT) may be practical convulsive and nonconvulsive forms of rTES.

There has been no systematic evaluation of the components of electrical stimulation that may impact on the intensity, shape and focality of intracerebral charge density. There is a need to develop an understanding of how variation in the parameters of electrical stimulation (intensity of stimulation, electrode geometry, size, positioning, direction of current flow, etc.) impact on patterns of stimulation (e.g., peak intensity, degree of focality, perceived directionality, etc.). In other words, we need to develop better understanding of the basic principles that shape the patterns of stimulation. The present study investigates how various parameters in electrical stimulation might be manipulated in order to characterize general principles on how variation in electrical parameters impact on outputs. The purpose of this study is to develop a set of rules, that might apply to stimulation in more complex biophysical environments. Specifically, we examined how variation in the perceived quality and location of pain is a function of key parameters of electrical stimulation. This was studied under conditions intended to maximize stimulation through the scalp (closer interelectrode distance), minimizing the contributions of Skull, CSF, and brain. It is hoped that the principles suggested here will provide a starting point for outlining the impact of these parameters on intracerebral current density.

Based on the literature cited above, we hypothesized that a unitary site of perceived pain would more commonly result from unidirectional than bidirectional stimulation as we believe that pain is experienced primarily at the point at which the electrical current exits the participant's head (i.e., one exit point with unilateral current, and essentially two exit points with bilateral current). Pain intensity would vary with the charge density at the cathode (i.e., a smaller cathode would be associated higher charge density and thus more pain). It was also hypothesized that the perceived location of pain would be largely determined by the location of the cathode (i.e., the primary location of the exit point of the electrical current).

Methods

Study 1

Nine subjects (2 women, 7 men), average age 35.0 years (range 25–47), participated in the first study. This study was approved by the MUSC Institutional Review Board and all subjects provided written informed consent. Subjects underwent a brief clinical interview to rule-out a history of epilepsy, neurological, psychiatric or general medical illness.

The electrical stimulator used was a modified MECTA Spectrum 5000Q (typically used for the delivery of electroconvulsive therapy). It contained all of the safety features used by this device in the delivery of ECT, plus additional safety features designed to limit the stimulus output to a minimal intensity that presented no seizure risk to participants. The stimulator delivered constant current, ultrabrief pulses. The pulse amplitude could vary between 3 and 20 mA, and the voltage cutoff (maximal voltage delivered before unit terminates stimulation due to excessive impedance) was 100 V.

Uncut Thymapad electrodes were used. Starting with the medial electrode, the researcher used a ruler to measure and place the medial electrode with the lower edge 1 cm above the subject's left eyebrow and the medial edge 2 cm lateral to the midline (George, Anderson, & Rastogi, OPT-TMS Operators Guide, 2005). The lateral electrode was also applied 1 cm above the eyebrows and spaced 1 cm from the lateral side of the medial electrode. See figure 1. This close interelectrode spacing maximized shunting of current through scalp.

Static impedance was checked and determined to be no more than 100 ohms. The MECTA system delivered brief electrical pulses (200 μ s) at 10 Hz for 4 second trials with a minimum of 26 seconds in between trials.

In an attempt to match participants in the overall subjective pain intensity of the electrical stimuli, parameter estimation by sequential testing (PEST) was used to adjust the intensity of the electrical stimulation to each participant's numeric scale pain rating of "7" out of 10 (where 0="no pain" and 10="worst pain imaginable"). Three subjects were stimulated at 7 milliAmps, four at 5 milliAmps, one at 4 milliAmps and another at 3 milliAmps.

Each subject received 16 stimulation trials using a 2 (current type; bidirectional versus unidirectional) X 2 (placement; anode medial versus cathode medial) design where trial order was randomized (4 trials in each condition). Subjects were blind to condition but the stimulation operator was not. The entire session for each subject took approximately 30 minutes.

After each stimulation trial, participants used a custom-developed software program (face-locator system) to rate the painfulness of the stimulus (see figure 2). Additionally, subjects used the mouse cursor to draw (on a picture of a human face) where they felt the sensations. Lastly, subjects indicated whether the stimulation felt like it "moved" across the scalp or whether it felt stationary.

Study 2

Ten volunteers (7 male, 3 female; mean age=30.9; range 20–47) participated in the second study (7 of whom also participated in the first study). We used four 2-inch (5.08cm) diameter Ag/AgCl electrodes similar to those used in ECT, and modified 2 of them locally to decrease the size to 1/2-inch (1.27cm) diameter. All electrodes were placed in the same manner described in Study 1. In addition to manipulating current type (bidirectional versus unidirectional) and placement (anode medial versus cathode medial), the size of the electrodes was manipulated (large electrode medial & large electrode lateral; small medial & small lateral; large medial & small lateral; large lateral & small medial) as well as the intensity of the electrical stimulation (high versus low). The high intensity stimulus was defined as the stimulus intensity (mA) that produced a subjective rating of 7 out of 10 (as in study 1) using 2 large electrodes and the cathode placed medially (determined using PEST). The low intensity stimulus was defined as half of the high intensity stimulus (high intensity mA X 0.5).

A 2 (current type; unidirectional versus bidirectional) X 2 (placement; anode medial versus cathode medial) X 2 (intensity; high versus low) X 4 (electrode size; large-medial--large-lateral versus small-medial--small-lateral versus large-medial--small-lateral versus small-medial--

large-lateral) design was implemented and participants received 2 trials for each condition (randomly ordered). Participants were masked to trial condition but the MECTA operator was not. After each trial, participants used the same software as in Study 1 to indicate the perceived intensity and location of the sensation.

Dependent Measures

Pain Intensity: Participants used the computerized visual analogue scale (VAS) to rate the painfulness of each stimulus. The scale was anchored with "0=no sensation at all" and "100=worst pain imaginable".

Area of sensation: After each stimulus, subjects used the custom-developed face-locator software system to draw the area of the sensation on the screen. After the completion of the study, a separate image-analysis program was used to analyze each image. The left, right, top and bottom edges of the sensation areas were determined and the area of the sensation was calculated as the width times the height (in pixels).

Center of sensation (x-axis): The horizontal center of the area of sensation was defined as the mid-point (in pixels) between the left and right edges of the sensation areas drawn by the subjects with the face-locator system.

Number of distinct sensations: The number of distinct areas of sensation was calculated for each face-locator drawing. Distinct areas of sensation were determined by analyzing the clusters of colored pixels and the ratio of clusters to space between them. For each image and for every triplet of colored pixels, any time the largest and smallest distances within the triplet of colored pixels equaled or exceeded a ratio of 4:1, the triplet was considered to be 2 distinct sensations.

Perception of movement: For each stimulus, participants indicated whether they perceived the electrical current to "move" across the scalp. A digital compass was used to indicate the direction of movement (if perceived). For each stimulus that was perceived to have a "movement" quality, the compass reading (0 to 359°) was converted into simple categories ("moving-laterally" if the compass value was between 180° and 359° and "moving-medially" if the value was 0° to 179°).

Image analysis: The face-locator images were broken down into 20 X 15 square voxels consisting of 100 pixels each. For each voxel, the mean number of colored pixels was determined across sets of images (based on stimulation conditions). The mean value for each voxel was then expressed visually as a shade of green (where dark green indicates few colored pixels and bright green indicates numerous colored pixels).

Statistical Analyses: For both studies, Hierarchical Linear Modeling (HLM) was used (Proc Mixed in SAS) to model the intensity and location of the perceived sensations produced by the electrical stimulation. Individual subject-level intercepts were included in the models as random effects. HLM has been shown to handle appropriately individual differences at the subject level and is not constrained by the assumption of independence of observations. This is important for these analyses, as we would expect systematic consistency within each subject over time and for repeated trials in the same stimulation condition. We would also expect systematic consistency within-individuals due to individual differences in pain tolerance and slight variation from subject to subject in terms of electrode placement and impedance.

Results

Study 1

Pain Intensity—A 2X2 (directionality by anode/cathode placement) HLM was run on visual analogue scale pain ratings with individual subject intercepts entered as random effects at level-1. The intraclass correlation coefficient was 0.84 suggesting significant clustering within individuals supporting the use of HLM. A main effect was found for anode/cathode placement, $F(1,132)=4.42$, $p=.04$. Placement of the cathode medially was associated with a mean VAS pain rating of 30.32 whereas lateral cathode placement resulted in a mean pain rating of 27.07. No interactions were observed.

Area of sensation—The same model was run with area of sensation (pixels²) as the dependent variable. Only conditions that produced a single sensation were included in the model. No significant main effects or interactions were observed.

Center of sensation (x-axis)—The same model was run with the center of the sensation along the horizontal axis of the face (pixels from the left edge of the screen) as the dependent measure. The intraclass correlation coefficient for this model was 0.49. A main effect was observed for cathode placement ($F(1,131)=8.60$, $p=.004$). Cathode-medial was associated with sensation 4.17cm left of midline while cathode-lateral was associated with sensation 4.62cm left of midline. A significant interaction effect was also observed ($F(1,131)=18.42$, $p<.0001$). Unidirectional current combined with medial cathode placement was associated with the most medial sensation of the 4 conditions (3.71cm left of midline), while unidirectional current with lateral cathode placement was associated with the most lateral sensation (4.85cm left of midline).

Number of distinct sensations—No significant effects were observed for cathode placement or current directionality on the number of distinct sensations perceived.

Perception of movement—None of the conditions examined was more likely than any of the others to produce significantly more "moving-laterally" or "moving medially" perceptions.

Image analysis—Face-locator images representing the locations of the perceptions of sensations for each condition were generated. Figure 3 shows the mean location of sensations for each of the cathode placement conditions. Figure 4 shows the mean location of sensations for each of the current directionality condition. Figure 5 shows the mean location of sensations for each of the four levels of the interaction between the two independent variables.

Study 2

Pain Intensity—A 4X2X2X2 (electrode size, anode/cathode placement, intensity, directionality) HLM was run on visual analogue scale pain ratings with individual subject intercepts entered as random effects at level-1. The intraclass correlation coefficient was 0.19 suggesting a fair bit of clustering within individuals thus supporting the use of HLM. Main effects were found for electrode size ($F(3,599)=15.47$, $p<.0001$) and stimulation intensity ($F(1,599)=1009.32$, $p<.0001$) on VAS pain ratings. The most painful condition involved two small electrodes (mean VAS rating=38.94) followed by placement of a large electrode medially and a small electrode laterally (mean=37.58). Two large electrodes produced less pain (mean=28.91), and the least pain was experienced with a large electrode placed medially and a small electrode placed laterally (mean=24.14). High intensity stimulation was more painful (mean=56.13) than low intensity stimulation (mean=10.59). Additionally, several interactions were observed including size by intensity ($F(3,599)=2.94$, $p<.0001$), size by cathode location by directionality ($F(3,599)=4.30$, $p=.005$) and size by cathode location by intensity by

directionality ($F(3,599)=4.24$, $p=.006$). The most painful condition involved the use of high intensity stimulation, unidirectional current, large anode placed laterally and the small cathode placed medially. The least painful condition involved the use of two large electrodes, anode placed medially, low intensity stimulation and unidirectional current.

Area of sensation—The same model described above was run with area of sensation (pixels², converted to centimeters²) as the dependent variable. Only conditions that produced a single sensation were included in the model. The intraclass correlation coefficient for this model was 0.18. Main effects were observed for size ($F(3,363)=9.79$, $p<.0001$) and intensity ($F(1,362)=128.19$, $p<.0001$). The largest area of sensation was produced with two large electrodes (mean area=3.00cm²). Placement of the small electrode medially with a large electrode laterally produced a mean sensation of 1.78cm². Two small electrodes and placement of the large electrode medially produced the smallest area of sensations (means=1.55 and 1.52cm², respectively). A size by intensity interaction was present ($F(3,361)=3.88$, $p=.01$). The largest area was associated with high intensity stimulation using two large electrodes (mean=4.11cm²) and the smallest area was associated with the use of a large electrode placed medially, a small electrode placed laterally, and low intensity current (mean=.53cm²).

Center of sensation (x-axis)—The same model described above was run with the center of the sensation along the horizontal axis of the face (pixels from the left edge of the screen) as the dependent measure. The intraclass correlation coefficient for this model was 0.34. Main effects were observed for electrode size ($F(3,599)=60.56$, $p<.0001$), intensity ($F(1,599)=4.50$, $p=.034$), and cathode placement ($F(1,599)=23.56$, $p<.0001$). A small electrode placed medially was associated with the center of the sensation 1.17cm left of midline. A large electrode placed medially was associated with the center of sensation 3.63cm left of midline. High intensity stimulation was associated with sensation 2.06cm left of midline while low intensity stimulation was felt 2.36cm left of midline. Anode placed medially was associated with sensation 2.57cm left of midline while cathode medially was felt 1.85cm left of midline. Several interactions were observed including size by intensity ($F(3,599)=3.82$, $p=.010$), cathode placement by directionality ($F(1,599)=9.66$, $p=.002$) and size by cathode placement by intensity ($F(3,599)=2.64$, $p=.049$). Low intensity stimulation with the large electrode medial and a small electrode lateral was associated with sensation 4.19cm left of midline, and low intensity stimulation with the large electrode lateral and a small electrode medial was associated with sensation 1.07cm left of midline. Cathode medial with unidirectional current was associated with sensation 1.60cm left of midline while anode medial with unidirectional current was felt 2.77cm left of midline.

Number of distinct sensations—The same model described above was run with the number of distinct sensations as the dependent measure. The intraclass correlation coefficient for this model was 0.20. Main effects were observed for size ($F(3,599)=16.94$, $p<.0001$), intensity ($F(1,599)=28.70$, $p<.0001$) and directionality ($F(1,599)=7.21$, $p=.008$). The use of two large electrodes produced 1.54 distinct sensations on average while the use of two small electrodes produced 1.32 distinct sensations. Placement of a large electrode medially and a small electrode laterally produced 1.22 sensations and placement of a small electrode medially and a large electrode laterally produced an average of 1.48 distinct sensations. High intensity stimulation produced a mean of 1.49 distinct sensations while low intensity stimulation produced an average of 1.29 sensations. Bidirectional current produced 1.44 distinct sensations on average while unidirectional current produced 1.29. A size by intensity interaction was observed ($F(3,599)=2.73$, $p=.04$). High intensity stimulation through a small electrode placed medially with a large electrode placed laterally produced the highest number of distinct sensations (mean=1.62), while low intensity stimulation through a large electrode placed medially with a small electrode placed laterally produced the lowest number (mean=1.08).

Perception of Movement—Placement of the cathode medially was associated with significantly more ratings (64%) of "moving medially" ($X^2=7.45$, $p=.006$). When a small electrode was placed medially and a large electrode was placed laterally, there were significantly more ratings (83%) of the sensation "moving medially." Lastly, when the cathode was placed medially and unidirectional current was used, there were significantly more ratings (75%) of the sensation "moving medially" ($X^2=11.51$, $p=.001$).

Image analysis—Face-locator images representing the locations of the perceptions of sensations for each condition were generated. Figure 6 shows the mean location of sensations for each of the four electrode size conditions. Figure 7 shows the mean location of sensations for each intensity condition, figure 8 shows the mean location for each cathode placement condition, and figure 9 shows the mean location for each directionality condition.

Discussion

These two studies in healthy young adults confirmed our pre-study hypotheses concerning the rules underlying focal electrical stimulation using alternating electrical current (referred to as FEAT - focal electrically-administered therapy). Using subjective ratings of pain and unpleasantness depicted graphically and with linear scales, we confirmed many of the initial observations from prior work. In both studies, the perceived center of stimulation moved toward the cathode, regardless of placement. Other trends were found. For example, this shift in subjective sensation was more prominent when the electricity was unidirectional. That is, unidirectional current produced a larger spread from center than did bidirectional current, moving the perceived sensation toward the cathode. Additionally, more intense stimulation, as well as stimulation with a smaller electrode, caused more pain. Unidirectional stimulation was perceived more painful when traveling from a large anode to a small cathode and less painful when traveling from a small anode to a large cathode. Finally, participants were more likely to perceive the electrical stimulation as moving towards a specific direction, when the intensity was high than when it was low.

These findings are important for at least two reasons. First, as the field of TMS and other brain stimulation techniques moves into clinical practice, it is important to develop sham stimulation methods that accurately match the active stimulation with respect to the type, amount, and location of pain. For example, the authors are employing an active TMS sham condition in a clinical trial using much of the same equipment (see related manuscript by Arana et al (23)). The results from these tests can be used to create ever more accurate sham conditions in these TMS clinical trials in depression and pain.

There is presently little understanding of how variation in the parameters of electrical stimulation (intensity of stimulation, electrode geometry, size, positioning, direction of current flow, etc.) impact on patterns of stimulation (e.g., peak intensity, degree of focality, perceived directionality, etc.). There is a need to develop better understanding of the basic principles that determine the patterns of stimulation. The use of cutaneous pain with close interelectrode spacing represented a novel approach to uncovering these basic principles, at least as they apply to this specific context. Use of the cutaneous pain model had two key advantages. It limited the complexity of modeling since (1) the stimulation paradigms used conditions that would maximize the extent to which current flowed through scalp, and not skull, CSF, and brain; and (2) this model took advantage of the fact that cutaneous pain was a reliable sensory event that could be described in terms of its intensity, geographical location, and other key parameters. Therefore, this work provided a template for how various parameters in electrical stimulation might be manipulated in order to characterize general principles on how variation in electrical parameters impact on physiological outputs.

The exciting aspect of this work is that in a simple system we have begun to understand some rules of focality and direction. Theoretically, these forms of transcranial electrical stimulation (TES), of which ECT is an example, can reach deeper, and in a focused way, than can stimulation techniques like TMS.

The purpose of this work was not to provide a model whereby one could assess scalp pain to infer patterns of intracerebral current density. It remains for future studies to determine the degree to which these initial findings apply to within-brain effects, as well as the factors that constrain applicability. We believe that although the model is imperfect, it may provide a starting point for further empirical investigation of several basic principles related to effects of electrical stimulation of the human brain. Future studies might focus on investigating the effects of stimulation configurations (e.g., anode/cathode placement, current type, intensity) on brain activation and ultimately human behavior.

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Figure 1.

Electrode placement (lower edge 1 cm above the subject's left eyebrow and the medial edge 2 cm lateral to the midline; the lateral electrode was also applied 1 cm above the eyebrows and spaced 1 cm from the lateral side of the medial electrode)

Figure 2.
Screen shot of the Face Locator program used to collect sensation and location data after each FEAT stimulation.

Figure 3. Study One: Subject-rated location of sensations (cathode placement main effect) represented in 10 pixel² voxels where brighter green is associated with more overlap between subjects with respect to perceptual locale.

Figure 4. Study One: Subject-rated location of sensations (current-directionality main effect) represented in 10 pixel² voxels where brighter green is associated with more overlap between subjects with respect to perceptual locale.

Figure 5.

Study One: Subject-rated location of sensations (cathode placement by directionality interaction) represented in 10 pixel² voxels where brighter green is associated with more overlap between subjects with respect to perceptual locale.

Figure 6.

Study Two: Subject-rated location of sensations (electrode size main effect) represented in 10 pixel² voxels where brighter green is associated with more overlap between subjects with respect to perceptual locale.

Figure 7.
Study Two: Subject-rated location of sensations (intensity main effect) represented in 10 pixel² voxels where brighter green is associated with more overlap between subjects with respect to perceptual locale.

Figure 8.
Study Two: Subject-rated location of sensations (cathode placement main effect) represented in 10 pixel² voxels where brighter green is associated with more overlap between subjects with respect to perceptual locale.

Figure 9.
Study Two: Subject-rated location of sensations (directionality main effect) represented in 10 pixel² voxels where brighter green is associated with more overlap between subjects with respect to perceptual locale.