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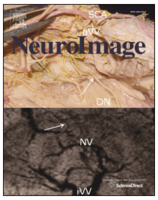

Visualizing Simulated Electrical Fields from Electroencephalography and Transcranial Electric Brain Stimulation: A Comparative Evaluation

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ABSTRACT

Electrical activity of neuronal populations is a crucial aspect of brain activity. This activity is not measured directly but recorded as electrical potential changes using head surface electrodes (electroencephalogram - EEG). Head surface electrodes can also be deployed to inject electrical currents in order to modulate brain activity (transcranial electric stimulation techniques) for therapeutic and neuroscientific purposes. In electroencephalography and noninvasive electric brain stimulation, electrical fields mediate between electrical signal sources and regions of interest (ROI). These fields can be very complicated in structure, and are influenced in a complex way by the conductivity profile of the human head. Visualization techniques play a central role to grasp the nature of those fields because such techniques allow for an effective conveyance of complex data and enable quick qualitative and quantitative assessments. The examination of volume conduction effects of particular head model parameterizations (e.g., skull thickness and layering), of brain anomalies (e.g., holes in the skull, tumors), location and extent of active brain areas (e.g., high concentrations of current densities) and around current injecting electrodes can be investigated using visualization. Here, we evaluate a number of widely used visualization techniques, based on either the potential distribution or on the current-flow. In particular, we focus on the extractability of quantitative and qualitative information from the obtained images, their effective integration of anatomical context information, and their interaction. We present illustrative examples from clinically and neuroscientifically relevant cases and discuss the pros and cons of the various visualization techniques.

Introduction

In this work, we show the value of several, common visualization methods using three well chosen and neuroscientifically relevant examples where electrical fields play a significant role. We are convinced that visualization can help to gain deeper insights into volume conduction phenomena. Those phenomena are often only statistically describable, and, at best, investigated by standard visualization techniques. Further, we want to contribute with this work to approach an answer to the question: "What aspects of visualization are helpful regarding electrical fields in neuroscientific research?".

We structured our work in sections as following. First, we introduce noninvasive neuroscientific techniques (electroencephalography (EEG) and transcranial direct current stimulation (tDCS)) that are relevant in this work and discuss visualization in this context. In the current work, tDCS was chosen exemplarily as a representative of a family of electric brain stimulation techniques, like transcranial alternating current stimulation (tACS), transcranial random noise stimulation (tRNS), transcranial electrical stimulation (TES) (Paulus, 2011; Ruffini et al., 2013) that employ scalp surface electrodes to inject electric currents. Second, we identify three generic criteria to evaluate visualization techniques in neuroscience, introduce common visualization techniques and explain their basic working principles. Third, we describe three clinically relevant examples to evaluate visualization methods. Fourth, we present visualization results and discuss the findings. Fifth, we conclude

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our work and summarize general advantages and disadvantages of standard visualization techniques.

Electroencephalography (EEG)

Noninvasive mapping of neuronal activity is important for a better understanding of human brain function. In clinical practice, for example, the mapping is essential for the diagnosis of neurodegenerative diseases and the identification of epileptogenic brain tissue (Rullmann et al., 2009). Electroencephalography (EEG) is a noninvasive technique that is directly sensitive to the electrical activity of neuronal populations, and therefore well suited to observe normal and pathological brain function in humans. Recording electrodes are placed on the head surface and pick up potential differences caused by Ohmic return currents, which are driven by electromotive forces in and around active neuronal areas. Electric flow fields mediate between those neural sources and the measured EEG. These fields are embedded in a very complicated volume conductor, the human head, which features many different structures of varying electrical properties (conductivities). Both the prediction of measurements from known sources (forward problem) and the estimation of the source locations from measurements (source reconstruction) involve modeling these fields. The accuracy and precision of these estimations depend on the accuracy of the head modeling, which, in the most general case, requires a voxelwise description of inhomogeneous and anisotropic conductivity values as well as a reasonable sampling of the tissue boundaries. For more information concerning head modeling and source reconstruction (Wendel et al., 2009).

In order to gain insights into the complicated relationship between neural activity and measured EEG, visualization of electrical fields is of great value. It allows assessing, in one glance, which features of the head exercise a large influence and therefore need to be modeled in greater detail. Visualization can also help to assess the effect of certain modeling errors and simplifications. Moreover, it can show, in a very demonstrative fashion, how pathological anomalies, such as holes in the skull, influence the way EEG reflects brain activity. One important prerequisite for field visualization is that the electrical field is explicitly computed within the three-dimensional head volume, using, for example, the finite element or the finite difference method (Bertrand, 1991; Dannhauer et al., 2011; Fuchs et al., 2007; Hallez et al., 2008; Marin et al., 1998; Rullmann et al., 2009; Schimpf et al., 2002; van den Broek et al., 1998; Wolters, 2003).

Transcranial direct current stimulation (tDCS)

Transcranial direct current stimulation (tDCS) is a noninvasive technique to modulate neural brain activity (e.g., Lozano and Hallett, 2013; Meideiros et al., 2012; M. Nitsche et al., 2008; Utz et al., 2010) by injecting low amplitude direct currents through surface electrodes. tDCS has been known for over a century, but has recently been rediscovered as a promising tool to support a wide range of clinical applications (Boggio et al., 2006; Brunoni et al., 2012; Flöel, 2014; Kuo et al., 2014; Nitsche and Paulus, 2009; Schjetnan et al., 2013). Moreover, it has been successfully applied in basic and cognitive neuroscience research (e.g., Kalu et al., 2012; Wirth et al., 2011). In this technique, frequently, large rectangular patch electrodes are used (normally $25-35cm^2$, e.g., (M.A. Nitsche et al., 2008)) in experimental settings and placed according to accepted EEG standards (e.g., 10-20). In some rare cases also smaller electrodes are employed in experiments (Caparelli-Daquer et al., 2012; Edwards et al., 2013). To study the impact of modeling tDCS for experimental settings, electrical current density is one of the main parameters to determine physiological effects for brain and other head tissues. Visualization of tDCS simulations (e.g., as current density plots, Wagner et al., 2014) can be helpful for assessing those effects as well as for understanding the way particular brain areas are stimulated depending on electrode montage and design, head geometry (e.g., skull thickness), and other factors.

Visualization of electrical fields

In general, when considering head modeling in EEG/MEG/tDCS analysis, the significance of certain modeling issues or particular features in the biological tissues (e.g., holes in the skull) are mostly assessed by visualizing and quantifying their final consequences, such as changes in surface potentials or mislocalization of dipolar sources (e.g., Dannhauer et al., 2011). These consequences are, however, mediated by the electric flow field in the head. Hence, visualizing the direct effects of above mentioned features in models or real head anatomy in terms of current flows and electrical potentials throughout the head might provide more direct insight into the nature of that relationship.

Generally, the literature on volume current visualization regarding EEG and tDCS (Berger, 1933; Nunez, 1981; Sharbrough et al., 1991) is relatively scarce. Often, visualization of electrical currents is based on simple voxelwise current density visualizations represented graphically as cones, arrows (Salvador et al., 2010; Shahid et al., 2013; Wagner et al., 2014), or as current density magnitudes using colormaps (Shahid et al., 2013; Wagner et al., 2014). Visualizations with more advanced techniques, such as streamlines, are rare in the EEG- (e.g., Wolters et al., 2006) or tDCS-related literature (e.g., Im et al., 2008; Park et al., 2011; Sadleir et al., 2012). Characterization of visualization methods for local or global examples to evaluate visualization methods and applicability for certain tasks and domains has not yet been analyzed sufficiently. Wolters et al. (2006) (for EEG) as well as Bangera et al. (2010) (for tDCS) demonstrated the impact of white matter anisotropy and highly conducting cerebrospinal fluid (CSF) onto volume currents by computing streamlines using line integral convolution (LIC, Cabral and Leedom, 1993). Very closely related to this paper is the work (Tricoche et al., 2008), where several advanced vector field methods are shown in the context of bioelectric fields for EEG. In most existing publications, volume current visualization is not the main focus, and visualization procedures are not used systematically to investigate the effect of features in real biological tissue (e.g., skull holes), assumptions in volume conductor models (e.g., modeling the CSF or not, taking into account anisotropy), or experimental settings (e.g., electrode montages). Such studies might help to better understand effects that otherwise can be assessed only by their final results, i.e., simulated sensor readings or source localization results (e.g., Dannhauer et al., 2011; Dannhauer et al., 2013; Lanfer et al., 2012).

Visualization of electrical flow fields in three dimensions can be based on either the scalar electrical potential or on the vector-valued current flow. In both cases, several principal techniques are available (see Section 2). The aim of this work is to demonstrate not only the advantages of certain methods, but also their drawbacks, as the applicability of these methods differ for each case, domain, and desired analysis. To achieve this goal, we will define a set of concise criteria for the usefulness of visualization techniques in the context of neuroscience and apply these to the evaluation of the presented algorithms.

Visualization Algorithms

In the last decade, visualization made a big step towards interactive and visually appealing methods, fuelled by the rapid development of affordable graphics hardware and computing devices. These developments made advanced visualization available also to neuroscience. It is important to stress that the scientific benefit of using visualization techniques is not just a matter of "pretty images", but lies in the extent to which these methods actually improve the perception, exploration, and interpretation of scientific results. Here, we identify three criteria that convey whether and to what extent a visualization technique is useful to a neuroscientist.

I. **Comparability** - The images produced by one method need to be comparable in a quantitative way over a series of subjects or time series. Colormaps play an especially important role in this context.

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