Modeling coherence with different electrode sizes

Physical model of coherent potentials measured with different electrode recording site sizes
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ABSTRACT

A question that still complicates interpretation of local field potentials (LFPs) is how electrode properties like impedance, size and shape affect recorded LFPs. Additionally, how any such effects should be considered when comparing LFP, electroencephalogram (EEG) or electrocorticogram (ECoG) data has not been clearly described. A generally accepted concrete physical model describes that an electrode records the spatial average of the voltage across its uninsulated tip. Yet the effects of this spatial averaging on recorded coherence have never been modeled. Using simulations based on this physical model, here we show that for any effects to occur, a spatial voltage gradient on a scale smaller than an electrode’s recording site must exist over the site’s surface. When this occurs, larger electrodes on average report higher coherence between locations, with the effect continuously increasing as the voltage profile over the extent of the recording site is increasingly non-uniform. We quantitatively compared published coherence estimates of LFP, ECoG and EEG data across a range of studies, and found a possible modest effect of electrode size in published ECoG data only. We used the model to quantify the expected coherence for any electrode size in relation to any given spatial frequency of a voltage profile. From this and existing estimates of the spread of voltages underlying each of these data types, our simulations quantitatively agree with the published data and importantly suggest that LFP coherence will be independent of recording site size within the range of microelectrodes typically used for extracellular recordings.

KEYWORDS

LFPs, local field potentials, ECoG, EEG, impedance
INTRODUCTION

For many years, local field potentials (LFPs) have proven to be an important data source for improving our understanding of the brain. Despite this, questions surrounding their interpretation still remain unanswered, but have been a recent topic of renewed interest in the literature (Bedard, et al. 2010; Katzner et al. 2009; Logothetis et al. 2007; Xing, et al. 2009).

One such question that often arises is: what effect do properties like electrode impedance and shape have on recorded LFPs? We argued previously (Nelson and Pouget 2010) that when interpreting LFP recordings from microelectrodes, neurophysiologists can ignore for all practical purposes the particular size and shape of recording sites provided that they are within the ranges normally used for extracellular recordings. The basis for this argument originates from a physical model of microelectrode recording circuits (Robinson 1968) that we confirmed experimentally in our previous work (Nelson et al. 2008). There we explicitly showed that when using an amplifier of appropriately high input impedance, which is available in some but not all commercially available recording equipment, the impact on recorded signals of the electrical impedance of the microelectrode/tissue interface is negligible. The voltage recorded by a microelectrode in this case will equal the average voltage present across its uninsulated tip. Yet recording site size could still potentially influence recordings on a physical basis by affecting what that average voltage at the electrode’s tip is. This could occur if the underlying voltage being measured varies spatially on a scale finer than an electrode’s recording site size. However, current estimates of the spatial extent of the LFP suggest that 95% of the signals recorded at a given point in space originate from within a 250 micron radius (Katzner et al. 2009), which well exceeds the size of microelectrode recording sites for the ranges of microelectrodes typically used by neurophysiologists (Yaeli et al. 2009; Lemon 1984; Tielen et al. 1971). Thus, the particular size of these recording sites should not affect the LFP signals they record.

Claims that electrode size and shape should affect recorded LFPs have been made in the literature (e.g. Berens et al. 2008; Pesaran 2009, Kay and Lazarra 2010) without mention or apparent consideration of this generally accepted theoretical basis of the nature of microelectrode recordings (Robinson, 1968).
Many neurophysiologists do have some familiarity with a notion that larger electrodes record signals from more distant sources, and that this results in differences between the signals recorded by electrodes of different sizes. But the separation of the discussion in the literature from the basic physical nature of the recordings may obscure to many in the field the fact that electrodes average only the signals that exist over the spatial extent of their recording site surface areas. Surprisingly, though electrode size has been modeled in different aspects before (e.g. Ollikainen et al. 2000, Moffitt & McIntyre 2005, Lempka et al 2011), models of how this simple spatial averaging directly affects recorded signals have not appeared in the literature to our knowledge. This is the case despite the existence of strong claims that, for example, this spatial averaging property should cause different microelectrode sizes within the brain to reveal fundamentally different voltage signals (Nunez and Srinivasan, 2006).

There have been some empirical investigations of the effect of electrode size on the coherence of recorded LFPs with unclear results. Bullock and McClune (1989) reported finding no difference in coherence when comparing electrode recording sites with 1 micron diameters to those with 50 micron diameters, nor when comparing those with 25 micron diameters to those with 250 micron diameters. Kay and Lazzara (2010) later compared coherence between electrodes of very different sizes (200 µm vs 2-3 µm diameters). They found that the much larger electrodes reported slightly more coherence, although the spectral power was the same between the different electrode sizes. Despite the very large difference in the size of the electrodes they compared, the effects that they report were very small, thus their results are not per se incompatible with our earlier claim. But if these effects do hold true for large electrode differences, it raises a question as to whether this should be considered when comparing LFPs to electroencephalogram (EEG) data recorded from the scalp or electrocorticogram (ECoG) data recorded from the cortical surface, both of which are typically done with much larger electrodes.

In addition to the empirical ambiguity surrounding the question, the theoretical prediction of how averaging signals across larger regions of space should be expected to affect the coherence of recorded signals is unclear a priori. Competing effects are present as some effects would cause larger electrodes to tend to report more coherence, while some effects would cause smaller electrodes to tend to report more
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coherence. Thus, we sought to test what the expected overall effect is through quantitative simulations based on the theoretical basis of microelectrode recordings.

Here we explicitly describe a simple physical model to clearly illustrate the theoretical basis through which claims about the effect of electrode size and shape on recorded potentials should be considered. Importantly, this model highlights that for any differences between recording sites to occur, the underlying voltage profile must vary appreciably over the extent of the larger recording site’s surface. We then use quantitative simulations of the model using simulated and real LFP traces to test the non-obvious result of whether larger electrodes should report higher levels of coherence. We find that the modeled low impedance electrodes do indeed report larger coherences between areas than the modeled high impedance electrodes. We show that this effect continuously increases as the voltage profile is increasingly non-uniform over the extent of the larger electrode’s recording site, and that it is robust with respect to the strength of the coherence gradient along the voltage profile. We then quantitatively compare coherence reported in LFP, ECoG and EEG data across several studies and lab groups, and find evidence for a possible modest effect of electrode size in ECoG data only. We extend our simulations to quantify the effect on recorded coherence of any given ratio of electrode size to the spatial frequency of the underlying neural activity. Combining this with published estimates of the spatial frequencies present in each neurophysiological data type confirms the trends we observed in the literature.

MATERIALS AND METHODS

The model. It is trivial to conclude but bears mentioning a priori that the LFP signal must vary appreciably over the size of the lower impedance electrode tip for the electrode impedance to have the possibility to make any difference at all in the resulting recorded value (Nelson and Pouget, 2010). This point should be further obvious if one considers the extreme opposite case in which the LFP signal is spatially uniform. It is clear that in this case, the particular locations over which the voltage is averaged by electrodes of different sizes would not matter.
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Figure 1A shows the most basic version of a physical model of how differences in coherence could be observed between electrodes of different sizes. In this model, some sub-regions are highly coherent between two distant locations while some are not. Potentials recorded in the sub-regions with high distant coherence are highly coherent with each other, while potentials in the sub-regions with low distant coherence are not coherent with either sub-region. Very low impedance electrodes that are large relative to the size of the sub-regions would extend across the sub-regions (Figure 1B, left) and would thus always report the average activity between the sub-regions. In contrast, micro-electrodes that are small relative to the size of the sub-regions would tend to fall into a single sub-region and would thus reflect the activity of one or the other sub-region by chance depending on the random precise placement of the electrode (Figure 1B, right). In this situation, the low impedance electrodes would reliably have moderate coherence as the voltage they record would always include that of the high distant coherence sub-region, but this activity would also always be averaged with that of the less coherent low distant coherence sub-region. In contrast, the microelectrodes would occasionally record very low coherence on some recordings when they happen to be in low distant coherence sub-regions, but they would also occasionally record very high coherences when both electrodes happened to be in high coherence sub-regions. Competing effects would thus be present in determining which electrode type would be expected to have the higher coherence on average, with the result depending on the properties of signal averaging before calculating coherence.

The basic model described above can be extended to make quantitative predictions for the expected effects of electrodes of particular sizes relative to the spatial variation of underlying neural activity. This can be done in the most general sense by modeling the underlying voltage profile as a spatial sine wave (Figure 6A), since any spatial variation of voltage can be described by the contributions of sine wave components at different spatial frequencies. In this version of the model, the voltage varies continuously by oscillating sinusoidally between high and low distant coherence activity instead of having each type of activity separately confined to distinct sub-regions as in the basic model. Electrode recording sites are modeled to be of precise sizes in relation to the spatial wavelength of the sinusoidal
voltage profile and placed at random phases of the voltage profile, averaging the activity present along their lengths. Using these results, the effects for any particular voltage profile and electrode size could then be predicted.

Simulating high and low distant coherent activity. To produce testable data that captures the key points of the above models, we created 4 LFP traces. Each of the two simulated electrode locations in the basic model was comprised of two traces: one corresponding to a high distant coherence sub-region and one corresponding to a low distant coherence sub-region. We did this both with purely simulated data and real LFP traces, following procedures described below. The goal in creating and selecting these traces for the primary simulations was to obtain two LFP traces that were highly coherent with each other, which represent the high distant coherence sub-regions in each location, and two LFP traces that were neither coherent with each other nor the previous traces, which represent the low distant coherence sub-regions in each location (see Figure 1A).

Using simulated data. We generated simulated LFP signals in Matlab (Natick, MA) by adding white noise to sinusoids with a simulated sampling rate of 1 kHz. The period of the sinusoid was set to 50.234 samples per cycle in order to avoid the unrealistic situation where this was exactly a multiple of the sampling period. This resulted in a signal frequency of just under 20 Hz. 200 trials of 4 seconds each were simulated for each session. The amplitudes and phases of the four signals across trials were determined by sampling from a multivariate normal distribution using the mvnrnd function in matlab. For the primary simulations, we set the correlation coefficient for both amplitudes and phases to 0.8 between the pair of high distant coherence signals and 0.2 between all other signal pairs. For all signals, the mean amplitude was set to 10 arbitrary units with a variance of 2 and the arbitrary mean phase was set to 180 degrees with a standard deviation of 60 degrees. The standard deviation of the independent white noise added to the sinusoids was set to 1 for the two high distant coherence traces, and 3 for the low distant coherence traces.
We performed two additional sets of simulations in order to investigate the effects when the coherence differences between the individual traces are smaller. To generate traces with a moderate coherence difference, we set the amplitude and phase correlation coefficients to 0.65 between the high coherence traces and 0.35 between all other traces. To generate traces with no coherence differences between them, we set the amplitude and phase correlation coefficients to 0.5 between all traces and we set the standard deviation of the independent white noise added to all traces to 1. All other parameters were identical parameters to those described above for the primary simulations.

For the primary simulations, the left panel of Figure 2A shows the 4 traces used from one sample trial using simulated data. The low coherence pair shows more white noise and uncorrelated deviation in their phases and amplitudes than the high coherence pair. The left panel of Figure 2B shows for one sample session the coherence of the 4 possible trace pairings between locations. This shows that the desired coherence pattern of a high coherence between the two high distant coherence traces, but a low coherence between all other pairings of traces was indeed achieved. For one of the additional simulations to generate traces with no coherence differences between pairings, the left panel of Figure 4A shows for one sample session the coherence of the 4 possible trace pairings between locations. This shows that the desired coherence pattern for this simulation of an equally moderate coherence between all pairings of traces across locations was again achieved, with some small random differences occurring each session by chance.

We also tested two other methods of simulating LFP traces with the desired coherence patterns. For one method the signal amplitudes were determined as described previously, but the relative phases of trace pairs rather than the absolute phases of each trace were determined according to independent normal distributions. In this method the relative phase between the traces of the higher coherence pair was selected to have a lower standard deviation than the relative phase between the traces of the lower coherence pair. In another method, both pairs were generated with the same phase distribution, but much more white noise was added to the lower coherence pair (100 arbitrary units), which served to sufficiently reduce the coherence involving those signals. Both of these alternative simulation methods yielded
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identical conclusions to the data we present here, so we thus decided to omit the results using these
methods for presentation clarity and simplicity.

Using real data. Data were collected from one adult monkey (*Macaca mulatta*). The
animal was cared for in compliance with the Guide for the Care and Use of Laboratory Animals and the
guidelines of the Vanderbilt Animal Care and Use Committee. Two recording chambers (RC-1, Gray
Matter Research; Bozeman, MT) were surgically implanted into the animal’s skull, targeting the frontal
eye fields in each area. An 8-Channel acute microdrive system (AC8-1, Gray Matter Research) was
placed in each chamber. Recordings were subsequently made with glass-insulated tungsten
microelectrodes (1-2 MΩ, Alpha Omega Engineering, Nazareth, Israel) from 1 to 2 millimeters below the
depth at which spiking activity was first observed on each electrode. LFPs were measured relative to an
externally grounded reference which was connected to the chamber and the microdrive casing. Voltage
signals were amplified (x 1) by a high impedance HST/8050-G1 head-stage (Plexon Inc., Dallas TX),
filtered from 0.2 to 300 Hz using a custom built analog filter (Plexon Inc.), further amplified (x 1000),
then digitally sampled at 1 kHz using a Plexon MAP system (Plexon, Inc.). The transfer function of the
entire recording system was estimated and adjusted for using procedures described previously (Nelson et
al., 2008). We performed a deconvolution using an inverse filter restricted to the bandwidth spanning
from 0.5 Hz to 450 Hz. Data from frequencies outside this range were attenuated too strongly to recover a
stable estimate.

Neural data was recorded while the monkey performed a search-step task, similar to that reported
in Murthy et al. (2001). Analyses were performed on data within a time window spanning from 50 to 650
ms following the target presentation, during which the recorded LFPs exhibited 20 Hz activity. 342
correct trials across all target locations were used. 4 out of 15 simultaneously recorded LFP traces were
selected from a single recording session. The traces were selected manually upon inspection of coherence
between the channels. For the primary simulations, the traces were selected such that the coherence was
high between one pair (designated to be the high distant coherence traces) and moderate to low between
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all other pairs. For an additional simulation performed in order to investigate the effects when coherence
differences between the individual traces were smaller, a separate group of 4 traces was selected such that
the coherence between all trace pairings was approximately equally moderate.

For the primary simulations, the right panel of Figure 2A shows the 4 traces used from one
sample trial using real LFP data. The right panel of Figure 2B shows for one sample session the
coherence of the 4 possible trace pairings between locations after assigning each trace to a location.
Again, the desired coherence pattern was achieved in which the coherence was high between the two high
distant coherence traces but low between all other pairings of traces. For the additional simulation using
traces with approximately equally moderate coherence between all trace pairings, the right panel of
Figure 4A shows for one sample simulated session the coherence of the 4 possible trace pairings between
locations. Again, the desired coherence pattern for this simulation of an approximately equally moderate
coherence between all pairings of traces across locations was achieved.

Simulating electrode recordings-basic model. Using the 4 LFP traces generated from simulated or
real data, for 500 simulated sessions we calculated the coherence between the locations for two simulated
very low impedance electrodes and two simulated micro-electrodes. To simulate the very low impedance
electrodes, we calculated a weighted average of the activity of the high and low distant coherence traces
for each location for each session (Figure 1B, left). To simulate the microelectrodes, the voltage for each
electrode was independently randomly selected to be either the high or low distant coherence trace for
each session (Figure 1B, right). To simulate different proportions of sub-region space having high or low
distant coherence, we adjusted what we refer to as the high distant coherent fraction. For the very low
impedance electrodes, this fraction determined the relative weights of the high and low distant coherence
traces when calculating the average between them. For microelectrodes, this fraction determined the
probability that a high or low distant coherence trace would be selected each session. Simulations were
run with this parameter set to 0.1, 0.25, 0.50, 0.75 and 0.9. Note that when using real data, the individual
traces themselves were the same between each session. Thus the same precise values were used for the
simulated very low impedance electrodes for every session, although the simulated microelectrode coherence values using the real data changed randomly between sessions.

Simulating electrode recordings—spatial sine-wave model. Using 4 simulated LFP traces, for 500 simulated sessions we calculated the coherence between locations for electrodes with different recording site lengths while the underlying voltage profile varied continuously between the high and low distant coherence traces for each location along a spatial sine wave. At the peak of the sine wave the voltage was set to the high distant coherence activity for that location, at the trough of the sine wave the voltage was set to the low distant coherence activity for that location, and in between the voltage was set to a continuously varying weighted average of the two. For example at the midway point of the sine wave, the voltage was the exact average of the two traces. Thus this weighted average precisely corresponds to the high distant coherence fraction of the basic model described above. The individual traces were generated using the same parameters as the primary simulations of the basic model, which were the parameters used to generate the results shown in Figures 2 and 3. Electrode recording sites of different sizes were then modeled by averaging across different lengths of the sinusoid while randomly determining the phase each session according to a uniform distribution spanning from 0 to 360 degrees. Recording site lengths were specified in units of the number of wavelengths of the underlying spatial sinusoid to allow for the generalization of the results to any voltage profile spatial frequency. The average activity along the recording site length was determined analytically through integration of the sinusoid.

Measuring coherence. We calculated the coherence across locations for each simulated session and electrode type, and report for all simulations the average coherence across sessions. We calculated the coherence using techniques described in Jarvis and Mitra (2001). For the simulated data, we used one large window with a length equal to that of the entire 4 seconds of the simulated trial. For the real data, we used a 200 ms window sliding in time across a trial with a 10 ms step size. We then report the average coherence across time windows for the period of the trial used for the analysis, with the center of the
window spanning from 150 to 550 ms after the initial appearance of the target. In both cases, the first in the series of discrete prolate spheriodal sequences were used to window the data, which provided optimal frequency localization for each finite temporal window (Slepian, 1983). This provided a frequency bandwidth of ±0.25 Hz and ±5 Hz for the simulated and real data respectively. We also investigated the results using the Fisher transformed and bias corrected z-scores of coherence as described in Bokil et al. (2007) and found no differences in the pattern of results.

RESULTS

Basic model

Figure 2C shows the resulting coherence between simulated very low impedance electrodes and microelectrodes based on the basic model (Figure 1A and B). The simulated very low impedance electrodes had higher coherence than the simulated microelectrodes using both simulated (left column) and real (right column) LFP traces.

The basic result of Figure 2C assumes a balance of sub-region space corresponding to high and low distant coherence activity. If on the other hand a location is completely comprised of a single sub-region, a trivial consequence of the model is that the high and low impedance electrodes will record the same values. To further elucidate the entire relationship of these results to the spatial inhomogeneity of the underlying voltage coherence profile, we manipulated the high distant coherence fraction of the basic model (see Materials and Methods) across a range of values (Figure 3). As expected, when this fraction is near the limits of 0 and 1, smaller differences between the electrode types are observed. But at even modest departures from uniformity, considerable differences between the electrodes appear. These differences peak when the voltage coherence profile is farthest from uniform.

The results of Figure 3 show that when there is a relatively large difference in distant coherence between two sub-regions, averaging across them serves to increase the distant coherence reported. To what extent does this still occur when the voltages in the sub-regions are distinct, but with smaller or no differences in distant coherence between them? To investigate this, we simulated additional sessions
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using both simulated and real LFP traces with smaller or no coherence differences between the pairs of traces (see Materials and Methods). Figure 4 shows that the increase in coherence for low impedance electrodes remained relatively strong for these simulations. Moreover, the increase continues to peak at a high distant coherence fraction of 0.5. Thus, the inhomogeneity of an underlying voltage profile regardless of its overall distant coherence gradient appears to be the key factor driving this effect. These results were also consistent across further simulations we performed at different overall levels of coherence while varying the coherence differences between the trace pairs (results not shown). This further indicates the generality and robustness of this effect.

LFP, ECoG and EEG comparisons

Given the effect shown by the basic model, one might expect electrode size differences to play a role when comparing coherences between EEG, ECoG and LFP data which are typically recorded with electrodes of very different sizes. EEG electrodes are typically 5 to 10 mm in diameter (Nunez and Srinivasan, 2006), ECoG electrodes tend to be about 2 to 5 mm in diameter for human studies (e.g. Canolty et al. 2006) or smaller for animal studies (e.g. Sharott et al, 2006; Taylor et al. 2005), whereas the recording sites for LFP electrodes can have lengths on the order of tens of microns or even smaller (Yaeli et al. 2009).

However, it is important to first note that the very nature of the underlying voltages themselves differs between these different sources of data. Cortical surface voltages underlying ECoG data are thought to be more spatially spread than intracranial voltages underlying LFP data (Nunez and Srinivasan, 2006, 2010). Scalp voltages underlying EEG data are in turn thought to be more spatially spread than cortical surface voltages underlying ECoG data (Nunez and Srinivasan, 2006, 2010). Thus, electrode sizes cannot be directly compared between the data types as the important factor described in the theoretical model that can lead to an effect of electrode size on recordings is the size of the electrode in relation to the spatial variation of the underlying voltage being measured. For example, the electrode size-related coherence effect that might result from one particular size of electrode when recording potentials at the
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cortical surface would be different than what would occur for the same electrode recording potentials
either within the brain or on the scalp. However, within each data type one can directly compare more
moderate electrode size differences.

To demonstrate these differences between the data types and investigate if any effects of
electrode size on coherence within any of the data types might be subtly visible across published studies,
we performed a quantitative literature search of published coherence values. Coherence will depend on a
number of factors, including frequency and behavioral state among others, though the effects of such
factors can be difficult to predict (Bullock et al, 1995). However, coherence shows a direct and consistent
dependence on electrode separation for all three data types, resulting largely from the volume conduction
of electrical signals. Thus it is important to consider the inter-electrode distance when comparing
coherence across studies, and in particular across data types. In Figure 5 we plot available data in the
literature for the coherence of different data types as a function of inter-electrode distance, documenting
the electrode size and signal types for each data series. When possible, we selected the highest frequency
data available in each study. We note the behavioral state of the subjects in each study in the figure
caption.

The differing spatial spread of the voltages underlying each data type is immediately apparent in
Figure 5. Similar coherences tend to be found at increased inter-electrode distances for ECoG data
relative to LFP data, and for EEG data relative to both ECoG and LFP data. For EEG data, scalp voltages
are spatially spread out enough that recordings have been previously shown to be independent of
electrode size for all practical purposes (Nunez and Srinivasan, 2006). For ECoG data however, further
inspection of Figure 5 reveals that a modest trend may exist for larger electrodes to report higher
coherece. Notably, this was investigated directly in one study (Wang et al., 2009) that found that 3 mm
diameter electrodes showed higher coherence at the same inter-electrode distances than 1.5 mm diameter
electrodes recorded from simultaneously in the same patient. This agrees with the qualitative prediction of
the basic model described above. For LFP data, there is insufficient published coherence results at
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multiple electrode distances to allow us to come to an empirically based conclusion of the presence or absence of a noticeable effect of electrode size on typical recordings of that data type.

Spatial sine-wave model

We used the spatial sine wave version of our model (Figure 6A) to quantify when and to what extent the effect of electrode size found in the basic model is expected to occur, and further to test if this agrees with the trends in the literature data shown in Figure 5. Figure 6B shows the resulting coherence for any ratio of an electrode’s recording site length to the wavelength of the underlying spatial sine wave of activity in the model. This ratio captures the amount that the voltage profile changes over the extent of a recording site, which is the key factor described by the physical model as leading to possible effects of electrode size on recorded voltages. Moreover this ratio provides a “common currency” to compare expected electrode-size related effects between data types, even as the nature of the underlying neural signals indeed varies between them. As anticipated given the results from the basic model, coherence generally increases as this ratio increases. However at both very low and very high values of this ratio, the coherence asymptotes and is generally insensitive to the precise electrode size. The results quantify a range between values of about 0.8 to about 8 where the ratio is more sensitive to the particular electrode size.

Quantitative predictions can be made from the information in Figure 6B by specifying one of the two variables in the ratio. For example, the corresponding wavelength of the highest spatial frequency present above noise levels in the human cortical surface potential has been estimated to be 2.5 mm per cycle (Freeman et al, 2000). For this spatial frequency, this ratio for typical ECoG electrodes would range between 0.8 and 2.0, as indicated on the figure. Modest effects of electrode size on coherence are indeed expected within this range, which is consistent with Wang et al. (2009) and the other ECoG studies shown in Figure 5. In contrast, the corresponding wavelength of the highest spatial frequency present above noise levels in the human scalp potential has been estimated to be 2.5 cm per cycle (Freeman et al, 2003). For this spatial frequency, this ratio for typical EEG electrodes would range between 0.2 and 0.4, as
indicated on the figure. No appreciable effects of electrode size are expected within this range, which
confirms previous evidence that EEG data is independent of electrode size for the electrodes typically
used to record it. For LFP data, the highest spatial frequency present above noise level within the brain
has not yet directly been shown. However, while it is not a simple step to convert the estimates of the
point spread function from Katzner et al. (2009) and Xing et al. (2009) into a maximum spatial frequency,
a wavelength on the order of 250 microns per cycle might provide a reasonable educated guess. At this
voltage profile wavelength, it seems reasonable that a 200 micron diameter electrode (with a
corresponding ratio of 0.8) might show subtle increases in coherence in some studies (Kay and Lazarra,
2010) but not others (Bullock et al., 1989). This would also suggest, however, that differences among the
smaller sizes of microelectrodes typically used during depth recordings would not occur. More evidence
of this spatial frequency limit in intracranial voltage is needed however to draw firmer conclusions about
the model’s prediction.

DISCUSSION

We developed and tested a simple physical model for LFP recordings of electrodes with large
differences in recording site sizes. The model predicts that low impedance electrodes tend to report higher
coherence than higher impedance microelectrodes. However, intrinsic to the model is that voltages must
vary on a spatial scale smaller than the size of the larger electrode recording site for the electrode size to
make a difference. Moreover, this difference between electrode sizes continuously increases as the
voltage profile over the length of the electrode’s recording site is increasingly inhomogenous. This effect
is robust with respect to the strength of the coherence gradient along the spatial voltage profile. We
compared previously published reports in the literature for the coherence of LFP, ECoG and EEG data
and found evidence for a modest effect of electrode size in ECoG data, but not in EEG or LFP data. We
further developed the model to quantify at what electrode sizes relative to a given voltage profile spatial
frequency the electrode size is expected to impact recorded coherence. Combining this with estimates in
the literature for the spatial frequencies present in all these data types confirms the suggestions of the
literature data.

As the model points out, the suggestion that a pair of lower impedance electrodes favors distantly
coherent activity relies upon the spatial voltage profiles at the two recording locations. For the extreme
example of spatially uniform voltages, the model trivially shows that there would be no expected effect of
recording site size. But as the voltage profiles increasingly depart from uniform, both the basic model and
the spatial sine wave model confirm that the electrode size effect continuously increases. In the basic
model this can be observed as the high distant coherence fraction changes (Figure 3 and 4). In the spatial
sine wave model this can be observed as the coherence increases continuously as the number of voltage
profile cycles along a recording site’s length increases (Figure 6), excluding the plateaus observed for
relatively very small or very large electrodes. The additional simulations varying the coherence gradient
(Figure 4) further show that this effect is general to any voltage gradient, regardless of the amount that the
distant coherence changes along it. It should be emphasized that though there were little to no coherence
differences between the combinations of trace pairs used for these additional simulations, the individual
traces were still distinct and sufficiently independent of each other, which is required for the effect to
occur.

As we mentioned, the results of the spatial sine wave version of the model shown in Figure 6 can
be used to estimate effects for LFP, ECoG or EEG data. The precision of any practical implication of the
model however is limited by the accuracy of the knowledge of the spatial frequencies present in the
underlying voltages. For LFPs, the scale of this spatial variation has yet to be sufficiently quantified. Still,
the estimates of Katzner et al. (2009) and Xing et al. (2009) do clearly suggest that LFP voltages will not
appreciably vary on a scale of tens of microns, which is the lengths of electrode recording sites in typical
use by neurophysiologists (Yaeli, et al., 2009). Thus the effects of microelectrode sizes for recording
LFPs should be negligible, as we have argued (Nelson and Pouget, 2010).

For ECoG data, further empirical evidence may be needed to corroborate the putative effect that
we have shown in literature data and our simulations. This evidence would be useful either in the form of
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further direct tests similar to the study of Wang et al. (2009), or corroboration of the estimates of Freeman et al. (2000) of the spatial frequencies present in cortical surface potentials. If it holds true, the effect for ECoG data would not suggest per se that data from larger electrodes is faulty. Rather it would just be an effect that must be kept in mind when interpreting that data, particularly when considering coherence.

The model we present implies that once the electrode size is small enough relative to the spatial variation of the underlying voltages being measured, recorded data should be independent of electrode size. This together with well understood sampling theory dictates that using such sufficiently small electrodes with inter-electrode spacing that is small enough to avoid spatial aliasing of the signal guarantees the ability to recover all of the information present in the underlying voltages. Thus, it may be advisable to attempt to accomplish this during EEG, ECOG or LFP electrode array design, though it is conceivable that some tradeoffs and limitations surrounding this may exist for some applications. Still, knowledge of the physical model of electrode recordings and the nature of the underlying signals one is trying to record should prove helpful for the choice and design of arrays for any application.

It should also be noted that multiple spatial frequencies are present in LFP, ECoG and EEG data. Our results show that the effect of electrode size, to the extent that it exists at all for a given data type, should be increasingly larger for the higher spatial frequency signals present. The ranges shown in Figure 6 for EEG and ECoG data correspond to the most affected spatial frequencies for these data types. Each data type also includes contributions from lower spatial frequency signals as well, which would correspond to regions to the left of these indicated ranges on the plot.

The model we present also suggests that the variance of coherence across sessions for different electrode sizes would be an interesting quantity to investigate empirically, with the prediction that this should be higher for smaller electrodes whenever the coherence is dependent on electrode size.

The model that we present is an intentionally simple model targeted at the electrodes themselves and exploring the theoretical physical nature of how and under what circumstances the sizes of their recording sites might affect their performance. Biological sources of signals could certainly be modeled, but the implications resulting from this would be tangential to our focus on electrodes and would come at
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a cost of undesirable added complexity. The basic model we tested applies the most extreme version of a
spatial voltage gradient, essentially a step function, to demonstrate whether or not the effect could be a
possibility for less extreme, more realistic profiles. This does not reflect a presumption that voltages in the
brain would actually change as a step function between boundaries. Beyond this, the spatial sine wave
model allows us to generalize to the expected effect for any spatial frequency present in the voltage
profile. More complicated profiles could of course be modeled, but as Fourier analysis dictates, these
would be identical to a summation of spatial sinusoids of different frequencies.

Existing studies have modeled electrode size under different contexts than what we have done
here. Ollikainen et al. (2000) considers the electrical shunting effect of covering the scalp with conductive
EEG electrodes. A notable pair of studies (Moffitt & McIntyre 2005, Lempka et al 2011) modeled the
effect of electrode recording site size on recording spiking activity within the brain using a more complex
finite element model with realistic biological sources of both the signals being measured and the noise
occluding it. Recording site sizes affect their model by changing the conductivity on the particular
locations of an electrode between the much lower value for that of recording sites and the much higher
value for that of the insulated shank. Thus the model they present did not directly look at the effects of
simple spatial averaging of potentials as the model we present does. A further inspection of their model
might reveal a near equivalence to that of the simple model we present here. However, it is not
immediately clear that this is the case. Notably, in their description of their model or their results, the
authors never explicitly mention this property of spatial averaging, which is inherent to the physical
model of electrode recordings espoused by Robinson (1968). Further inspection of this in the model they
present could be of theoretical interest. Interestingly, the model they present produces results for spiking
activity amplitude that are similar to what we show here for LFP, ECoG and EEG coherence.
Specifically, they suggest that spike recording is fairly independent of recording site size over the range
of contact sizes typically employed by neurophysiologists (177 to 1250 µm², the tungsten microelectrode
equivalent of about 2.4 to 0.5 Mohm impedances (Yaeli et al., 2009)), but they did find decreased
amplitudes for a very large electrode that they simulated (10,000 µm², the tungsten microelectrode equivalent of at least < 0.1 Mohm impedance (Yaeli et al., 2009)).

In contrast, the model we present is macroscopic and considerably simple. We believe this is the appropriate level of complication for the aim of this study, which is to provide a simple intuitive model for members of the field to understand and apply. This is in contrast to more complicated models which may be treated too often as a “black box” by many readers rather than engendering an intuitive understanding of their underlying function.

We believe more adherence to and understanding of the physical nature of electrode recordings in the field and in the literature will aid the discussion of the putative effects of recording site shape and size on recorded potentials. Too many previous claims in the literature that these properties are important to account for while interpreting LFP data (Berens et al. 2008; Pesaran 2009; Kay and Lazarra 2010) do not appear to adhere to any theoretical basis or provide any explanations as to precisely how or why effects of these properties would come about. The simple model we explore in our simulations provides a more solid theoretical basis on which to judge these claims. The results for LFP data indicate to the contrary, that these properties likely do not have a substantial effect for the electrodes typically employed by neurophysiologists. Data comparing micro-electrodes of different impedances within this range of typical use will clearly be important to draw firmer conclusions.
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REFERENCES


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Figure legends

Figure 1. Simple model of an LFP activity profile to produce a difference in recorded coherence between electrode types. A: Diagram of discrete sub-regions in two distant locations with different patterns of coherent activity. The sub-regions between the locations with high distant coherence are highly coherent with each other, while those sub-regions with low distant coherence are neither coherent with each other, nor with the high distant coherence sub-regions. B: Basic model of different electrode types within the two locations. Very low impedance electrodes span both sub-region types and are modeled to average the activity between them for each session. Microelectrodes are located in only one sub-region at a time and are modeled to report the activity of a single randomly selected sub-region for each session.

Figure 2. Simulated coherence patterns using simulated and real LFP traces. The left column corresponds to results using simulated LFP traces and the right column corresponds to results using real LFP traces. A: Sample individual signals for the signals with high distant coherence (red and blue) and the signals with low distant coherence (green and magenta). B: Direct inter-sub-region coherence across two locations as labeled on the figure for the four sub-region combinations. The high-high (blue) trace shows the direct coherence between the high distant coherence sub-regions in each location (see Figure 1A); the high-low (green) trace shows the direct coherence between the high distant coherence sub-region in location 1 and the low distant coherence sub-region in location 2; the low-high (red) trace shows the direct coherence between the low distant coherence sub-region in location 1 and the high distant coherence sub-region in location 2; and the low-low (magenta) trace shows the direct coherence between the low distant coherence sub-regions in each location. C: Average coherence across 500 sessions for simulated very low impedance electrodes (black lines) and simulated microelectrodes (gray lines). The high distant coherence fraction was set to the default value of 0.5.

Figure 3. Simulated coherence patterns of the basic model while varying the high distant coherence fraction. A: Average coherence across 500 sessions for simulated very low impedance electrodes and
simulated microelectrodes while setting the high distant coherence fraction to 0.25 (top row), 0.5 (middle row),
and 0.75 (bottom row). The left column corresponds to results using simulated LFP traces and the right column
corresponds to results using real LFP traces. B: Average 20 Hz coherence while varying the high distant coherence
fraction. The left panel shows the very low impedance electrode (black) and microelectrode (grey) average 20 Hz
coherence across 500 simulated sessions using simulated (dashed) and real (solid) LFP traces at different values of
the high distant coherence fraction. The right panel shows for the same data the difference between the
simulated very low impedance electrodes and microelectrodes.

**Figure 4.** Simulated coherence patterns of the basic model while varying the amount of coherence difference between sub-regions. The left column corresponds to results using simulated LFP traces and the right column corresponds to results using real LFP traces. A: Direct inter-sub-region coherence across two locations as labeled on the figure for the four sub-region combinations. The left panel reflects an example session of the simulations with no coherence difference between the individual traces (corresponding results shown in light grey in panels B and C). The right panel reflects an example session of real LFP traces selected to have approximately equally moderate coherence. Conventions are the same as in Figure 2B. B: Average 20 Hz coherence while varying the sub-region coherence difference and the high distant coherence fraction. Both panels show the very low impedance electrode (thick) and microelectrode (thin) average 20 Hz coherence across 500 simulated sessions. Results where the underlying traces had high, moderate or no coherence differences are shown in black, dark grey and light grey, respectively. The high coherence difference results are duplicated from Figure 3B, and shown here for comparison. C: Difference in coherence between simulated very low impedance electrodes and microelectrodes for the data in panel B. Plotting conventions are the same as in panel B.

**Figure 5.** Coherence against inter-electrode distance data in the literature for LFP, ECoG and EEG data. The referring article as well as the data type and the approximate electrode diameter for each data series is
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shown in the legend. Bullock et al. (1990) data are from their Figure 2B, 20-40 Hz, collected during slow-wave sleep and paradoxical sleep. We report the average across these two. This study lists the electrode shank diameter to be 50 µm, suggesting the diameter across the uninsulated tip is at least less than this. Jia et al. (2011) data are from their Figure 8D, 30-50 Hz, showing spontaneous activity with the subject under anesthesia. This study indicates the electrodes used had impedances of 0.4 MΩ. Given the geometrical constraints and the relation between impedance and surface area described in Yaeli et al. (2009), this likely suggests a tip size less than 50 µm. Bullock and McClune (1989) data are from their Figure 4 lower panel, 35-40 Hz, collected with the subject under light anesthesia. Wang et al. (2009) data are from their Figure 2B, 60-120 Hz, collected with the subject awake and relaxed with their eyes open. Bullock et al. (1995) data reflect averages of data shown in their Figures 3, 4 and 5, corresponding to frequency ranges spanning from 20 to 80 Hz, collected during slow wave sleep, alert or sedated behavioral states. Barry et al. (2005) data are from the regression line in their Figure 1 top panel, 1.5 – 25 Hz, collected with the subject in an awake resting state with their eyes closed.

Figure 6. Spatial sine-wave model and results A: Model illustration. In this version of the model, the amount of distant coherence at each point in space is varied continuously following a sine wave. Different sizes of electrode recording sites are modeled to average the underlying activity along their lengths with a randomly selected initial phase for each simulated session. B: Simulated coherence against the ratio of electrode recording site length to the wavelength of the sinusoidal voltage profile. The average 20 Hz coherence across sessions using simulated data is shown. The putative ranges corresponding to typical EEG and ECoG electrodes at the corresponding highest spatial frequency of the voltage underlying each data type are indicated. For LFP recordings this spatial frequency is presently not clearly known.
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