Complexity analysis of spatiotemporal pattern of local field potentials from motor cortex.

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Abstract. Aggregate signals that reflect activities of a large number of neurons in the cerebral cortex, local field potentials (LFPs) have been observed to mediate gross functional activities of a relatively small volume of the brain tissues. There are several bands of the oscillations frequencies in LFPs have been observed across multiple brain areas. The signature oscillation of the local field potentials (LFPs) in the primary motor cortex (MI) is over β range and it has been consistently observed both in human and non-human primates around the time of visual cues and movement onsets. However, its dynamical behavior has not been well characterized. Furthermore, spatiotemporal dynamics of β oscillations has been documented based on the phase gradient of β oscillations, but not in terms of the inherent dynamics of the oscillations themselves. Here, we used the complexity measure derived from cluster coefficients of a recurrent network and analyzed a wide-band and β band of the LFPs in MI recorded from a non-human primate. We show a rather unique temporal profile of the complexity of the dynamical behavior of the oscillation, which are not resembling either the power of the oscillation or the phase locking of β oscillations. Furthermore, there appears to show some spattiotemporal patterns over the recorded part of MI. Our new approach may give us more insight as to how local circuitry of the cortex is spatially organized for its function.

1. Introduction

Cortical rhythms have been extensively studied since early descriptions of oscillations in sensorimotor cortex by Berger and Jasper and Penfield. Since In particular, local field potentials (LFPs) and electroencephalograms (EEG) in the β frequency range (15-40 Hz) are ubiquitous in the motor cortex of mammals including monkeys and humans across the upper limb area of the primary motor cortex (MI). The dynamics of the β oscillation has been grossly characterized, based on a temporal profile of the amplitude of the oscillations, such as event related synchronization (ERS) and event related desynchronization (ERD) [**?**], and phase locking to the instruction cues [**?**]. However, the dynamical properties of β oscillations have not been well characterized. Recently, it has been reported that phase of β oscillations propagated as plane waves along the rostrocaudal axis of the motor cortex during motor preparation and execution, and are believed to subserve cortical information transfer [**?**]. However, it has not been shown inherent dynamics of LFPs, in particular, β oscillations, and their spatiotemporal dynamics.

[**?**], [**?**]

2. Method

2.1. Behavior task and data collection

All of the surgical and behavioral procedures were approved by the University of Chicago IACUC and conform to the principles outlines in the Guide for the Care and Use of Laboratory Animals. One monkey was trained to perform a visuomotor task using a two-link exoskeleton manipulandum [**?**]. The monkey was required to move a cursor on a horizontal screen that was aligned to the monkey's hand to the position of a target. When the monkey successfully reached the current target, a new target was displayed at a random location within a workspace while the current target disappeared. The monkey received a juice reward after successfully acquiring five or seven consecutive targets.

We recorded local field potentials (LFPs) from up to 96 channels simultaneously at 1 kHz from MI in the monkey using an Utah microelectrode array (Blackrock Microsystems; 1 mm in length and 400μm inter-electrode spacing) implanted contralateral to the moving arm. We analyzed 1000 consecutive successful trials. The LFPs were bidirectionally lowpass filtered at 200 Hz with a 3rd order Butterworth filter. The partitioned into a series of windows of 150 ms starting from the following time windows istarting $[-100, 50]$ ms in relation to visual cue onset, incremented by 10 ms up to $[200, 350]$ ms.

2.2. Recurrence Networks

Given an univariate time series $\{u(i), i = 1, 2, \cdots, N\}$, one can reconstruct the phase space trajectory of the underlying dynamics using the method of delays ref. [**?**]

$$\mathbf{x}_i = (u(i), u(i+\tau), \cdots, u(i+(m-1)\tau)), \tag{1}$$

where $\mathbf{x}_i \in \mathbb{R}^m$, τ is the embedding delay determined as the first local minimum of the auto mutual information and m is the embedding dimension which can be determined using the false nearest neighbor (FNN) approach. One can visualize the dynamics of the phase space trajectories using the method of recurrence plots ref. [**?**]. A Recurrence plot (RP) is a graphical representation of the recurrence matrix, which is a closeness test depicting the times when two states visit roughly the same area in phase space. This closeness can be defined based on Euclidean or Manhattan or maximum norm. A recurrence matrix $\mathbf{R}$ depicting the closeness between the pairs of state vectors can be given as ref. [**?**, **?**]

$$R_{i,j}(\epsilon) = \Theta(\varepsilon - \|x_i - x_j\|), \tag{2}$$

where $\Theta(\cdot)$ is the Heaviside function, $\|\cdot\|$ is a distance norm, and ε is the recurrence threshold specifying the maximum spatial distance of neighboring states. The recurrence matrix is a binary, symmetric matrix with an entry of 1 if the distance between two states is less than the recurrence threshold ε, else the entry is 0. The recurrence matrix can be reinterpreted as an adjacency matrix after the following transformation ref. [**?**, **?**],

$$\mathbf{A} = \mathbf{R} - \mathbf{I}, \tag{3}$$

where $\mathbf{I}$ is the identity matrix. The above operation simply eliminates the artificial self-loops. The adjacency matrix $\mathbf{A}$ represents an undirected, unweighted complex network known as the recurrence network ref. [**?**]. The recurrence network can be characterized using graph theoretical methods to reflect the dynamically invariant properties of the associated dynamical system. In this work, we compute the global clustering coefficient C of the recurrence network. Given a network with N nodes and V vertices, the local clustering coefficient of a node i can be defined as the likelihood that the neighbors of i will also be neighbors of each other. Formally, the local clustering coefficient of a node i can be given as ref. [**?**],

$$c(i) = \frac{\sum_{j,r} A_{i,j} A_{j,r} A_{r,i}}{k_i(k_i - 1)}, \tag{4}$$

where k is the degree of a node. The Global clustering coefficient is simply the average of local clustering coefficient computed over all the nodes of a network and is given as,

$$C = \frac{1}{N} \sum_{i \in \mathcal{N}} c(i). \tag{5}$$

We divided the LFP data from all the 96 channels into 8 overlapping windows for each event and computed the recurrence network measure C for each window. In order to find the optimal embedding parameters, we computed the first minimum of the auto mutual information for data from all the channels and found that τ varied between 2 to 4. Similarly, to determine the embedding dimension, we used the improved FNN approach [**?**] to avoid spurious effects due to noise and found that the embedding dimension varied between 3 to 5 for all the data. Thus we fixed the embedding delay at 6 and the embedding dimension at 5 (it varied between 3 and 5 as per the modified FNN method) to construct recurrence networks of the same size. Instead of specifying the recurrence threshold ε, we fix the recurrence rate $RR = 0.03$ so that we obtain recurrence networks with approximately the same number of edges so that we can compare the networks obtained from different time windows [**?**].

3. Results

3.1. Temporal profiles of cluster coefficients

The cluster coefficients

3.2. Spatiotemporal profiles of cluster coefficients

As shown in Fig. **??**, most causal interactions were detected for Time Window 2 than other two intervals. These causality networks were obtained from the data set1, and we obtained similar results using data sets 2 and 3 as well. In order to look into the causality network consistency over data sets, we plotted the degrees of all neurons for 3 data sets in Fig. 6. All data sets had similar distributions of degrees and same 'hub' neurons 9 and 15 - neurons with unusually high degree. Interestingly neurons recorded from a same electrode were not interacting with one another, but they were causally influencing on neurons from different electrodes.

4. Discussions

5. References

In the online version of *Journal of Physics: Conference Series* references will be linked to their original source or to the article within a secondary service such as INSPEC or ChemPort wherever possible. To facilitate this linking extra care should be taken when preparing reference lists.

Two different styles of referencing are in common use: the Harvard alphabetical system and the Vancouver numerical system. For *Journal of Physics: Conference Series*, the Vancouver numerical system is preferred but authors should use the Harvard alphabetical system if they wish to do so. In the numerical system references are numbered sequentially throughout the text within square brackets, like this [2], and one number can be used to designate several references.

5.1. Using BIBTEX

We highly recommend the `iopart-num` BIBTEX package by Mark A Caprio [**?**], which is included with this documentation.

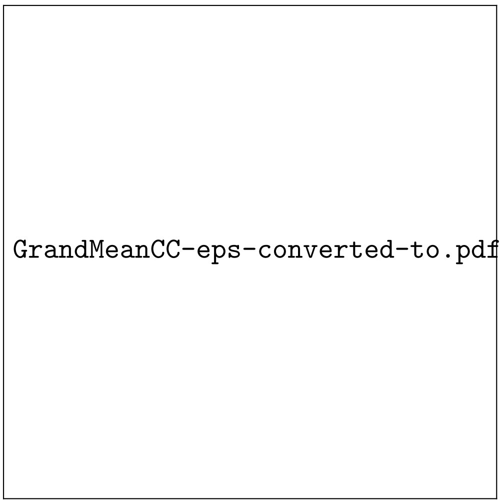

Figure 1. Figure caption for first of two sided figures.

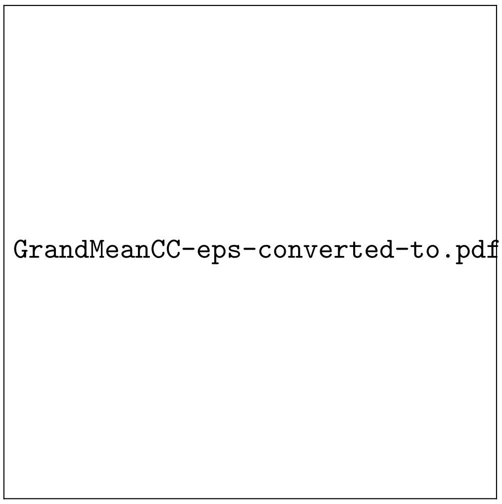

Figure 2. Figure caption for second of two sided figures.

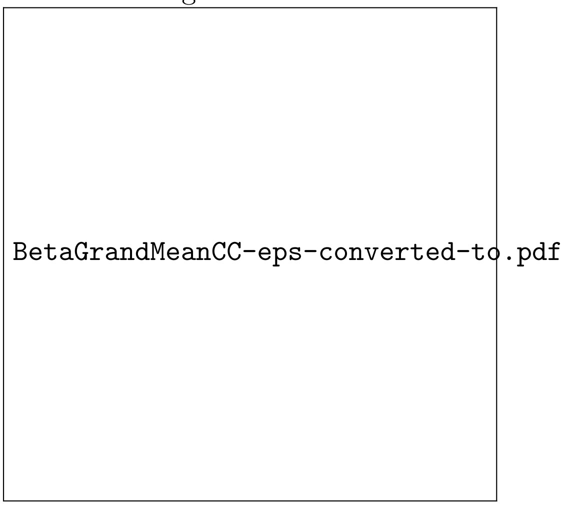

Figure 3. Figure caption for first of two sided figures.

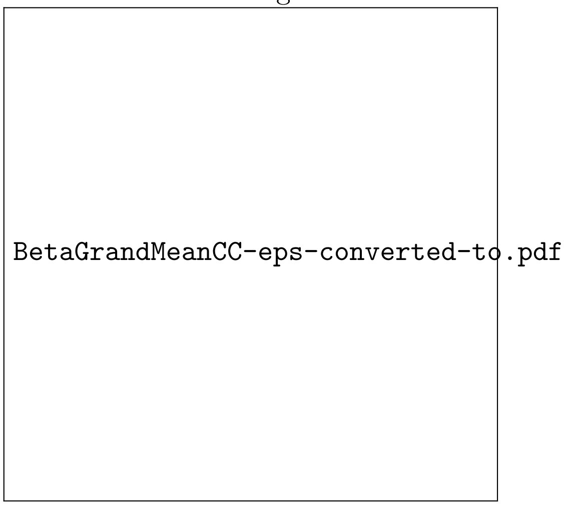

Figure 4. Figure caption for second of two sided figures.

5.2. Reference lists

A complete reference should provide the reader with enough information to locate the article concerned, whether published in print or electronic form, and should, depending on the type of reference, consist of:

- name(s) and initials;
- date published;
- title of journal, book or other publication;
- titles of journal articles may also be included (optional);
- volume number;
- editors, if any;
- town of publication and publisher in parentheses for *books*;
- the page numbers.

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Figure 5. The degrees of all neurons obtained for Time Window 2 are illustrated over 3 data sets. Similar distributions of degrees and same hub neurons 9 and 15 were observed for all 3 data sets.

Up to ten authors may be given in a particular reference; where there are more than ten only the first should be given followed by '*et al*'. If an author is unsure of a particular journal's abbreviated title it is best to leave the title in full. The terms *loc. cit.* and *ibid.* should not be used. Unpublished conferences and reports should generally not be included in the reference list and articles in the course of publication should be entered only if the journal of publication is known. A thesis submitted for a higher degree may be included in the reference list if it has not been superseded by a published paper and is available through a library; sufficient information should be given for it to be traced readily.

degrees-eps-converted-to.pdf

Figure 6. The degrees of all neurons obtained for Time Window 2 are illustrated over 3 data sets. Similar distributions of degrees and same hub neurons 9 and 15 were observed for all 3 data sets.

5.3. Formatting reference lists

Numeric reference lists should contain the references within an unnumbered section (such as `\section*{References}`). The reference list itself is started by the code `\begin{thebibliography}{<num>}`, where `<num>` is the largest number in the reference list and is completed by `\end{thebibliography}`. Each reference starts with `\bibitem{<label>}`, where 'label' is the label used for cross-referencing. Each `\bibitem` should only contain a reference to a single article (or a single article and a preprint reference to the same article). When one number actually covers a group of two or more references to different articles, `\nonum` should replace \bibitem{<label>} at the start of each reference in the group after the first.

For an alphabetic reference list use \begin{thereferences} ... \end{thereferences} instead of the 'thebibliography' environment and each reference can be start with just \item instead of \bibitem{label} as cross referencing is less useful for alphabetic references.

5.4. References to printed journal articles

A normal reference to a journal article contains three changes of font (see table 1) and is constructed as follows:

- the authors should be in the form surname (with only the first letter capitalized) followed by the initials with no periods after the initials. Authors should be separated by a comma except for the last two which should be separated by 'and' with no comma preceding it;
- the article title (if given) should be in lower case letters, except for an initial capital, and should follow the date;
- the journal title is in italic and is abbreviated. If a journal has several parts denoted by different letters the part letter should be inserted after the journal in Roman type, e.g. *Phys. Rev.* A;
- the volume number should be in bold type;
- both the initial and final page numbers should be given where possible. The final page number should be in the shortest possible form and separated from the initial page number by an en rule '– ', e.g. 1203–14, i.e. the numbers '12' are not repeated.

A typical (numerical) reference list might begin

[1] Strite S and Morkoc H 1992 *J. Vac. Sci. Technol.* B **10** 1237
[2] Jain S C, Willander M, Narayan J and van Overstraeten R 2000 *J. Appl. Phys.* **87** 965
[3] Nakamura S, Senoh M, Nagahama S, Iwase N, Yamada T, Matsushita T, Kiyoku H and Sugimoto Y 1996 *Japan. J. Appl. Phys.* **35** L74
[4] Akasaki I, Sota S, Sakai H, Tanaka T, Koike M and Amano H 1996 *Electron. Lett.* **32** 1105
[5] O'Leary S K, Foutz B E, Shur M S, Bhapkar U V and Eastman L F 1998 *J. Appl. Phys.* **83** 826
[6] Jenkins D W and Dow J D 1989 *Phys. Rev.* B **39** 3317

which would be obtained by typing

```
\begin{\thebibliography}{9}
\item Strite S and Morkoc H 1992 {\it J. Vac. Sci. Technol.} B {\bf 10} 1237
\item Jain S C, Willander M, Narayan J and van Overstraeten R 2000
{\it J. Appl. Phys}. {\bf 87} 965
\item Nakamura S, Senoh M, Nagahama S, Iwase N, Yamada T, Matsushita T, Kiyoku H
and  Sugimoto Y 1996 {\it Japan. J. Appl. Phys.} {\bf 35} L74
\item Akasaki I, Sota S, Sakai H, Tanaka T, Koike M and Amano H 1996
{\it Electron. Lett.} {\bf 32} 1105
\item O'Leary S K, Foutz B E, Shur M S, Bhapkar U V and Eastman L F 1998
{\it J. Appl. Phys.} {\bf 83} 826
\item Jenkins D W and Dow J D 1989 {\it Phys. Rev.} B {\bf 39} 3317
\end{\thebibliography}
```

5.5. References to Journal of Physics: Conference Series articles

Each conference proceeding published in *Journal of Physics: Conference Series* will be a separate *volume*; references should follow the style for conventional printed journals. For example:

[1] Douglas G 2004 *J. Phys.: Conf. Series* **1** 23–36

Table 1. Font styles for a reference to a journal article.

Element	Style
Authors	Roman type
Date	Roman type
Article title (optional)	Roman type
Journal title	Italic type
Volume number	Bold type
Page numbers	Roman type

5.6. References to preprints

For preprints there are two distinct cases:

(1) Where the article has been published in a journal and the preprint is supplementary reference information. In this case it should be presented as:

[1] Kunze K 2003 T-duality and Penrose limits of spatially homogeneous and inhomogeneous cosmologies *Phys. Rev.* D **68** 063517 (*Preprint* gr-qc/0303038)

(2) Where the only reference available is the preprint. In this case it should be presented as

[1] Milson R, Coley A, Pravda V and Pravdova A 2004 Alignment and algebraically special tensors *Preprint* gr-qc/0401010

5.7. References to electronic-only journals

In general article numbers are given, and no page ranges, as most electronic-only journals start each article on page 1.

- For *New Journal of Physics* (article number may have from one to three digits)

  [1] Fischer R 2004 Bayesian group analysis of plasma-enhanced chemical vapour deposition data *New. J. Phys.* **6** 25

- For SISSA journals the volume is divided into monthly issues and these form part of the article number

  [1] Horowitz G T and Maldacena J 2004 The black hole final state *J. High Energy Phys.* JHEP02(2004)008

  [2] Bentivegna E, Bonanno A and Reuter M 2004 Confronting the IR fixed point cosmology with high-redshift observations *J. Cosmol. Astropart. Phys.* JCAP01(2004)001

5.8. References to books, conference proceedings and reports

References to books, proceedings and reports are similar to journal references, but have only two changes of font (see table 2).

Points to note are:

- Book titles are in italic and should be spelt out in full with initial capital letters for all except minor words. Words such as Proceedings, Symposium, International, Conference, Second, etc should be abbreviated to *Proc.*, *Symp.*, *Int.*, *Conf.*, *2nd*, respectively, but the rest of the title should be given in full, followed by the date of the conference and the town or city where the conference was held. For Laboratory Reports the Laboratory should be spelt out wherever possible, e.g. *Argonne National Laboratory Report.*
- The volume number, for example vol 2, should be followed by the editors, if any, in a form such as 'ed A J Smith and P R Jones'. Use *et al* if there are more than two editors. Next comes the town of publication and publisher, within brackets and separated by a colon, and finally the page numbers preceded by p if only one number is given or pp if both the initial and final numbers are given.

Table 2. Font styles for references to books, conference proceedings and reports.

Element	Style
Authors	Roman type
Date	Roman type
Book title (optional)	Italic type
Editors	Roman type
Place (city, town etc) of publication	Roman type
Publisher	Roman type
Volume	Roman type
Page numbers	Roman type

Examples taken from published papers:

[1] Kurata M 1982 *Numerical Analysis for Semiconductor Devices* (Lexington, MA: Heath)
[2] Selberherr S 1984 *Analysis and Simulation of Semiconductor Devices* (Berlin: Springer)
[3] Sze S M 1969 *Physics of Semiconductor Devices* (New York: Wiley-Interscience)
[4] Dorman L I 1975 *Variations of Galactic Cosmic Rays* (Moscow: Moscow State University Press) p 103
[5] Caplar R and Kulisic P 1973 *Proc. Int. Conf. on Nuclear Physics (Munich)* vol 1 (Amsterdam: North-Holland/American Elsevier) p 517
[6] Cheng G X 2001 *Raman and Brillouin Scattering-Principles and Applications* (Beijing: Scientific)
[7] Szytula A and Leciejewicz J 1989 *Handbook on the Physics and Chemistry of Rare Earths* vol 12, ed K A Gschneidner Jr and L Erwin (Amsterdam: Elsevier) p 133
[8] Kuhn T 1998 *Density matrix theory of coherent ultrafast dynamics Theory of Transport Properties of Semiconductor Nanostructures* (Electronic Materials vol 4) ed E Schöll (London: Chapman and Hall) chapter 6 pp 173–214

6. Tables and table captions

Tables should be numbered serially and referred to in the text by number (table 1, etc, **rather than** tab. 1). Each table should be a float and be positioned within the text at the most convenient place near to where it is first mentioned in the text. It should have an explanatory caption which should be as concise as possible.

6.1. The basic table format

The standard form for a table is:

```
\begin{table}
\caption{\label{label}Table caption.}
\begin{center}
\begin{tabular}{llll}
\br
Head 1&Head 2&Head 3&Head 4\\
\mr
1.1&1.2&1.3&1.4\\
2.1&2.2&2.3&2.4\\
\br
\end{tabular}
\end{center}
\end{table}
```

The above code produces table 3.

Table 3. Table caption.

Head 1	Head 2	Head 3	Head 4
1.1	1.2	1.3	1.4
2.1	2.2	2.3	2.4

Points to note are:

(1) The caption comes before the table.
(2) The normal style is for tables to be centred in the same way as equations. This is accomplished by using `\begin{center}` ... `\end{center}`.
(3) The default alignment of columns should be aligned left.
(4) Tables should have only horizontal rules and no vertical ones. The rules at the top and bottom are thicker than internal rules and are set with `\br` (bold rule). The rule separating the headings from the entries is set with `\mr` (medium rule). These commands do not need a following double backslash.
(5) Numbers in columns should be aligned as appropriate, usually on the decimal point; to help do this a control sequence `\lineup` has been defined which sets `\0` equal to a space the size of a digit, `\m` to be a space the width of a minus sign, and `\-` to be a left overlapping minus sign. `\-` is for use in text mode while the other two commands may be used in maths or text. (`\lineup` should only be used within a table environment after the caption so that `\-` has its normal meaning elsewhere.) See table 4 for an example of a table where `\lineup` has been used.

Table 4. A simple example produced using the standard table commands and `\lineup` to assist in aligning columns on the decimal point. The width of the table and rules is set automatically by the preamble.

A	B	C	D	E	F	G
23.5	60	0.53	−20.2	−0.22	1.7	14.5
39.7	−60	0.74	−51.9	−0.208	47.2	146
123.7	0	0.75	−57.2	—	—	—
3241.56	60	0.60	−48.1	−0.29	41	15

7. Figures and figure captions

Figures must be included in the source code of an article at the appropriate place in the text not grouped together at the end.

Each figure should have a brief caption describing it and, if necessary, interpreting the various lines and symbols on the figure. As much lettering as possible should be removed from the figure itself and included in the caption. If a figure has parts, these should be labelled (a), (b), (c), etc. Table 5 gives the definitions for describing symbols and lines often used within figure captions (more symbols are available when using the optional packages loading the AMS extension fonts).

Table 5. Control sequences to describe lines and symbols in figure captions.

Control sequence	Output	Control sequence	Output
`\dotted`	······	`\opencircle`	○
`\dashed`	- - - -	`\opentriangle`	△
`\broken`	– – –	`\opentriangledown`	▽
`\longbroken`	— — —	`\fullsquare`	■
`\chain`	— · —	`\opensquare`	□
`\dashddot`	— · · —	`\fullcircle`	●
`\full`	——	`\opendiamond`	◊

Authors should try and use the space allocated to them as economically as possible. At times it may be convenient to put two figures side by side or the caption at the side of a figure. To put figures side by side, within a figure environment, put each figure and its caption into a minipage with an appropriate width (e.g. 3in or 18pc if the figures are of equal size) and then separate the figures slightly by adding some horizontal space between the two minipages (e.g. `\hspace{.2in}` or `\hspace{1.5pc}`. To get the caption at the side of the figure add the small horizontal space after the `\includegraphics` command and then put the `\caption` within a minipage of the appropriate width aligned bottom, i.e. `\begin{minipage}[b]{3in}` etc (see code in this file used to generate figures 1–3).

Note that it may be necessary to adjust the size of the figures (using optional arguments to `\includegraphics`, for instance `[width=3in]`) to get you article to fit within your page allowance or to obtain good page breaks.

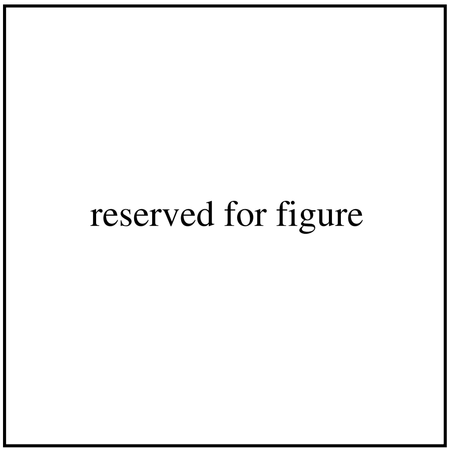

Figure 7. Figure caption for first of two sided figures.

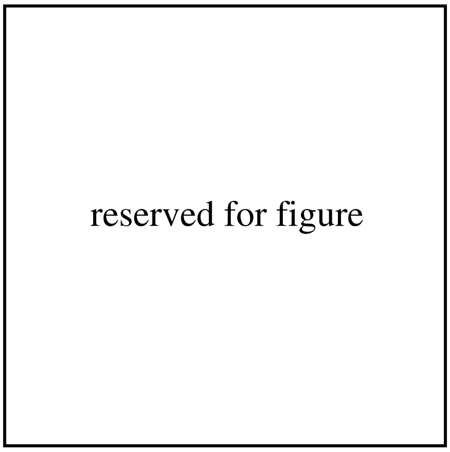

Figure 8. Figure caption for second of two sided figures.

Using the graphicx package figures can be included using code such as:

```
\begin{figure}
\begin{center}
\includegraphics{file.eps}
\end{center}
```

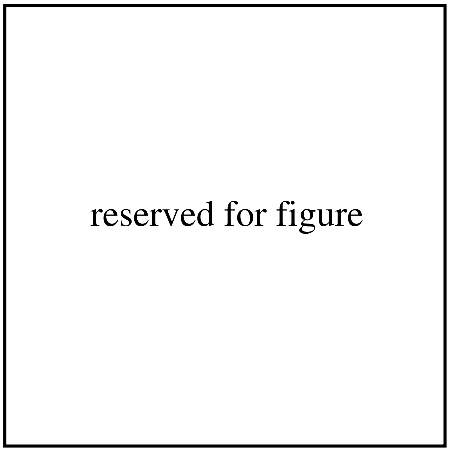

Figure 9. Figure caption for a narrow figure where the caption is put at the side of the figure.

```
\caption{\label{label}Figure caption}
\end{figure}
```

References