Inference of hand movements from local field potentials in monkey motor cortex

Carsten Mehring[1,5], Jörn Rickert[1,5], Eilon Vaadia[2], Simone Cardoso de Oliveira[3], Ad Aertsen[1] & Stefan Rotter[1,4]

The spiking of neuronal populations in motor cortex provides accurate information about movement parameters. Here we show that hand movement target and velocity can be inferred from multiple local field potentials (LFPs) in single trials approximately as efficiently as from multiple single-unit activity (SUA) recorded from the same electrodes. Our results indicate that LFPs can be used as an additional signal for decoding brain activity, particularly for new neuroprosthetic applications.

The activity of single neurons in the motor cortex is related to various parameters of movement, such as force or direction, but quantitative data about the information carried by LFP signals in this area[1–5] is lacking. Here we compare the decoding power of multiple LFPs with multiple SUAs and multiple multiunit activities (MUAs) recorded in the motor cortex of two rhesus monkeys (*Macaca mulatta*) performing center-out arm movements (for details, see **Supplementary Methods** online and refs. 2,6).

Trial-averaged activity of all three types of signals (LFP, SUA and MUA) typically showed a clear directional tuning for movements of both the contralateral and the ipsilateral arm (**Fig. 1**). Tuning began well before movement onset: about 100 ms beforehand for the LFPs and 150 ms for SUAs and MUAs (see **Supplementary Fig. 1** online).

Next we calculated decoding power of all three signal types as the probability of inferring the movement target correctly from single-trial neuronal activity (for details, see **Supplementary Methods** and **Supplementary Fig. 2**). Individual single units had an average decoding power of 0.28 for movements of the contralateral arm and 0.19 for the ipsilateral arm, as compared to a chance level of 0.125 (**Fig. 2a**). The decoding power of individual LFPs was comparable: 0.25 and 0.21 for contra- and ipsilateral movements, respectively. Thus, a single LFP channel carried essentially the same amount of information about movement target as did the spike train of a single cell. MUAs showed decoding power of 0.22 and 0.16 for contra- and ipsilateral movements, respectively. LFPs, SUAs and MUAs allowed movements of the ipsilateral arm to be decoded with only slightly lower accuracy than movements of the contralateral arm. Correlations between ipsi- and contralateral decoding power were generally weak (**Fig. 2b**).

Individual neurons and individual LFP and MUA channels were poor predictors of movement target on a single-trial basis. Therefore, we computed the decoding power of multiple channels as a function of the number of electrodes (**Fig. 3a**). For all signals, the probability of correct decoding increased monotonically with the number of electrodes, reaching 0.87 using the LFPs from 48 electrodes, 0.84 using all the SUAs and 0.77 using the MUAs extracted from the same electrodes during the same recording sessions. The best results were obtained by combining information from LFPs and SUAs or LFPs and MUAs, yielding decoding powers of 0.95 and 0.94, respectively, for 48 electrodes.

Correlations between mean evoked potentials[1] and correlations between trial-by-trial fluctuations of simultaneously recorded LFPs[2] in motor cortex can be relatively high. Thus, to test the influence of correlations among simultaneously recorded LFPs on the decoding, we compared the decoding power of simultaneously recorded LFPs (correlations present) to that of LFPs recorded on different days (correlations largely absent). We observed essentially no difference between the two groups (**Fig. 3b**). In view of this finding, we conclude that the decoding power of multiple channels shown in **Figure 3a** represents a reasonable estimate for large multielectrode arrays with an electrode spacing comparable to ours.

The temporal evolution of decoding power (**Fig. 3c**) showed similar profiles for LFPs, SUAs and MUAs: decoding power was continuously above chance level ($P < 0.001$) by 125 ms (SUA), 100 ms (MUA) and 75 ms (LFP) before movement onset (see **Supplementary Methods**). After a steep rise, a broad maximum in decoding power was reached at roughly 150 ms (SUA and MUA) and 250 ms (LFP) after movement onset. By computing the ratio between the decoding power of the signal recorded before movement onset and the decoding power of the complete signal, we found that all three types of signals already carried 45–55% of their decoding power before movement onset.

Finally, we predicted full movement trajectories from the single-trial LFP, SUA and MUA signals recorded from eight electrodes (examples shown in **Fig. 3d,e**). To quantify prediction accuracy, we calculated the correlation coefficient between predicted and real movement trajecto-

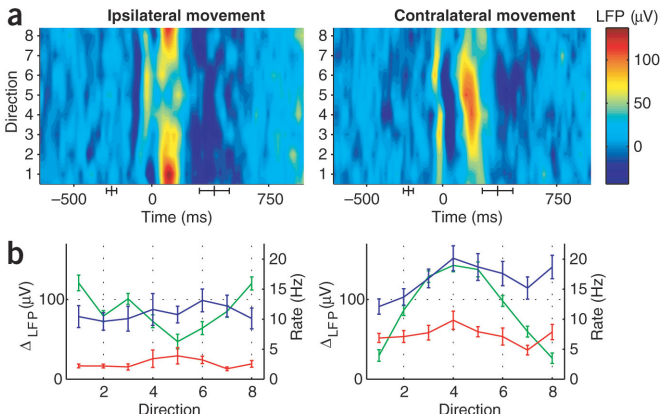

Figure 1 Example of LFP, SUA and MUA tuning, averaged over 20 trials per target. (**a**) Averaged evoked potentials from one electrode during ipsilateral (left) and contralateral (right) movements are shown in color code for all eight directions. Trials were aligned to movement onset (at origin). The black symbols below the *x* axis indicate mean and temporal jitter (s.d.) of cue onset time and when the monkey reached the target area. (**b**) Tuning curves of a LFP (green, same data as above), SUA (red) and MUA (blue) recorded simultaneously from the same electrode (see **Supplementary Methods** for description of how tuning curves were obtained).

[1]Neurobiology & Biophysics, Institute of Biology III, Albert Ludwigs University, Schänzlestrasse 1, 79104 Freiburg, Germany. [2]Department of Physiology and The Interdisciplinary Center for Neural Computation, The Hebrew University, Hadassah Medical School, PO Box 12272, Jerusalem 91120, Israel. [3]Institut für Arbeitsphysiologie, Universität Dortmund, Ardeystrasse 67, 44139 Dortmund, Germany. [4]Theory & Data Analysis, Institute for Frontier Areas of Psychology and Mental Health, Wilhelmstrasse 3a, 79098 Freiburg, Germany. [5]These authors contributed equally to this work. Correspondence should be addressed to C.M. (carsten.mehring@biologie.uni-freiburg.de).

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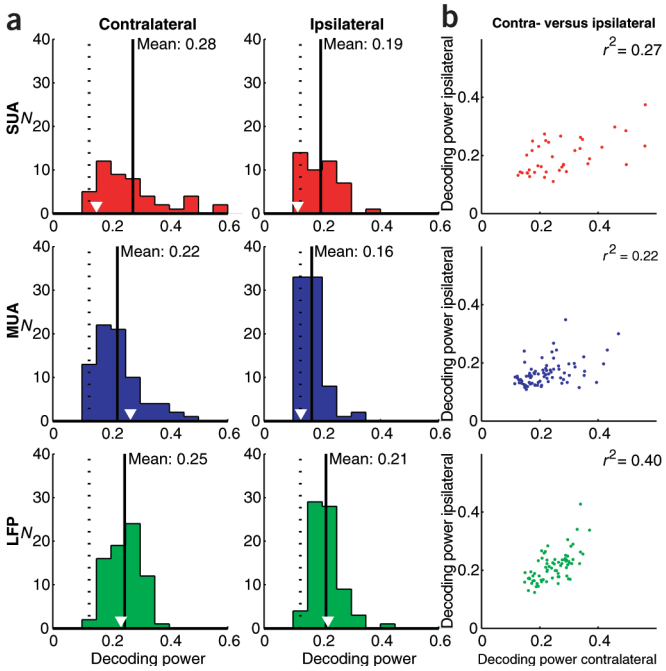

Figure 2 Decoding of movement target from individual SUAs, MUAs and LFPs. (**a**) Distribution of decoding power for individual SUA (top), MUA (middle) and LFP (bottom) channels, for contralateral (left) and ipsilateral (right) movements from 74 LFP channels (30 from monkey G, 44 from monkey P), 77 MUA channels (31 from monkey G, 46 from monkey P) and 52 well-isolated single units with stable firing rates across trials (24 from monkey G, 28 from monkey P; also compare **Supplementary Fig. 3**). White triangles, decoding power of the LFP, SUA and MUA shown in **Figure 1**. Dotted lines, chance level (0.125). (**b**) Correlation between contra- and ipsilateral decoding power.

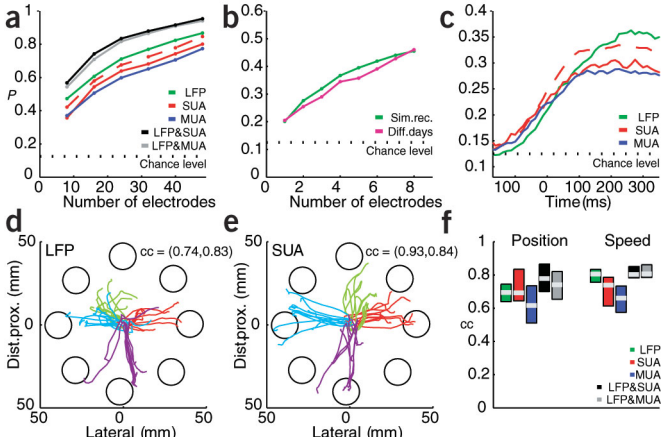

Figure 3 Decoding of movement target and trajectories from multielectrode recordings. (**a**) Increase in decoding power with number of recording electrodes. The accumulated decoding power of a subset of selected single units with stable firing rates across trials (solid lines) was only slightly lower than that of the whole recording set regardless of stability (dashed lines), although their number was much smaller (approximately 0.6 versus 1.6 units per electrode, on average). Standard deviations of decoding power of SUA (stable SUA), MUA and LFP were 0.15 (0.18), 0.13 and 0.11 for recordings from 1 day (8 electrodes) and decreased to 0.08 (0.11), 0.09 and 0.06 for the combined recordings from 6 days (48 electrodes). (**b**) Decoding power of simultaneously recorded LFPs (green) and multiple LFPs selected from different days (magenta). (**c**) Time-resolved decoding power of signals simultaneously recorded from eight electrodes, showing decoding power of signal epochs of 50-ms length immediately before the time indicated on the *x* axis. Line colors and styles as in **a**. (**d**) Example trajectories predicted from the activity of eight simultaneously recorded LFPs. Colors indicate movements to four different targets. The correlation coefficient (*cc*) between predicted and real trajectories is at upper right, separately for lateral and distal-proximal axis. (**e**) Example trajectories predicted from SUAs recorded from the same eight electrodes as LFPs in **d**. Colors and correlation coefficients as in **d**. (**f**) Accuracy of trajectory prediction for recordings from eight electrodes. Correlation coefficient between predicted and real trajectory was calculated for the time courses of position (left; correlation coefficients were first computed separately for *x* and *y* axes and then averaged) and of speed (right). Box plots show distribution of 20 correlation coefficients. Light gray lines, medians; box margins, lower and upper quartiles.

ries for both left- and right-handed movements from a set of ten different recording sessions from both monkeys (**Fig. 3f**). Notably, the average quality of prediction for LFPs was nearly as high as for SUAs and slightly higher than for MUAs. By combining the activity of LFPs and SUAs, or LFPs and MUAs, we obtained prediction accuracy superior to that provided by using either LFPs, SUAs or MUAs alone (**Fig. 3f**). We also predicted the time course of hand speed (length of the velocity vector) from the neuronal signals. Here, the average accuracy of LFPs was a little higher than that of SUAs or MUAs (**Fig. 3f**). The LFP signals also allowed us to determine which arm the monkey moved, with an average decoding power of more than 0.9 for eight simultaneously recorded LFPs.

In summary, we have shown that local field potentials in the motor cortex contain substantial information about arm movements. This demonstrates the feasibility of using the LFPs as an important additional signal for the reconstruction of purposeful arm movements. Thus, our findings are a significant first step for the development of new solutions for controlling neuronal motor prostheses[7–9]. Our results complement a recent study[10] showing that other features of the LFPs (gamma oscillations) in another brain area (parietal cortex) can be used to differentiate between two possible directions of saccadic eye movements. Based on our investigation, a further assessment of the use of the LFP for prosthetic applications can be achieved by experiments incorporating visual feedback of a brain-controlled actuator.

Note: Supplementary information is available on the Nature Neuroscience website.

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COMPETING INTERESTS STATEMENT
The authors declare that they have no competing financial interests.

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