Selective Movement Preparation Is Subserved by Selective Increases in Corticomuscular Gamma-Band Coherence

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Introduction

Neuronal oscillations entail rhythmic fluctuations in the excitability of groups of neurons. These excitability fluctuations have been hypothesized to mechanistically affect the efficiency of interactions between connected neuronal groups (Fries, 2005). In particular, when oscillations in two neuronal groups are mutually coordinated (i.e., when the oscillations are coherent), efficient interaction is likely to occur (Womelsdorf et al., 2007). Activated groups of neurons often show oscillatory activity in the gamma band (Gray et al., 1989; Fries et al., 2001). These oscillations are modulated during cognitive tasks and have therefore been implicated to subserve a functional role in cognition and behavior (Tallon-Baudry et al., 1997; Womelsdorf et al., 2006). Together, this led to the hypothesis that long-range gamma-band synchronization facilitates neuronal communication between behaviorally relevant neuronal groups.

The interpretation of estimates of interareal synchronization based on noninvasive recordings is difficult because of volume conduction effects, although modern source localization techniques alleviate this interpretational problem to a certain extent (Schoffelen and Gross, 2009). These techniques have yielded valuable insight into the recruitment of synchronized networks of brain regions (Gross et al., 2002; Jerbi et al., 2007). Here, we studied long-range neuronal interactions in the human corticospinal system. In particular, we measured brain activity in sensorimotor regions with magnetoencephalography (MEG) and motor unit activity with electromyography (EMG), thus bypassing the problem of volume conduction effects altogether. In previous work, we successfully used the corticospinal system as a model system to show that gamma-band synchronization leads to effective neuronal communication (Schoffelen et al., 2005). However, in that study, only one corticospinal connection was assessed. Therefore, we were not able to test a key prediction of the hypothesis. This prediction states that, in order for neuronal synchronization to be instrumental for neuronal communication, it should be selectively modulated between neuronal groups, depending on the behavioral relevance of these groups for the task at hand.

In this study, we used a bimanual motor task to test this selectivity prediction. We studied the neuronal interactions between sensorimotor regions in the brain and e motorneurons innervating respective contralateral forearm muscles. We selectively modulated the behavioral relevance of one of these corticospinal connections by presenting a response cue, indi-
cating the hand with which the subjects had to respond on an imperative go cue.

We hypothesized gamma-band corticomuscular coherence to be selectively increased in the behaviorally relevant corticospinal connection (i.e., between a motor effector and the corresponding contralateral sensorimotor cortex, when this motor effector was cued, compared with when it was not cued to respond). The results of our analysis support this hypothesis. We found selective changes in long-range synchronization, both spatially confined to the relevant corticospinal connection and spectrally confined to the gamma band. In contrast, analysis of local synchronization revealed a readiness effect in the beta band in sensorimotor cortices.

These findings suggest that long-range gamma-band synchronization is selectively increased in behaviorally relevant neuronal connections and thus subserves a functional role in cognition by linking the relevant nodes in a neuronal network.

**Materials and Methods**

**Subjects.** Eleven healthy subjects (five females; mean age, 24 years; range, 21–28; four left-handed) participated in the experiment. All subjects gave written informed consent according to the Declaration of Helsinki.

**Experimental paradigm.** The subjects were seated comfortably with their forearms in a relaxed position, supported by cushions on the armrests of the MEG chair. Figure 1A schematically shows the paradigm. At the beginning of a trial, subjects were asked to fixate on a small cueing stimulus that was projected on a screen in front of them. This cue consisted of a little white triangle pointing either to the left or to the right and was presented for 1 s. Subsequently, the cueing stimulus was replaced by a white fixation dot, and the subjects had to extend both their wrists against two compliant levers connected to two force transducers and to keep the measured force within a specified window, which was defined between 1.1 and 1.5 N. The lower boundary of the force window was selected based on visual inspection of EMG traces obtained during a few pilot sessions, in which clear tonic EMG activity was observed once the wrist extension was sufficient to cross this boundary. Subjects received feedback about the exerted force by the color of two dots, presented to either side of the fixation dot, which turned from red to green as soon as the required force level at the respective side was reached. This force calibration interval ended when the force exerted by both wrists was within the prespecified window for >1 s. The disappearance of the colored dots marked the beginning of a 1 s baseline interval, in which only the fixation dot was presented to the subject. The fixation dot was continuously present on the screen in the time interval between the offset of the cueing stimulus and the onset of the visual stimulus. The stimulus was a concentrically contracting sinusoidal grating (diameter, 5 deg; spatial frequency, 2 cycles/deg; contrast, 100%; velocity, 0.8 deg/s). The subjects’ task was to react as fast as possible to a speed change of the stimulus that could occur at any moment between 150 and 3000 ms after stimulus onset. Subjects had to respond by increasing the extension of the left or right wrist, corresponding with the previously cued direction. Importantly, the subjects had to maintain a constant extension of the noncued wrist until the end of the response interval.

A trial was considered successful if (1) the subject responded with the cued wrist within 600 ms after the speed change of the stimulus; (2) the applied force was within the specified window until the speed change of the stimulus for the cued side, and until the end of the response interval for the noncued side. As soon as the applied force on one of the levers drifted out of the specified window before the speed change, the trial was aborted. To maximize the amount of trials suitable for analysis, we used an increasing hazard rate. This means that the instantaneous probability of the stimulus’ speed change increased with time. For more information, see Schoffelen et al. (2005). Approximately 10% of the trials were catch trials, in which no speed change occurred and which ended after 3 s of visual stimulation.

Each subject performed a sequence of 300 trials, divided into six blocks. The response cues were randomly pointing to the right or to the
left. The subjects received feedback about their responses. There was a 1 s interval between the end of the response feedback and the onset of the cue stimulus of the following trial, allowing for eye blinks.

Before the experimental recording session, subjects performed two blocks of unimanual contractions. These blocks consisted of 20 trials of 8 s each, in which subjects were asked to extend either their right or left wrist while fixating on a colored fixation cross. The color changed from red to green as soon as the force applied to the lever was within the specified window between 1.1 and 1.5 N. The data in these blocks were used to select sensors for a region of interest analysis.

Data acquisition. The force applied to the levers was measured by strain gauges. Apart from being digitized and recorded in parallel with the electrophysiological data, the force signals were also fed into a second, separate A/D converter, and a software window discriminator was implemented to detect whether the force was within the specified window.

MEG was acquired with a 151-sensor axial gradiometer system (Omega 2000 whole head MEG system; CTF Systems). Bipolar surface EMG was recorded from the left and right musculus extensor carpi radialis longus using two Ag/AgCl electrodes, which were placed over the muscles with a 3 cm interelectrode distance, with the proximal electrodes placed 4 cm distal to the external epicondyle of the humerus. The electrode data were filtered at 300 Hz and digitized at 1200 Hz. Before and after the MEG recording, the subject’s head position relative to the gradiometer array was determined using coils positioned at the subject’s nasion and at the bilateral external auditory meatus.

EMG/MEG preprocessing. All analyses were done with FieldTrip, an open-source Matlab toolbox for neurophysiological data analysis (Oostenveld et al., 2011). Only data segments between the start of a trial and the speed change of the stimulus were analyzed. Segments that were contaminated by eye movements, muscle activity, or jump artifacts in the superconducting quantum interference devices were discarded. The power line interference was removed by estimating and subtracting the 50, 100, and 150 Hz components in the MEG data, using a discrete Fourier transform on 5 s data segments including the artifact-free data segments of interest.

To estimate the EMG amplitude, we high-pass filtered the raw EMG at 10 Hz (Kühler et al., 2000) and computed the absolute value of the Hilbert transform of the filtered signals. This procedure gives a time-dependent estimate of the total power of the signal generated by the muscular units and hence provides information with respect to the timing of spiking activity of the motorneurons. This is exactly the information that is relevant for the estimation of corticomuscular coherence (Halliday and Farmer, 2010). Taking the absolute value of the Hilbert transform is a nondestructive operation, which is closely related to the original signals and may be considered in the analysis of the instantaneous power spectrum of signal x. Single segment power spectra and cross-spectra were obtained by averaging across the tapers.

Coherence was computed according to the following:

\[ \text{Coh}_{xy} = \frac{|S_{xy}|}{\sqrt{S_{xx} \times S_{yy}}} \]

where \( S_{xy} \) denotes the mean across segments. Power spectra were averaged across segments and log-transformed. The log transformation was applied to stabilize the variance to facilitate the stratification (see below).

Statistical analysis: sensor level. We compared different sets of data segments and computed t spectra (Bauer et al., 2006; Lange et al., 2011) (for the comparison of power, to account for differences in absolute power between the subjects because of variability in the subject’s exact position with respect to the sensor array) and z spectra (Bokil et al., 2007; Maris et al., 2007) (for the comparison of coherence, to account for the differences in the bias, introduced by different numbers of data segments across subjects), for each individual subject.

Unpaired t statistics were computed for each signal and each frequency bin according to the following:

\[ T(f) = \frac{(x_1 - x_2)}{\sqrt{1/(n_1 + 1/n_2) \times (1/s_1^2 + 1/n_1 + 1/n_2 - 2/n_1^n_2)}} \]

where \( x_1 \) denotes the average power in condition a, \( n_a \) is the number of observations, and \( s_a^2 \) is the variance of the power in condition a.

Z spectra for the difference in coherence between MEG-EMG channel pairs and each frequency bin were computed according to the following:

\[ Z(f) = \frac{(1/n_1 \times (x_1 - x_2))}{\sqrt{1/(2nt_1 - 2) + 1/(2nt_2 - 2)}} \]

where \( x_c \) denotes the coherence in condition a, \( nt_a \) is the numbers of tapers applied in condition a, and \( \text{Tanh}^{-1} \) is the inverse hyperbolic tangent.

For the group statistics, we pooled the individual subjects’ t and z spectra. We used these pooled t or z values as first-level test statistic, but
based the statistical inference on a nonparametric permutation test (Nichols and Holmes, 2002; Maris and Oostenveld, 2007). In the case of the \( r \) and \( z \) spectra, exchanging the conditions is equivalent to swapping the sign of the values in the spectrum. By recomputing the average spectrum, after having swapped the sign of the individual spectra in a random subset of subjects, an observation under the null hypothesis is obtained. A reference distribution is generated by repeating this step multiple times and the likelihood of the observed data is computed by comparing it with the reference distribution. To control the false alarm rate, we applied a clustering algorithm (Maris and Oostenveld, 2007). This was done in the following way. For each channel and frequency bin, we computed two critical \( t \) values (in the case of coherence, \( z \) values) by comparing the observed value with the reference distribution obtained at that channel frequency bin. The critical values were taken such that 2.5% of the highest values obtained by permuting the single subjects’ observations exceeded the positive critical value, and 2.5% of the lowest values were smaller than the negative critical value (this corresponds to a two-sided \( p \) value of 0.05, uncorrected). Subsequently, the observed and permuted data were thresholded at these critical values and spatiotemporal clusters were formed consisting of threshold exceeding channel frequency points neighboring in frequency space and in physical space. For each cluster, a second-level test statistic was computed by summing the suprathreshold (or infrathreshold) \( r \) values (\( z \) values). The reference distributions of the cluster-based test statistic were obtained by taking the most extreme value of the test statistic in each permutation. The cluster-based test statistics in the observed data were tested against these reference distributions to obtain a corrected \( p \) value for each cluster.

**Sensors of interest analysis of corticomuscular coherence.** Brain signals that are coherent to the EMG are typically picked up at sensors overlying contralateral motor regions. We therefore constrained our initial analysis of corticomuscular coherence to two subsets of sensors. We selected two subsets of 10 MEG sensors overlying both motor regions. These sensors were selected from the spatial topography of the corticomuscular coherence based on the preexperiment unimanual contraction data. Artifact-free data segments were cut into 0.4 s nonoverlapping segments, and corticomuscular coherence spectra were computed with a spectral smoothing of \( \pm 5 \) Hz. For each subject and frequency bin, we applied a spatial normalization step to achieve an equal weighing across the subjects. For a given frequency bin, we subtracted the mean coherence value across all MEG sensors and divided the resulting value by the SD across the sensors. Subsequently, we averaged the spatially standardized coherence spectra across the subjects and frequency bins. For each of the unimanual contraction conditions, we selected the 10 MEG sensors that displayed the highest standardized coherence with the EMG. \( Z \) spectra of the difference in corticomuscular coherence were analyzed in two runs, using different multitaper settings. For frequencies <30 Hz, we used a spectral smoothing of \( \pm 5 \) Hz, and for frequencies >30 Hz, we used a spectral smoothing of \( \pm 12.5 \) Hz. For each subject and region of interest, the spectra were averaged across the 10 MEG sensors, and the regions of interest were combined for each subject, according to the following formula:

\[
Z_{\text{pooled}} = \frac{Z_{\text{left}} - Z_{\text{right}}}{\sqrt{2}}.
\]

The resulting spectra were pooled across subjects, and a nonparametric permutation test was performed.

**Source analysis.** For the analysis of the neuronal sources, we used a beamformer method, DICS (Dynamical Imaging of Coherent Sources) (Gross et al., 2001). Each subject’s brain volume was divided into a regular grid. The grid positions were obtained by a linear transformation of the grid positions in a canonical 8 mm grid. This canonical grid was based on a template brain (Montreal Neurological Institute), and for each subject, we computed the linear transformation optimally aligning the subject’s brain volume to the template brain, using SPM2 (http://www.fil.ion.ucl.ac.uk/spm). We applied the inverse of this linear transformation to the grid positions of the canonical grid to obtain subject-specific dipole grids. This procedure facilitates the group analysis, because no spatial interpolation of the volumes of reconstructed activity is required.

For each grid position, we constructed spatial filters. These filters have the property that they optimally pass activity from the location of interest, while other activity, which is present in the data, is suppressed. The filter weights are calculated with the following formula:

\[
w(r, f) = (L'(r)[C(f) + \lambda I]^{-1}L(r))^{-1}L'(r)[C(f) + \lambda I]^{-1},
\]

where \( L(r) \) is the forward model for the location \( r \) of the lead field matrix, \( C(f) \) is the cross-spectral density (CSD) matrix between all MEG signal pairs at the frequency \( f \), \( \lambda \) is a regularization parameter, and \( I \) is the identity matrix.

To compute the lead field matrices, we used a single-channel volume conduction model, based on the shape of the inside of the skull (Nolte, 2003). The inside of the skull was derived from each individual subject’s structural magnetic resonance image, which was spatially aligned to the MEG sensors. Despite the fact that, in this volume conduction model, there is no truly magnetically silent direction, we excluded the most silent direction from the lead fields, since this direction potentially picks up a lot of noise.

To analyze the location of the sources accounting for the significant sensor level effects, we computed the CSD matrix between all MEG sensor pairs from the Fourier transforms of the tapered data epochs at the frequencies of interest. As we had found significant sensor-level effects in the beta and gamma bands, those two bands were subjected to source level analysis. For each subject, and within each of the frequency bands, we identified the frequency bin that yielded the most extreme \( r \) value (for power comparisons), or \( z \) value (for coherence comparisons), averaged across sensors. Spatial filters were constructed for each grid location, based on the identified frequency bin, and the Fourier transforms of the tapered data epochs were projected through the spatial filters, using the following formula:

\[
d(r, f) = w(r, f)F(f),
\]

where \( F \) is an \( N \times M \) matrix, containing the Fourier coefficients at frequency \( f \), of \( N \) channels and \( M \) single tapered data epochs. The matrix \( d \) represents the Fourier coefficients in three orthogonal directions (3 \( \times \) \( M \) matrix) for a dipole at location \( r \). We estimated the orientation in which the power of the dipole was maximal, by singular value decomposition of the real part of the dipole-level cross-spectral and projected the Fourier coefficients on this direction, yielding a 1 \( \times \) \( M \) fast Fourier transform vector. This vector represents the Fourier coefficients for the dipole with an orientation in the direction of maximal power. \( T \) statistics (for the comparison of power) and \( z \) statistics (for the comparison of coherence) at each voxel were subsequently computed in the same way as it was computed at the sensor level.

The individual functional statistical volumes were combined across subjects. We used a nonparametric permutation test to assess significance and correct for multiple comparisons in the same way as described for the sensor level statistical analysis (Nichols and Holmes, 2002; Maris and Oostenveld, 2007).

**Stratification.** Our experimental procedures aimed at keeping the motor output constant while modulating motor preparation as a function of time (visual stimulation vs prestimulus period) or effector side (right vs left wrist cued). However, the motor output was not under direct control of the experimenter and the motor output produced by the subjects could not be constrained within an arbitrarily narrow window (Fig. 1B). To minimize effects of small changes in motor output, we therefore performed a post hoc stratification of the data based on the EMG amplitudes. The goal of the stratification was to obtain, from each of the two conditions, a subset of trials such that the distribution of EMG power values across the trials constituting the subsets was identical for each of the two conditions. This approach has been adjusted from Roelfsema et al. (1998) and a similar strategy has been successfully applied to control for EMG fluctuations (Schepfelen et al., 2005). The following procedure was applied to the single subject data and for each frequency bin separately.

We binned the observations in each condition according to the \( \log_{10} \) transformed power estimates of both EMG signals. The bin centers were obtained for each EMG signal separately by dividing the range of all EMG power values into eight equally spaced bins. In this way, each of the
between the left EMG and the set of right hemisphere sensors, for the connection constructed from data obtained during a preexperimental recording with unimanual contractions, for the left wrist extension (A, C) and the right wrist extension (B, D). Coherence spectra were spatially z-scored before averaging across subjects. Selected sensors of interest are shown as white circles on the topographies.

Figure 2. Selection of sensors of interest for corticomuscular coherence analysis. Spatial topographies (A, B) and spectral signatures (C, D) of corticomuscular coherence obtained during a preexperiment recording with unimanual contractions, for the left wrist extension (A, C) and the right wrist extension (B, D). Coherence spectra were spatially z-scored before averaging across subjects. Selected sensors of interest are shown as white circles on the topographies.

Results
On average, an experimental session yielded 260 (SEM, 14) 400 ms artifact-free data segments for condition left, and 269 (SEM, 10) data segments for condition right. The stratification procedure, in which we aimed at equalizing the motor output across the two conditions, yielded on average 202 (SEM, 9) data segments for both conditions. In addition, we analyzed the time segments before the onset of the visual stimulus. An experimental session delivered on average 231 (SEM, 7) data segments in the baseline interval for condition left, and 228 (SEM, 5) for condition right. Figure 1B illustrates the motor behavior of an example subject for all trials in condition left. Single trials have been time-locked to different events to illustrate the effects of these key events on motor output. Note that, for some traces, the three time axes partially overlap because of variability in the duration of the different temporal intervals.

Selection of region of interest sensors
Figure 2, A and B, shows spatial topographies of the corticomuscular coherence between the left EMG and all MEG sensors (Fig. 2A), and between the right EMG and all MEG sensors (Fig. 2B), spatially z-scored and averaged across subjects and the frequency range between 10 and 40 Hz. From these topographies, constructed from data obtained during a preexperimental recording session, two sets of 10 MEG sensors were selected for the region of interest analysis for corticomuscular coherence (white circles). Figure 2, C and D, shows the spatially z-scored coherence spectra averaged across the selected 10 MEG sensors, for the connection between the left EMG and the set of right hemisphere sensors (Fig. 2C), and for the connection between the right EMG and the set of left hemisphere sensors (Fig. 2D).

Condition left versus condition right during stimulus interval: coherence
Figure 3 shows the effect of the response cue on corticomuscular coherence during the stimulus interval, for a single representative subject. Figure 3, A and C, shows the coherence for the corticospinal connection to the left arm muscle, for the response left condition (Fig. 3A) and the cued condition (Fig. 3C). Figure 3, B and D, shows the coherence for the corticospinal connection to the right arm muscle, for the cued condition (Fig. 3B) and the uncued condition (Fig. 3D). The thick black lines represent the situation in which the respective corticospinal connection was cued for the response. E, Z-transformed coherence difference between the cued and uncued conditions, for the left response side (gray line) and the right response side (black line).

Figure 3. Spatially specific readiness effect on corticomuscular coherence in a representative single subject. Raw coherence spectra are shown for the two corticospinal connections ([right primary motor cortex (M1) to left arm muscle (A, C) and left M1 to right arm muscle (B, D)] in the two response conditions (response left (A, B) and response right (C, D)). The thick black lines represent the situation in which the respective corticospinal connection was cued for the response. E, Z-transformed coherence difference between the cued and uncued conditions, for the left response side (gray line) and the right response side (black line).
but did not reach significance on the other side ($p < 0.1$, nonparametric permutation test, corrected). Figure 4B shows the readiness effect pooled across hemispheres. There is a significant increase in corticocortical coherence in the frequency band between 40 and 45 Hz ($p < 0.05$, nonparametric permutation test, corrected). We did not find a significant effect of handedness on the readiness effect (results not shown). Figure 4C shows for each of the corticospinal connections the corticocortical coherence averaged between 35 and 52 Hz for the cued versus the uncued conditions (C). Source analysis results of the readiness effect on gamma-band corticocortical coherence, showing the statistically significant cluster (D).

We further tested the spatial specificity of this effect, and performed a beamformer analysis to analyze which regions in the brain showed a significant readiness effect (Fig. 4D). To this end, we computed $Z$-transformed coherence differences in gamma-band corticocortical coherence between each of the EMGs and the brain, when the EMG was on the cued side versus when it was not on the cued side. For each subject, the $Z$ volume of coherence between the right EMG and the brain was subsequently mirrored in the sagittal plane and pooled with the $Z$ volume of coherence between the left EMG and the brain. Figure 4D shows that the significant increase in gamma-band corticocortical coherence is confined to cortical regions in the vicinity of primary motor cortex contralateral to the cue side.

**Condition left versus condition right during stimulus interval: power**

To investigate whether the changes found in corticocortical coherence could be confounded by changes in oscillatory brain activity, we computed $T$ spectra of the power difference between condition left and condition right. Statistical analysis revealed two significant clusters of sensors, overlaying left and right sensorimotor cortices. The frequency range contributing to the significant effect was confined to the beta band (17.5–25 Hz in the left hemisphere cluster, and 15–27.5 Hz in the right hemisphere cluster), and the sign of the effect indicated that this beta-band activity is decreased in sensorimotor cortex contralateral to the cued response hand compared with the ipsilateral cortex. Figure 5A shows the $t$ spectra, averaged across the sensors contributing to each of the clusters, which are shown in the topography (red line: cluster in left hemisphere, $p < 0.05$, nonparametric permutation test, corrected; blue line: cluster in right hemisphere, $p < 0.05$, nonparametric permutation test, corrected). Analysis of the neuronal sources accounting for this finding revealed bilateral sensorimotor cortices. Figure 5B shows the clusters of significant voxels projected onto a template brain ($p < 0.05$, nonparametric permutation test, corrected). We did not observe condition-specific modulations of cortical oscillatory activity in the gamma-frequency band.

**Prestimulus versus stimulus interval: power**

To further investigate the readiness effect on cortical beta-band oscillatory activity, we compared the condition-specific stimulus intervals with their respective condition-specific prestimulus intervals. The onset of the visual stimulus elicited a broadband decrease in oscillatory activity in almost all MEG sensors (data not shown), with a frequency between 8 and 30 Hz. Statistical analysis revealed a significant cluster of sensors consisting of almost all MEG sensors in each condition ($p < 0.0005$, corrected). This broadband decrease appeared to consist of several separate spatio-spectral minima, in the alpha- and beta-frequency bands. The topography of the decrease in beta-band activity was condition specific and involved sensors overlaying sensorimotor regions. We therefore focused on the beta band in the following. Figure 5C–F show the difference in beta-band activity between
the prestimulus interval and the stimulus interval, for condition 
left (Fig. 5C,E) and condition right (Fig. 5D,F). Onset of the 
visual stimulus led to a widespread decrease in beta-band activity 
(16–30 Hz), with a minimum over central MEG sensors. This 
decrease was lateralized for the conditions, being stronger in the 
hemisphere that was cued to respond. Figure 5C shows the topo-
graphical distribution for the beta-band decrease for condition 
left with the average spectrum of the eight sensors showing the 
strongest decrease in this frequency band. Figure 5D shows the 
same effect, but then for condition right. Next to the lateralized 
beta-band decrease in central MEG sensors, the topographies 
show a clear decrease in beta-band oscillatory activity in posteri-
or MEG sensors. Source reconstruction of the stimulus-
induced beta decrease revealed significant effects in motor 
regions, contralateral to the cued response side, and in visual 
regions (Fig. 5E,F).

Discussion

In this study, we used the corticospinal connection as a model 
connection to test for selectivity of cognitive modulations of 
long-range gamma band synchronization. Subjects had to main-
tain a bilateral wrist extension in anticipation of an imperative go 
cue. We aimed at selectively manipulating the subjects’ readiness 
to respond with one of their hands, by providing a directional cue 
before each trial, indicating the side of the required response. We 
analyzed corticomuscular coherence during the interval in which 
the isometric contractions were maintained, and we observed 
that low gamma-band (40–47 Hz) corticomuscular coherence 
between the nodes of the cued long-range connection was selectivity increased. Also, we found that the onset of the vi-
Corticomuscular coherence has been found to be not solely mediated by the efferent connection between cortical regions and the spinal cord (Kilner et al., 2004; Riddle and Baker, 2005; Patino et al., 2008), and studies of the direction of information flow between the cortex and the spinal cord suggest a bidirectional flow of information (Mima et al., 2001; Witham et al., 2010) during simple motor behavior. However, future work is needed to address the question of directionality in our data, possibly using nonlinear analysis methods (Jin et al., 2010).

Another interesting question is whether the implications of our finding can be generalized to long-range corticocortical in-
teractions as well. In fact, several studies reported on long-range corticocortical gamma-band synchronization (Saalmann et al., 2007; Gregoriou et al., 2009). These studies used microelectrode recordings in awake monkeys to investigate connections between neurons with overlapping receptive fields in lateral intraparietal cortex (area LIP) and area MT (Saalmann et al., 2007), and connections between the frontal eye fields (FEFs) and area V4 (Gregoriou et al., 2009). Using a visual attention paradigm, it was shown that spatial attention to a location inside the receptive fields of the recorded neurons led to an increase in gamma-band synchronization. Yet other studies report oscillations in lower frequency bands (beta band) to be synchronized between area LIP and FEFs (Buschman and Miller, 2007), and between dorsal premotor cortex and the parietal reach region (Pesaran et al., 2008). In our study, the frequency band showing a significant effect across the population is a relatively narrow band and low in

neural activity in the motor system (Murthy and Fetz, 1996; Baker et al., 2001; Courtemanche et al., 2002; Brovelli et al., 2004; Jensen et al., 2005). These oscillations have been shown to relate to movement preparation (Crone et al., 1998; Pfurtscheller and Lopes da Silva, 1999; Neuper and Pfurtscheller, 2001) and response selection (Kaiser et al., 2001; Doyle et al., 2005). In the present study, we found cue-specific differences in the amplitude of stimulus-
induced local beta-band desynchronization in sensorimotor cor-
tices. These findings are in line with converging evidence that 
beta-band oscillations in the motor system favor the existing mo-
tor state (Chen et al., 1998; Gilbertson et al., 2005). Yet we did not find an effect of the response cue on long-range beta-band syn-
chronization. Corticomuscular beta-band coherence is a robust 
phenomenon that has been extensively studied (Conway et al., 
1995; Gross et al., 2000; Baker et al., 2003; Pohja et al., 2005; 
Witham et al., 2010) and that has been shown to vary with task 
requirements (Kilner et al., 2000) and performance (Kristeva et al., 2007). In a recent study, van Wijk et al. (2009) used a cued 
choice response task to study corticocortical phase synchroni-
ization. They reported a relative increase in beta-band phase 
synchronization during the time the subject was not cued, while 
at the same time already performing the isometric muscle con-
tractions. Conversely, the unpredictable go cue in our exper-
iment may have engaged the motor system in such a way that it 
enabled us to observe long-range gamma-band synchronization 
(Schoffelen et al., 2005).
frequency compared with the cortical band-limited effects in the gamma-frequency range typically reported in visual, somatosensory, or motor activation studies (Bauer et al., 2006; Hoogenboom et al., 2006; Cheyne et al., 2008). The specificity of the frequency band may thus be related to the experimental task and (the spatial extent of) the activated network.

In conclusion, we found that a directional response cue selectively increases long-range gamma-band synchronization in the neural network that needs to be established for a specific cognitive task. This finding supports the hypothesis that gamma-band synchronization has a role in shaping cognition by allowing for efficient neural communication between relevant nodes of a neural network.

References


