Decoding and cortical source localization for intended movement direction with MEG

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Figure Legends

Figure 1. The center-out task with accompanying speed profile during overt wrist movement. The subject controls the 2-D cursor position using wrist movements. The cursor needs to go to the center and stay there for a hold period until the peripheral target appears. Then the cursor moves to the target and stays there for another hold period to complete the trial successfully. The target changes color when hit by the cursor, and disappears when the holding period has finished. There was a 1-second interval between trials. The bottom trace shows the speed profile of the cursor from a representative trial, and the dotted lines delimit the pre-movement/planning period within which a time window was identified and used for decoding the intended movement direction for overt movement trials.

Figure 2. Effects of signal smoothing (*A*) and MEG signal modulation by movement directions (*B*, *C*) for one MEG sensor (gradiometer) above the contralateral sensorimotor area. Data were collected from Subject S1. *A*: Raw MEG trace (the solid gray line) overlaid by its smoothed version (the dashed black line) during a single overt trial. Time 0 represents movement onset. *B*: Each trace represents the average of smoothed signals of all repetitions for each movement direction for one subject. Data were aligned to movement onset (Time 0, the vertical dashed line). The vertical solid line indicates average target onset time. The four traces were normalized to the maximum of absolute amplitude. There is a clear downward deflection of MEG signals about 100 to 200 ms before movement onset. The amplitude of this downward deflection varies across different movement directions. Furthermore, the gray area indicates the average time window used for sensor-space decoding analysis (time of interest) across all subjects. *C*: Same as *B*, except that the data were from imagined movement and aligned to target onset (Time 0, the vertical solid line). The vertical dashed line indicates average movement onset time. Position of this MEG sensor is shown in the inset, and the gray area represents the whole-head helmet. F: Front, L: Left, R: Right.

Figure 3. Modulation of MEG responses examined in 2-D space using the first two components of LDA. The LDA analysis projects activities of all MEG sensors above the sensorimotor area (sensor positions shown in the inset) into a low-dimensional space, where modulation of MEG responses by intended movement direction can be easily

visualized. The figure shows a 2-D projection of single-trial MEG responses averaged over -200 to 0 ms relative to movement onset (Subject S1). They clearly form four distinct clusters corresponding to four different intended movement directions. The green plus signs, black squares, blue circles, and red triangles represent single-trial MEG responses for movement in the up, down, left, and right directions.

Figure 4. Temporal dynamics of decoding accuracy during center-out movement. Decoding accuracies were calculated every 10 ms using MEG data within that 10-ms interval. *A*: Overt non-delayed. *B*: Imagined non-delayed. *C*: Overt delayed. *D*: Imagined delayed. For each plot, the thin gray lines represent decoding accuracies for individual subjects, and the thick black line represent the decoding accuracy averaged over all subjects. Time 0 corresponds to movement onset for overt movement and target onset for imagined movement. For movement with delay (*C*, *D*), average delay periods were marked with double-arrow lines.

Figure 5. Localization of active cortical areas for overt (*A,C*) and imagined (*B,D*) movements. MCE was used to localize active cortical sources during the time period used for decoding analysis in Subject S1. Data were averaged over all repetitions for leftward movement. *A,C*: Cortical activity from -200 to 0 ms relative to the onset of overt movement. *B,D*: Cortical activity from 300 to 420 ms relative to target onset for imagined movement. The contralateral motor cortical area shows strong activation. In addition, there is a certain degree of visual and ipsilateral motor cortical activity.

Figure 6. Localization of cortical sources modulated by intended movement direction. Combination of MCE with bootstrapping created multiple estimates of cortical activity for each movement direction, and a likelihood ratio test was used to examine whether a cortical source (a triangular surface patch on brain surface plots) was modulated by intended movement direction. Surface patch color represents the significance of modulation, as measured by the chi-square statistic calculated within the time period used for decoding analysis in Subject S1. Hotter (red) color indicates stronger modulation. *A*, *C*: Left/contra and right/ipsilateral hemisphere activity during overt movement. *B*, *D*: Left/contra and right/ipsilateral hemisphere activity during imagined movement. *p-values* of 10^{-3} and 10^{-5} correspond to chi-square statistics of 16.2 and 25.9, respectively. The contralateral motor cortical area is significantly modulated by intended movement direction. In addition, the visual cortical areas and the left inferior

frontal gyrus also show modulation.

Figure 7. Temporal dynamics of cortical activity modulation by movement direction. The source-space MANOVA test was performed in 10-ms intervals to characterize movement modulation of cortical activity, and the resulting F-statistics were plotted as a function of time for overt (*A*) and imagined (*B*) movements. A *p-value* of 10^{-5} approximately corresponds to an F-statistic of 25.3. Thin gray lines represent the F-statistics for individual subjects (non-delay task), and the thick black lines represent the average over all subjects. Cortical activity becomes highly modulated right before movement onset for overt movement and 300 to 400 ms after target onset for imagined movement.

Supplemental Figure 1. EMG activity for both overt and imagined movements. EMG activity shown in this figure is the total muscle activity summed over wrist flexor and extensor muscles (flexor carpi radialis and extensor carpi radialis). *A & B*: These two plots show EMG activity and cursor movement for overt and imagined movement, respectively (Subject S4, rightward movement, Time 0 is target onset). EMG signals are rectified and averaged over all trials (blue curves), and the baseline EMG activity during rest is removed. Cursor movement (displacement from the center target) is also averaged over all trials (red curves). EMG and cursor movement for overt and imagined movement are normalized to their respective maximum value during overt movement. Onsets of EMG activity and cursor movement are marked with black arrows in *A*. *C*: EMG activity within the time window used for decoding movement direction (computed over all repetitions for each subject). Percentage changes from baseline were calculated for EMG activity and averaged for all trials. Error bars represent standard deviation. For overt movement, an increase in EMG activity will precede actual cursor movement, as governed by dynamics of limb movement. Temporally, EMG activity significantly overlaps with cortical activity representing intended movement as shown by previous animal studies (Moran and Schwartz 1999). Because we used time windows immediately before overt movement onset to decode intended movement direction, it is inevitable that there is an increase in EMG activity within those time windows as shown in *A* and *C*. Nevertheless, our data showed that there is no increase in EMG activity during imagined movement (*B* and *C*), which suggests that paralyzed patients could generate cortical activity encoding intended movement direction for brain-machine interface applications.

Supplemental Figure 2. Temporal dynamics of MEG sensor activity modulation by movement direction. The sensor-space MANOVA test was performed in 10-ms intervals to characterize movement modulation of magnetic activity, and the resulting F-statistics were plotted as a function of time for overt non-delayed (A), imagined non-delayed (B), overt delayed (C), and imagined delayed (D). For each plot, the thin gray lines represent the F-statistics for individual subjects, and the thick black lines represent F-statistics averaged over all subjects. Time 0 corresponds to movement onset for overt movement and target onset for imagined movement. Note that the MANOVA curves were used to find the optimal decoding window for the paper, so it is natural that the shape of the traces above are similar to the decoding accuracies shown in Figure 4.

Supplemental Figure 3. Comparison between cortical areas that are active and cortical areas that are tuned to intended movement direction. *A & B*: This is duplicated from Figure 5, which shows cortical areas that are active during overt and imagined movement, respectively. Color represents cortical source current amplitude, and the unit of the color bar is nAm. Hot color (yellow) indicates active areas. *C & D*: This is duplicated from Figure 6, which shows cortical areas that are tuned to movement directions during overt and imagined movement, respectively. Color represents F-statistic values. Hot color (yellow) indicates that activity of certain cortical area is significantly modulated by intended movement direction.

Supplemental Figure 4. Number of principal components that explain 99% of the variability in the sources. For each plot, the thin gray lines represent the number of components for individual subjects (non-delayed task), and the thick black lines represent the average over all subjects. Time 0 corresponds to movement onset for overt movement (A) and target onset for imagined movement (B). Note that the number of components needed to account for 99% of the variability in the sources reaches its minimum at the time of the movement for the overt task, and approximately at the time when the cursor starts moving in the imagined task.

Table Legends

Table 1. Summary of single-trial decoding accuracies (%) across all 9 subjects for overt and imagined movements. Subjects S1-S5 performed the non-delayed center-out task, and Subjects S6-S9 performed the delayed center-out task. MEG sensors above the sensorimotor area were used. The time window for decoding analysis was determined based on the sensor-space MANOVA analysis. MEG signals within that time window were averaged. Intended movement direction was decoded using a Bayesian classifier with leave-one-out cross validation. The chance level

is 25%. The average decoding accuracies across all subjects are 67% and 62.5% for overt and imagined movement, respectively.

Supplemental Table 1. Decoding accuracy (%) relative to movement onset. Decoding results for target direction in the overt task for subjects without delay. The decoding window was chosen such that it always preceded movement onset by different time periods, which have been shown to be acceptable values for the delay between cortical activity and the start of movement (Moran and Schwartz, 1999). The length of the decoding window was 100ms for every subject based on the peak of the MANOVA curve (see Methods section). Chance accuracy is 25%. Accuracies are still above chance level even when decoding with data 250ms before movement onset. By doing that, the period containing EMG activity is not used for decoding, but it also ignores any motor cortical activity that occurs concurrently to that EMG activity, which decreases the results compared to what was shown in the paper. For ease of comparison, the third row shows decoding accuracies using decoding windows right before movement onset (copied from Table 1 overt movement condition in the main text).