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Supplementary Materials for

The somatosensory cortex receives information about motor output

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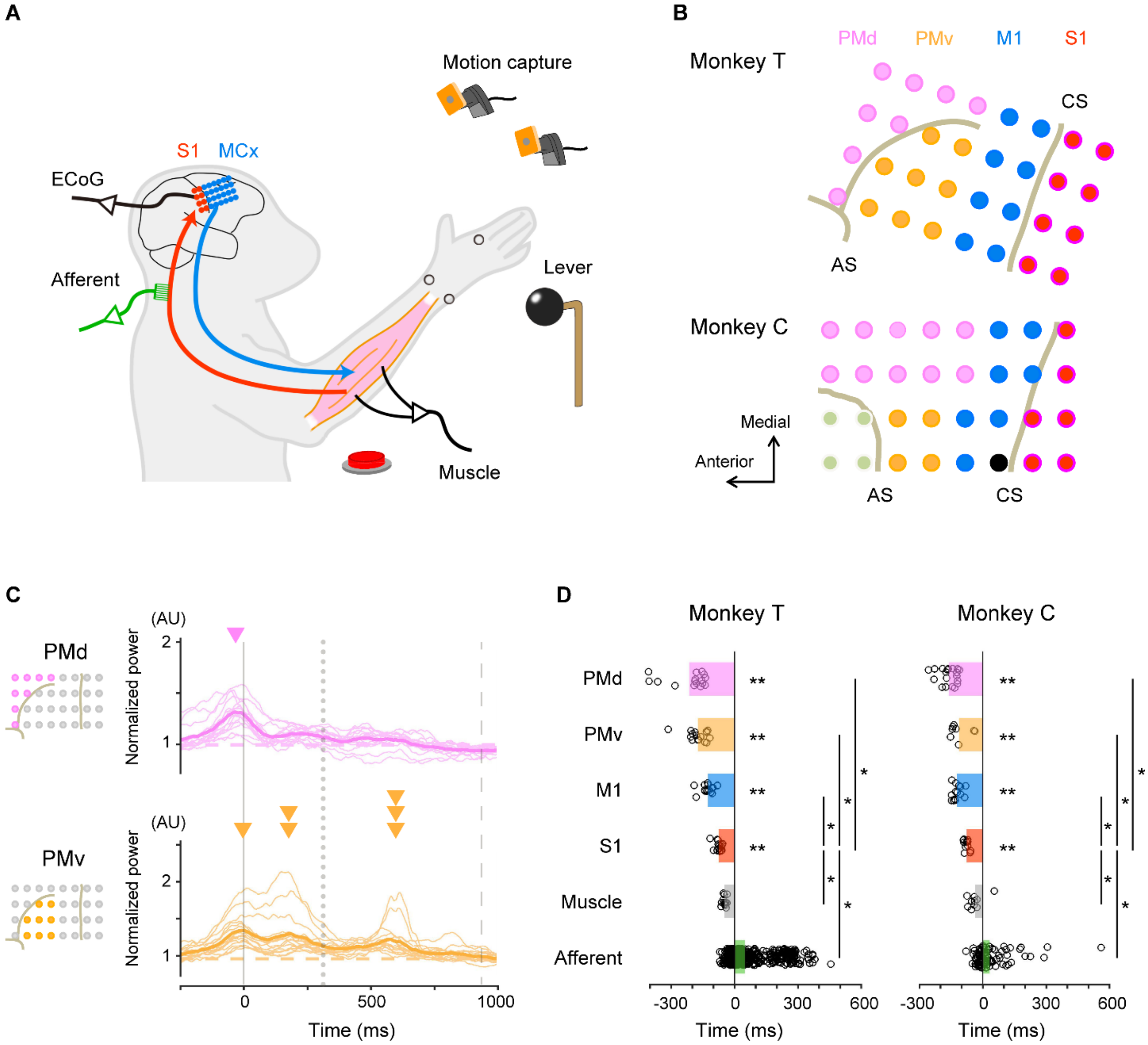

A
Motion capture
S1
MCx
ECoG
Afferent
Lever
Muscle
B
PMd
PMv
M1
S1
Monkey T
CS
AS
Monkey C
Medial
Anterior
AS
CS
C
PMd
(AU)
2
1
Normalized power
PMv
(AU)
2
1
Normalized power
0
500
1000
Time (ms)
D
Monkey T
Monkey C
PMd
PMv
M1
S1
Muscle
Afferent
-300
0
300
600
Time (ms)
-300
0
300
600
Time (ms)

Fig. S1. Closed-loop sensory-motor circuits were simultaneously recorded from monkeys. (**A**) Cortical activity (ECoG), neural ensemble activity in peripheral afferents, forelimb muscle activities, and position of forelimb joints were simultaneously recorded from monkeys performing a reach-to-grasp task. Open circles on the hand and wrist represent some of the reflective markers for recording angular position of forelimb joints. MCx; motor cortex, S1; primary somatosensory cortex. (**B**) Electrode placement for ECoG recording from the motor and somatosensory cortices in Monkey T and C. AS; anterior sulcus, CS; central sulcus, M1; primary motor cortex, PMd; dorsal premotor cortex, PMv; ventral premotor cortex. (**C**) Modulations of activity of premotor cortex in Monkey T aligned to movement onset. *Top and bottom*; modulations of high-gamma activity in PMd and PMv. Thin lines represent the activity recorded from each electrode, and thick lines their respective averages. The vertical solid, dotted, and dashed lines represent times of the onset of movement, pulling the lever, and the end of the movement, respectively. Arrowheads represent the peak times of respective activities. (**D**) Onset times of activities (Student's unpaired *t*-test; *$P < 0.01$). Noteworthy significant differences between S1 activity and other activities were tested. Other significance comparisons were omitted for visualization purposes. The onset times of PMd, PMv, M1, and S1 activities were less than zero (Student's unpaired *t*-test; Monkey T; n = 16 signals, Monkey C; n = 12 signals, **$P < 0.001$). Superimposed bar graphs, mean.

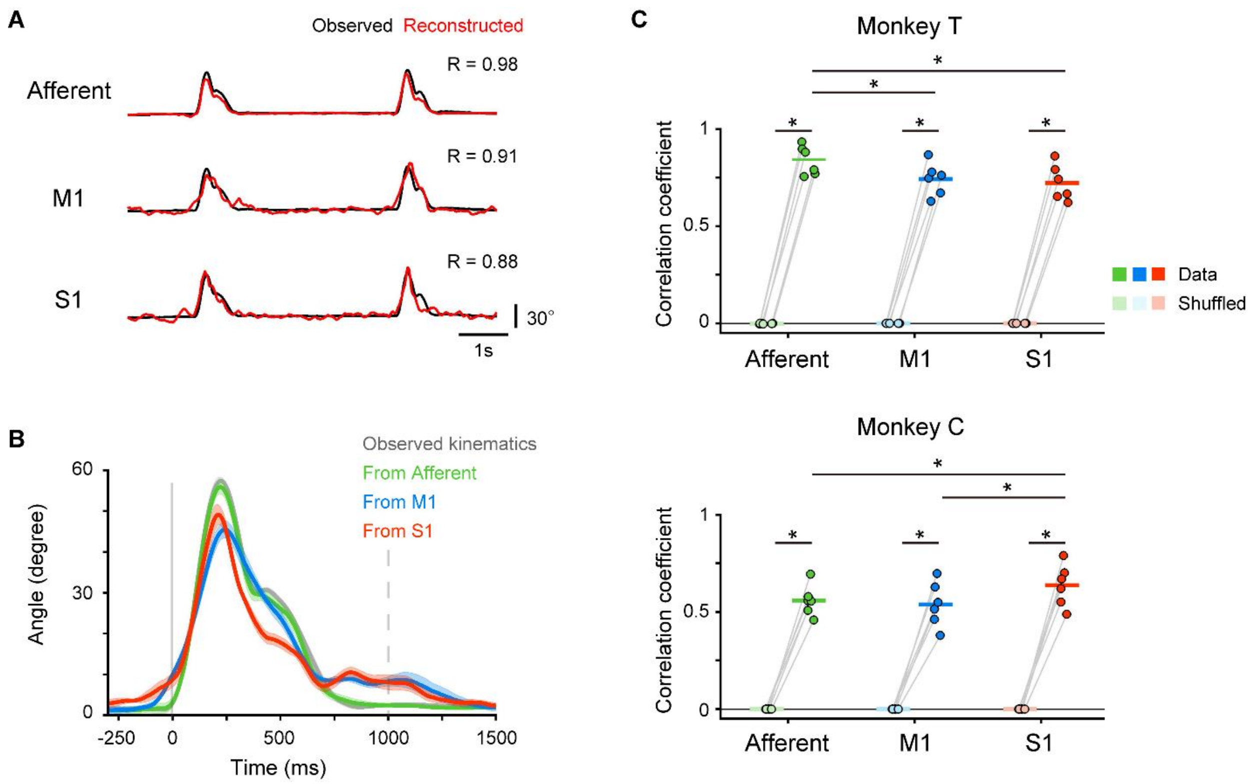
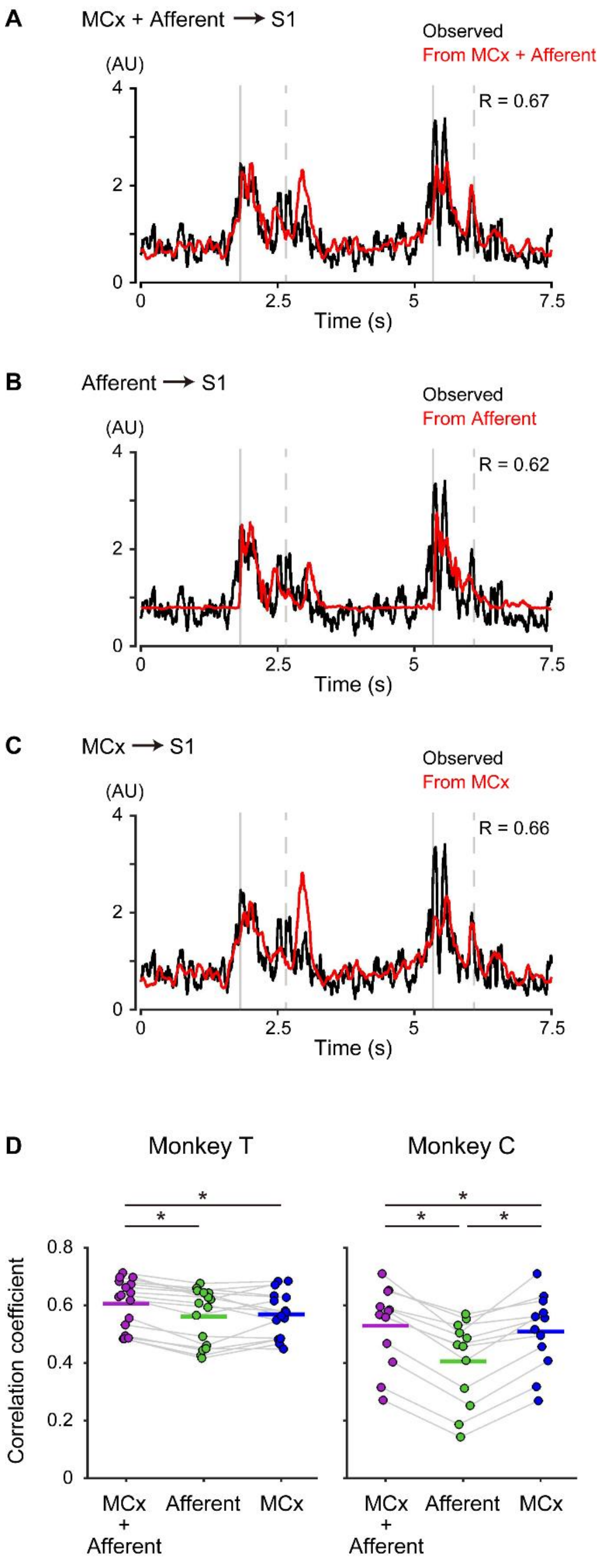


Fig. S2. Peripheral afferents, M1, and S1 activities encode forelimb joint kinematics. (**A**) Reconstruction of the shoulder joint angle along the flexion-extension axis using the neural ensemble activity in peripheral afferents and high-gamma activity in M1 and S1 of Monkey T. Black and red traces show the observed and reconstructed angle profiles, respectively. R is the correlation coefficient between these traces. (**B**) Average kinematics of the observed (Observed kinematics; gray) and reconstructed kinematics of a shoulder joint using neural ensemble activity in peripheral afferents (Afferent; green), high-gamma activity in M1 (M1; cyan), and high-gamma activity in S1 (S1; red) aligned to movement onset (time = 0). The vertical solid and dashed lines represent movement onset and average time of end of movement, respectively. Solid lines, mean; shading, s.d.. (**C**) Mean decoding accuracy pooled across joints (Monkey T; n = 6 joints, Monkey C; n = 6 joints, *P < 0.01). Filled circles depict correlation coefficients between the observed traces and those reconstructed from the data; open circles depict correlation coefficients between observed traces and those reconstructed from random shuffling of activity. Superimposed bars, mean.



A
MCx + Afferent → S1
Observed
From MCx + Afferent
(AU)
R = 0.67
Time (s)
B
Afferent → S1
Observed
From Afferent
(AU)
R = 0.62
Time (s)
C
MCx → S1
Observed
From MCx
(AU)
R = 0.66
Time (s)
D
Monkey T
Monkey C
Correlation coefficient
MCx + Afferent
Afferent
MCx

Fig. S3. Both MCx and peripheral afferent activities contribute to the decoding of S1 activity. (**A**, **B**, **C**) Reconstruction of the activity in S1 using the combined activities in both MCx and peripheral afferents (A), the activity in peripheral afferents alone (B), or the activity in MCx alone (C) of Monkey T. Examples of two successive movements are shown. Black, the observed activity in S1; red, the reconstructed activity in S1. R, correlation coefficient between the observed and reconstructed activities. Vertical solid lines, movement onset; vertical dashed lines, the end of the movement. (**D**) Mean decoding accuracy pooled across ECoG electrodes in S1. The correlation coefficient between the observed and reconstructed traces (Monkey T; n = 16 signals, Monkey C; n = 12 signals, *$P < 0.05$). Superimposed bars, mean.

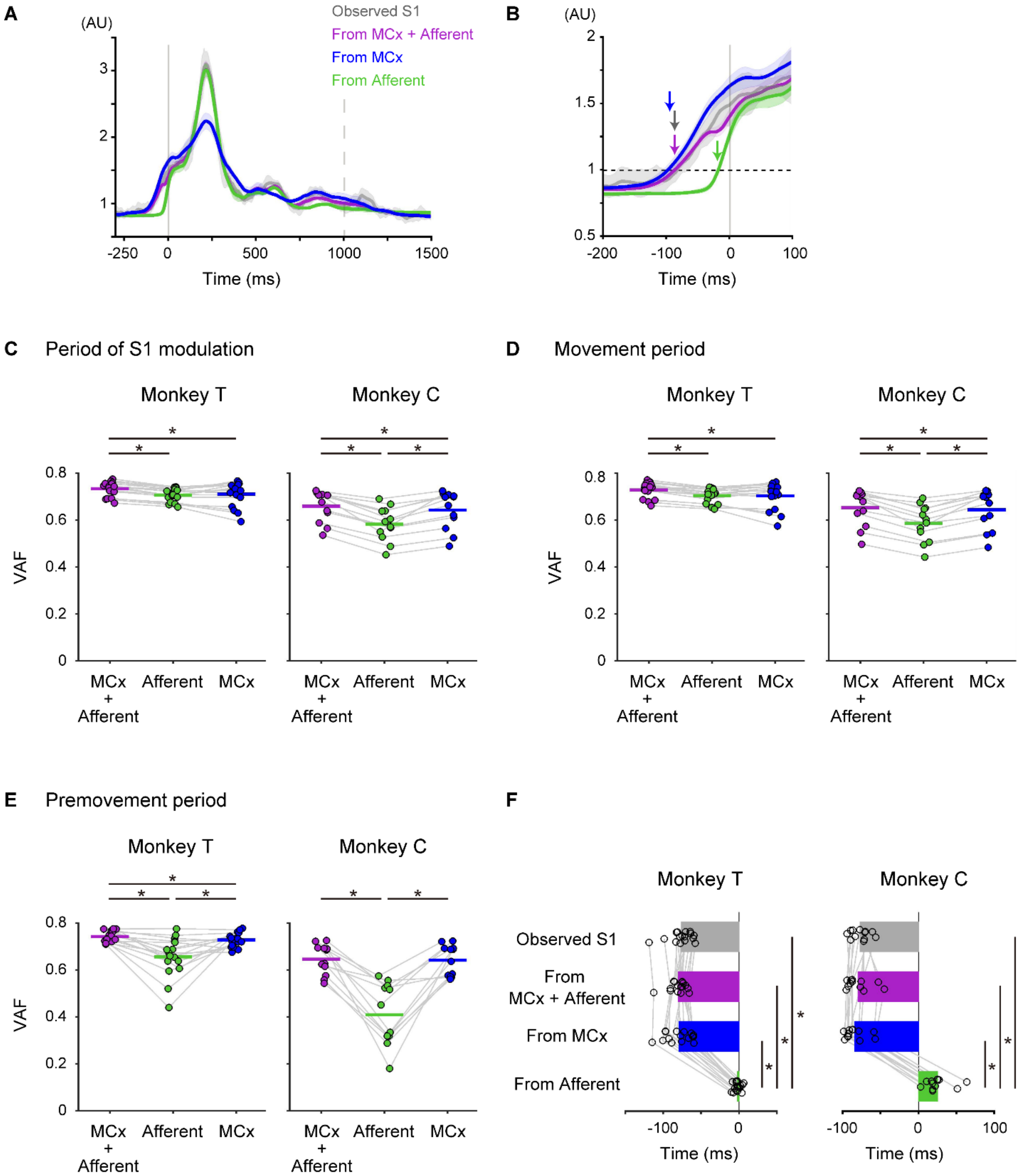
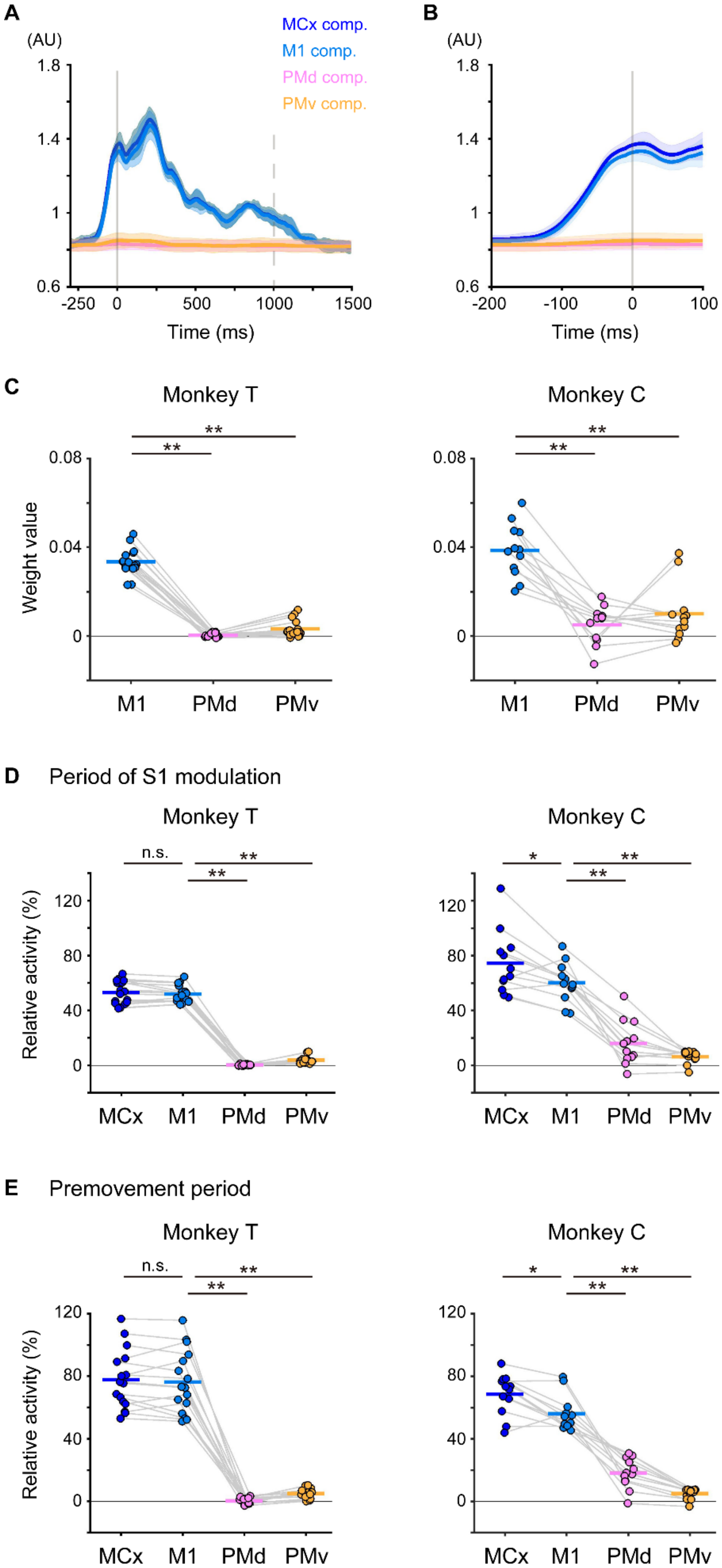

A
(AU)
Observed S1
From MCx + Afferent
From MCx
From Afferent
Time (ms)
B
(AU)
Time (ms)
C
Period of S1 modulation
Monkey T
Monkey C
VAF
MCx + Afferent
Afferent
MCx
D
Movement period
Monkey T
Monkey C
VAF
E
Premovement period
Monkey T
Monkey C
VAF
F
Monkey T
Monkey C
Observed S1
From MCx + Afferent
From MCx
From Afferent
Time (ms)

Fig. S4. MCx, not peripheral afferent, activity contributes to the decoding of premovement S1 activity. (**A**) Average modulation of the observed (S1; gray) and reconstructed activity in S1 using combined activities in MCx and peripheral afferents (MCx + Afferent; purple), high-gamma activity in MCx (MCx; blue) and neural ensemble activity in peripheral afferents (Afferent; green) aligned to movement onset (time = 0; from the same session in Fig. 2C). Vertical solid line; movement onset, dashed line; average time of end of movement. Solid lines, mean; shading, s.d.. (**B**) Magnification of (A). Horizontal dashed line; threshold for the onset of modulation. Arrows; onset time. (**C**) Mean decoding accuracy pooled across ECoG electrodes in S1. Variance accounted for (VAF) between the observed and reconstructed traces in the period during which S1 modulation was detected (-100 ms to 1,400 ms around movement onset for Monkey T, -100 ms to 1,500 ms for Monkey C). (**D**, **E**) Mean decoding accuracy pooled across ECoG electrodes in S1. VAF between the observed and reconstructed traces during the movement period (D, 0 ms to 1,000 ms around movement onset) and during the premovement period (E, -100 ms to 0 ms around movement onset). (**F**) Onset time of the observed activity of S1 and the reconstruction from combined activities in MCx and peripheral afferents, that from MCx activity alone, and that from peripheral afferents activity alone. Monkey T; n = 16 signals, Monkey C; n = 12 signals, $*P < 0.05$. Superimposed bars and bar graphs, mean.



A
(AU)
1.8
1.4
1
0.6
-250
0
500
1000
1500
Time (ms)
MCx comp.
M1 comp.
PMd comp.
PMv comp.
B
(AU)
1.8
1.4
1
0.6
-200
-100
0
100
Time (ms)
C
Monkey T
Monkey C
Weight value
0.08
0.04
0
**
M1
PMd
PMv
D
Period of S1 modulation
Monkey T
Monkey C
Relative activity (%)
120
80
40
0
n.s.
*
**
MCx
M1
PMd
PMv
E
Premovement period
Monkey T
Monkey C
Relative activity (%)
120
80
40
0
n.s.
*
**
MCx
M1
PMd
PMv

Fig. S5. M1 activity is a better predictor of S1 activity than premotor cortex. (**A**) Average modulations of the observed S1 activity (S1; gray), and MCx (blue), M1 (cyan), PMd (magenta), and PMv (orange) components in the reconstruction aligned to movement onset (from the same session in Fig. 2C). Vertical solid line; movement onset, dashed line; average time of end of movement. Solid lines, mean; shading, s.d.. (**B**) Magnification of (A). (**C**) Weight values given to electrodes over each cortical area. (**D**) Area of each component above the baseline normalized by S1 (MCx; blue, M1; cyan, PMd; magenta, PMv; orange) in the period during which S1 modulation was detected (-100 ms to 1,400 ms around movement onset for Monkey T, -100 ms to 1,500 ms for Monkey C). (**E**) The areas above the baseline of each component in the reconstruction normalized by S1 (MCx; blue, M1; cyan, PMd; magenta, PMv; orange) during the premovement period (-100 ms to 0 ms around movement onset). Monkey T; n = 16 signals, Monkey C; n = 12 signals, *$P < 0.05$, **$P < 0.001$. Noteworthy significant differences between M1 activity and other activities were tested. Other significance comparisons were omitted for visualization purposes. Superimposed bars, mean. n.s., not significant.

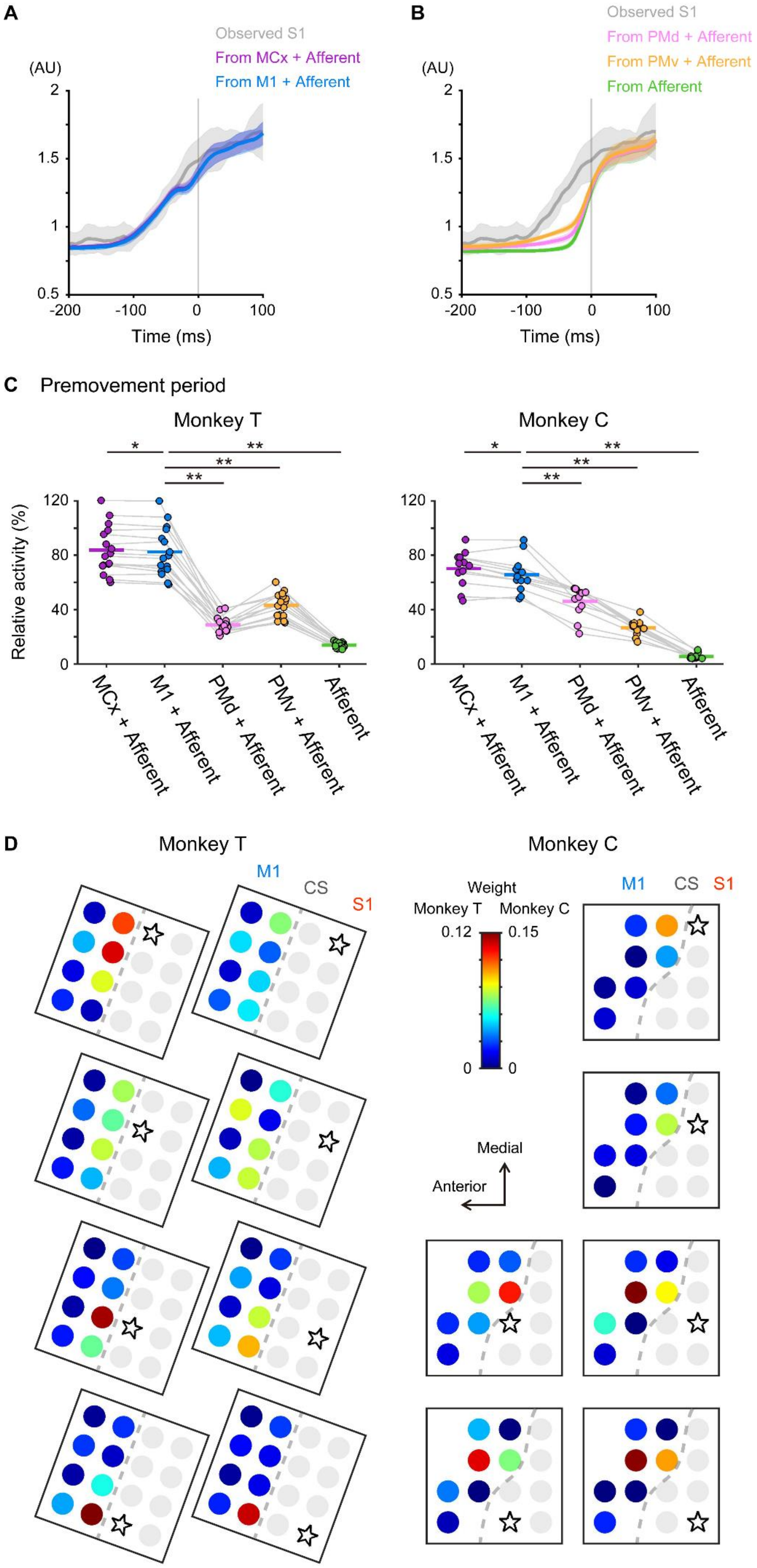

A
Observed S1
From MCx + Afferent
From M1 + Afferent
(AU)
2
1.5
1
0.5
-200
-100
0
100
Time (ms)
B
Observed S1
From PMd + Afferent
From PMv + Afferent
From Afferent
(AU)
Time (ms)
C
Premovement period
Monkey T
Monkey C
Relative activity (%)
120
80
40
0
MCx + Afferent
M1 + Afferent
PMd + Afferent
PMv + Afferent
Afferent
D
Monkey T
Monkey C
M1
CS
S1
Weight
Monkey T
Monkey C
0.12
0.15
0
0
Medial
Anterior

Fig. S6. M1 activity contributes to the decoding of premovement S1 activity. (**A**) Average modulation of the observed S1 activity (S1; gray), the reconstruction using combined activities in MCx and peripheral afferents (MCx + Afferent; purple), and the reconstruction using combined activities in M1 and peripheral afferents (M1 + Afferent; cyan) aligned to movement onset (from the same session in Fig. 2C). Vertical line; movement onset. Solid lines, mean; shading, s.d.. (**B**) Average modulation of the observed activity in S1 (S1; gray), the reconstruction using combined activities in PMd and peripheral afferents (PMd + Afferent; magenta), the reconstruction using combined activities in PMv and peripheral afferents (PMv + Afferent; orange), and the reconstruction using peripheral afferents activity alone (Afferent; green) aligned to movement onset (from the same session in Fig. 2C). Vertical line; movement onset. (**C**) Area of the reconstructed activity above the baseline during the premovement period (-100 ms to 0 ms around movement onset). Data are normalized to the total amount of the observed activity in S1 during the premovement period (Monkey T; n = 16 signals, Monkey C; n = 12 signals, $*P < 0.05$, $**P < 0.001$). Noteworthy significant differences between combined activities in M1 and peripheral afferents and other activities were tested. Other significance comparisons were omitted for visualization purposes. Superimposed bars; mean. (**D**) Color maps represent weight values of M1 activity at each electrode on the grid in models that predict the activity in an S1 electrode the position of which is indicated by the star.

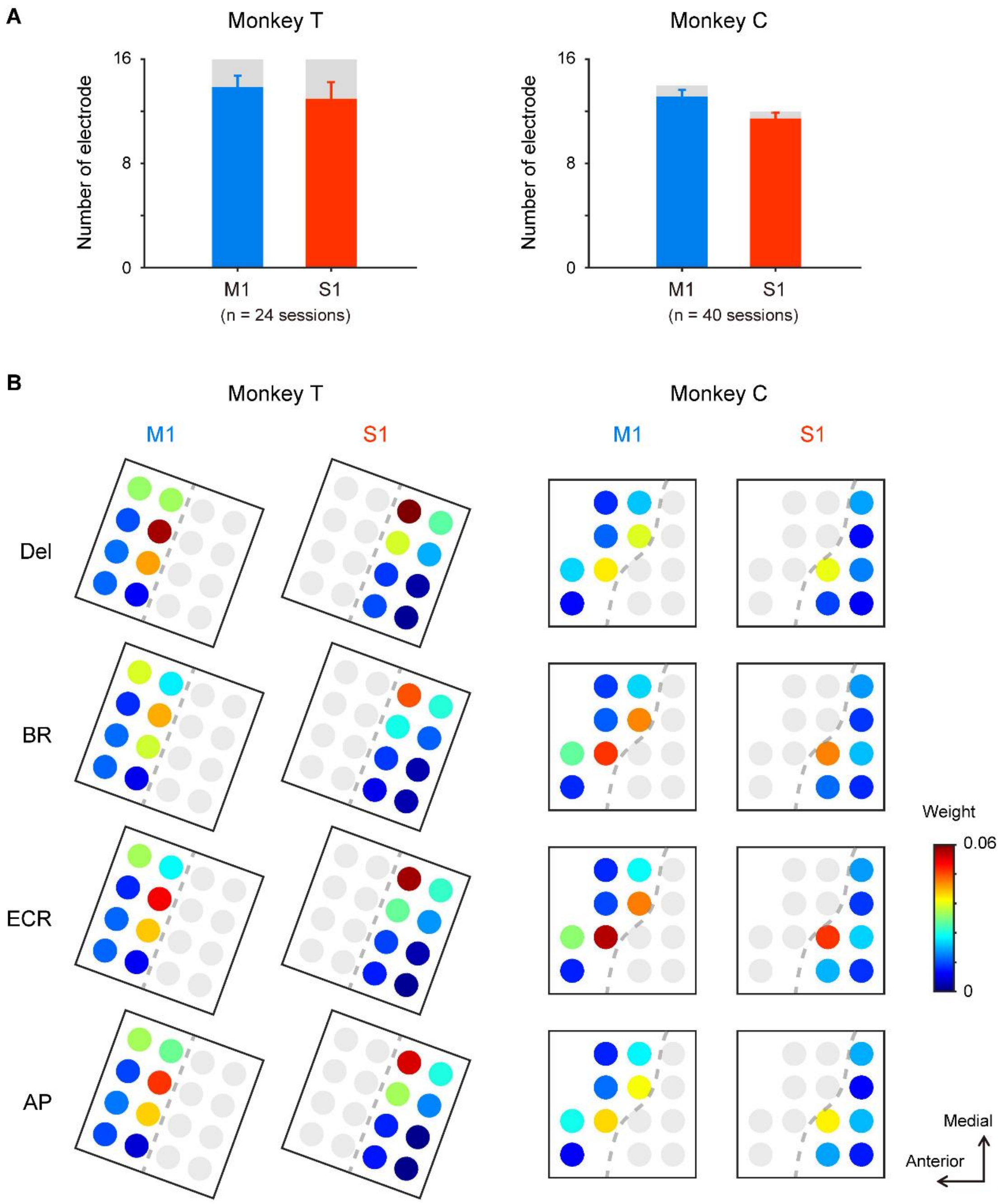
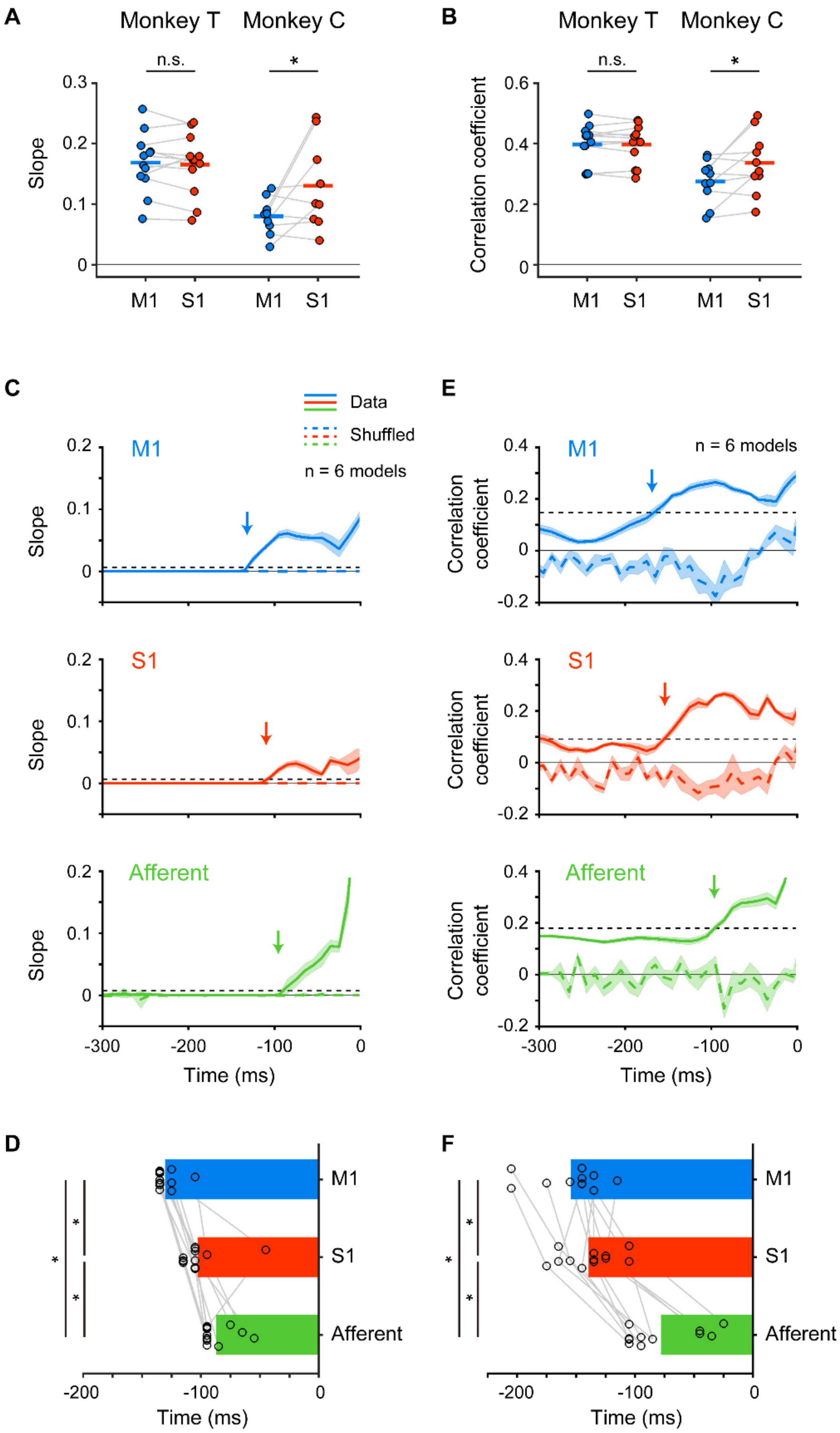


Fig. S7. Premovement activity in a core area encodes muscle activity. (**A**) The average number of M1 or S1 electrodes selected by the SLiR for the prediction of muscle activity. Gray bars represent the number of M1 or S1 electrodes on the grid. Error bars, s.d.. (**B**) Color maps represent weight values of M1 and S1 activities at each electrode on the grid in models that predict the activity of individual forelimb muscles.



A
Monkey T
Monkey C
n.s.
*
Slope
0.3
0.2
0.1
0
M1
S1
M1
S1
B
Monkey T
Monkey C
n.s.
*
Correlation coefficient
0.6
0.4
0.2
0
M1
S1
M1
S1
C
Data
Shuffled
n = 6 models
M1
S1
Afferent
Slope
0.2
0.1
0
-300
-200
-100
0
Time (ms)
E
M1
n = 6 models
S1
Afferent
Correlation coefficient
0.4
0.2
0
-0.2
-300
-200
-100
0
Time (ms)
D
M1
S1
Afferent
*
-200
-100
0
Time (ms)
F
M1
S1
Afferent
*
-200
-100
0
Time (ms)

Fig. S8. Premovement activities in M1 and S1 encode EMG burst. (**A**, **B**) Average slopes of regression lines (A) and correlation coefficients (B) pooled across muscles (Monkey T; n = 12 muscles, Monkey C; n = 10 muscles, $*P < 0.05$, from the same data in Fig. 6, B and C). Superimposed bars, mean. n.s., not significant. (**C**, **E**) Average slopes of the regression lines (C) and correlation coefficients (E) were plotted against the end of 50-ms sliding windows. Solid lines, mean; shading, s.d.; dashed black line, threshold for onset of activity; arrows, onset. (**D**, **F**) Onset times of the activity in M1, S1 or peripheral afferents that encodes peak EMG amplitude pooled across electrodes. Onset times of the activity in M1 and S1 were earlier than that of peripheral afferents (D; slopes, F; correlation coefficient, Monkey T; n = 12 muscles, $*P < 0.05$). Superimposed bar graphs; mean.

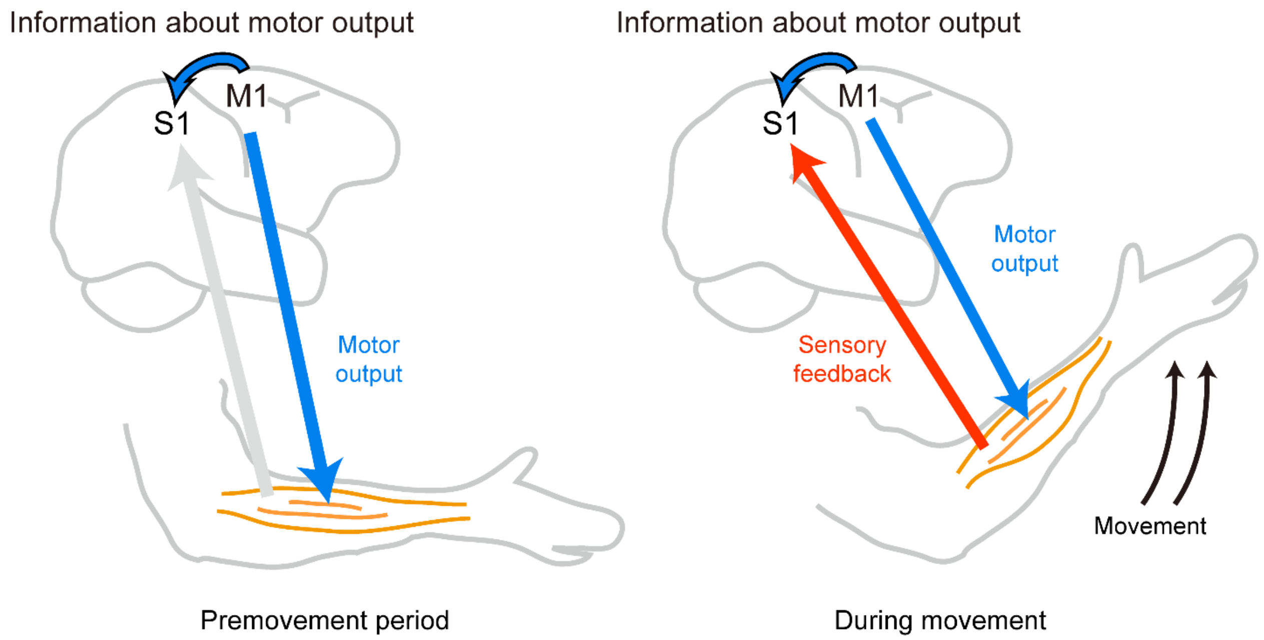


Fig. S9. Proposed temporal dynamics in which S1 receives information about motor output and somatosensory feedback signals. (*left*) In the premovement period, S1 receives information about motor output from M1 or a common input source with M1. (*right*) During the movement, S1 uninterruptedly receives information about motor output and concurrently receives somatosensory feedback signals from peripheral afferents.

Table S1. Calculation of the joint angles.

Joint Angle	Two Vectors	
shoulder FE	cross product of a vector from m3 to m2 and one from m3 to m1	vector from m3 to m7
shoulder AA	vector from m3 to m1	vector from m3 to m7
elbow FE	vector from m7 to m3	vector from m7 to the center of m8 and m9
elbow PS	projection of a vector from m7 to m3 on a plane with a normal vector from m7 to the center of m8 and m9	projection of a vector from m8 to m9 on the same plane
wrist FE	cross product of a vector from m8 to m10 and one from m8 to m9	vector from the center of m8 and m9 to m7
wrist RU	vector from m9 to m8	vector from the center of m8 and m9 to m10

Joint angles were calculated from the two vectors presented in the right columns. In particular, Euler angles were used to represent relative joint rotations.