Supporting Information

Shokur et al. 10.1073/pnas.1308459110

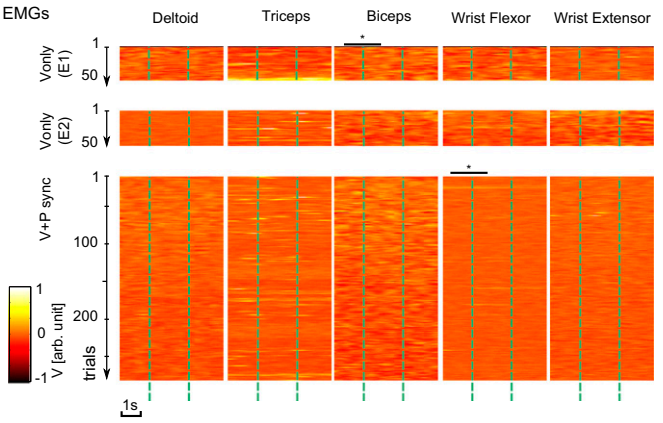

Fig. S1. Single-trial electromyograms (EMGs) of the five arm muscles recorded simultaneously with the neurons shown in Fig. 2*A*.

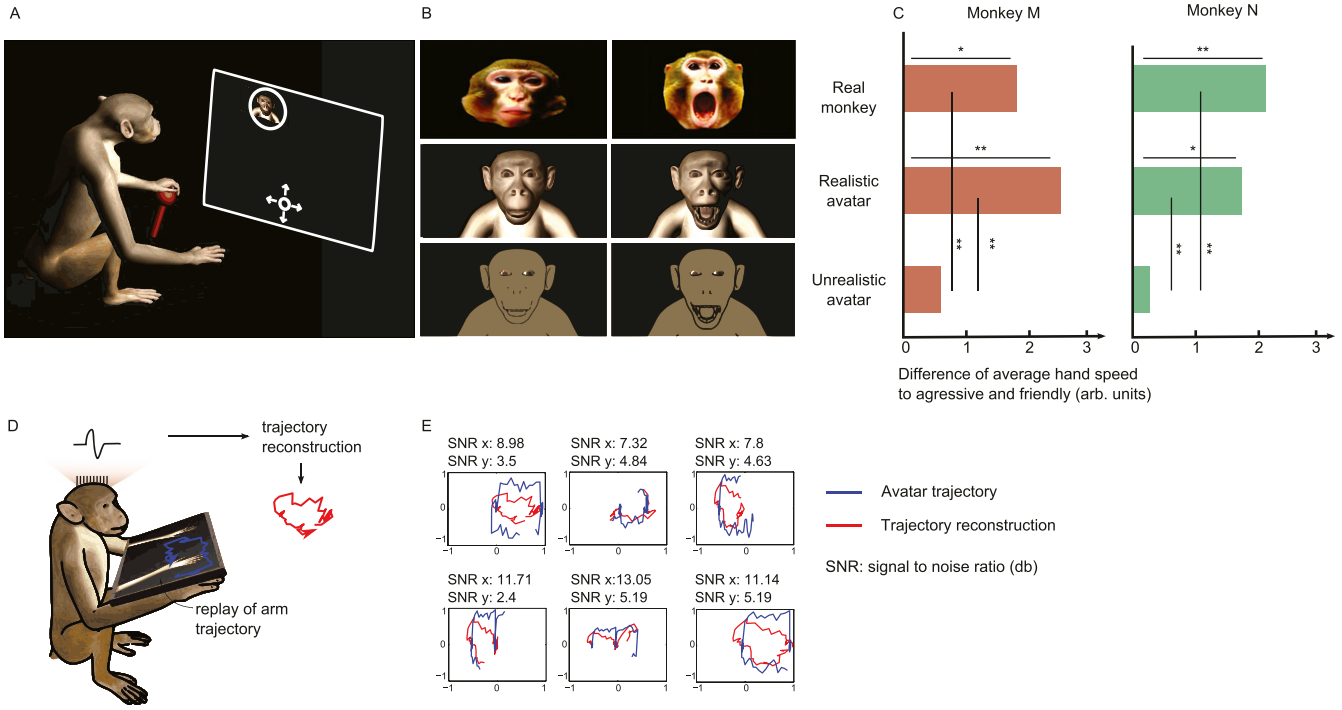

Fig. S2. Monkey responses to the realistic 3D avatar. (*A*) Schematics of an experimental task that required naive monkeys to perform center-out reaching movements toward peripheral targets that could be empty white rings or, less frequently (10% of all trials), rings framing images of monkey faces. Monkeys M and N were naive to the avatar at that time, but were proficient in the center-out joystick task (tests were done before experiments described in this paper). A target was randomly placed in one of four positions equidistant to the center, and the monkeys were rewarded for placing a cursor over it. (*B*) The images could have a friendly facial expression (lip smacking, *Left*) or an aggressive expression (bared teeth, *Right*). Three types of images were tested: photograph of a real monkey (*Top*), realistic monkey avatar (*Middle*), or unrealistic monkey avatar (*Bottom*). (*C*) For both monkeys, average reaching speed was lower ($P < 0.05$, *t* test) for targets representing aggressive vs. friendly faces, but only for realistic images (photographs or realistic avatar). This effect was not observed for the unrealistic avatar ($P > 0.3$ for both). (*D*) Schematics of an experiment in which monkeys passively observed an avatar arm move on the screen. Although the avatar was not connected to the joystick or a brain machine interface (BMI), primary motor (i.e., M1) and somatosensory (i.e., S1) neuronal ensembles were attuned to the avatar movements. (*E*) Avatar trajectories on the screen and their reconstructions from cortical modulations. Six center-out movements are shown. Blue lines indicate trajectories of the avatar arm; red lines indicate trajectories reconstructed with an unscented Kalman filter.

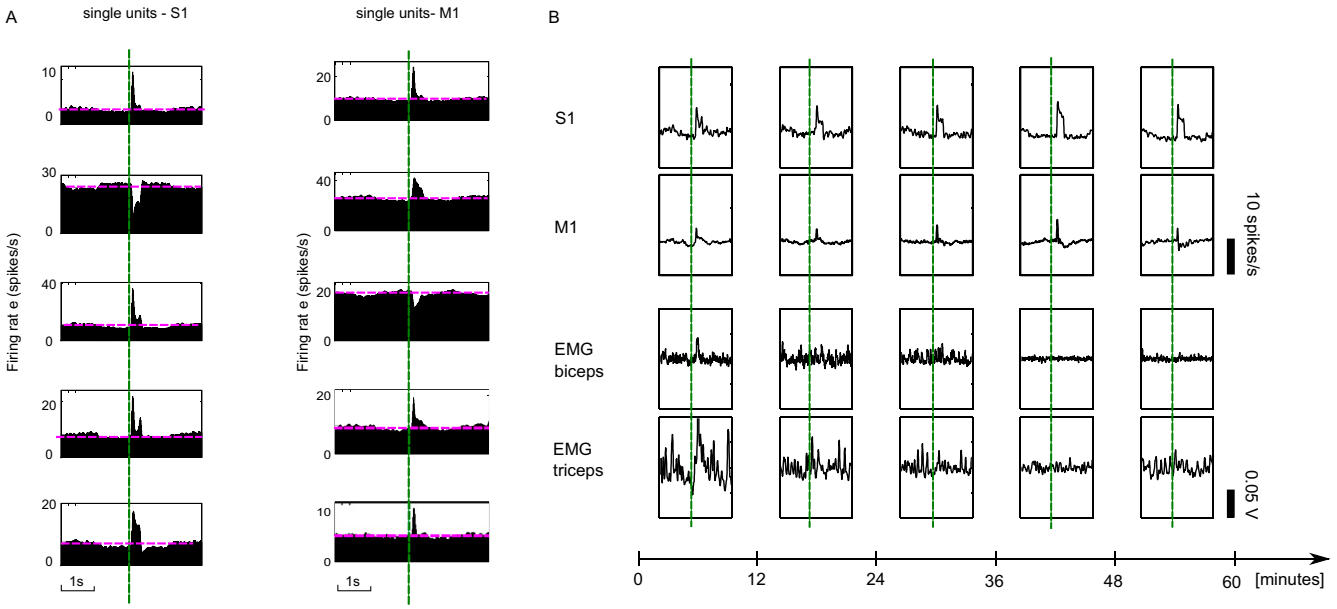

Fig. S3. Cortical responses to air puffs. (*A*) Peristimulus time histograms (PSTHs) for five S1 (*Left*) and five M1 (*Right*) neurons. PSTHs are aligned on the onsets of air puffs applied to the forearm (green vertical line). Pink horizontal line indicates baseline rate. Both S1 and M1 neurons clearly responded to the air puffs. (*B*) Average PSTHs for the population of S1 and M1 and average rectified EMGs of two arm muscles (biceps and triceps) calculated for consecutive 12-min epochs during a 60-min session. The neurons responded to air puffs throughout the session. EMG activity modulations were observed in the beginning of the session, but subsided after 12 min.

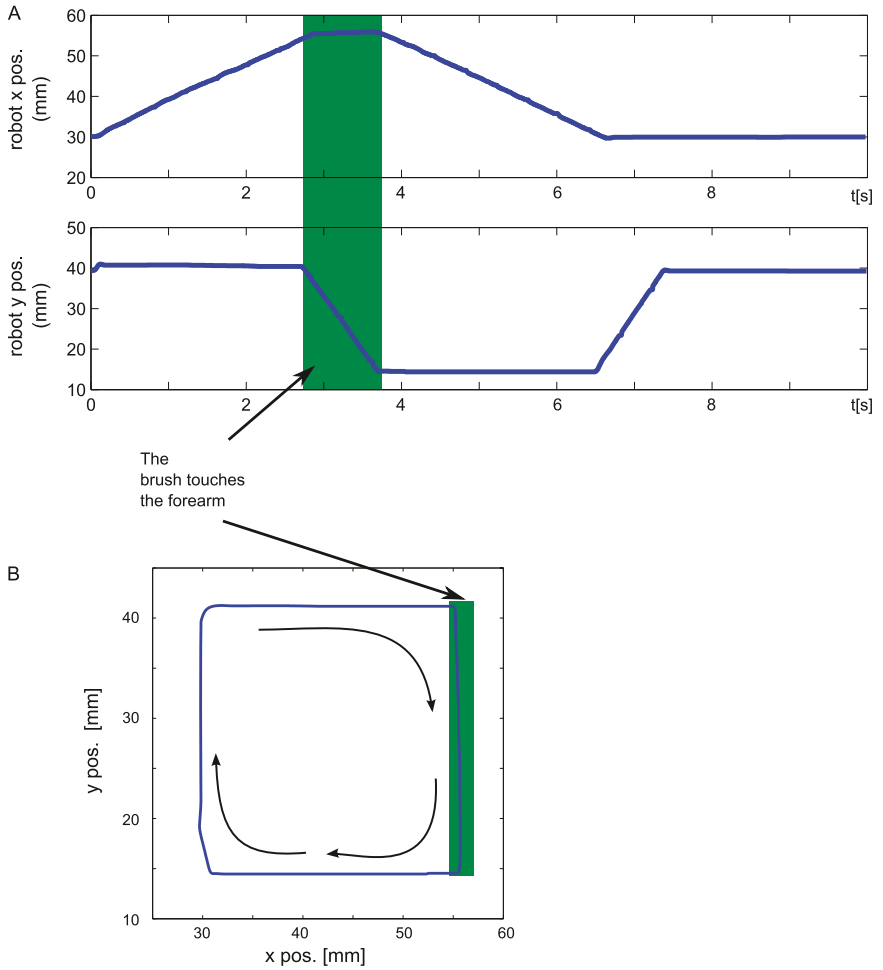

Fig. S4. Robot path: (*A*) *x* and *y* coordinates of the Cartesian robot over time and (*B*) the robot's path shown on the *x*–*y* plane. Areas shaded green indicate robot positions where it touched the monkey's forearm with the brush.

Table S1. Number of neurons with significant excitatory, inhibitory responses across trial types, cortical areas and monkeys

Monkey, cortical area, response type	Trial type			
	Vonly, E1 (%)	V+P sync (%)	Vonly, sync (%)	Vonly, async (%)
Monkey M				
S1				
Excited	1 (2)	44 (73)	31 (50)	1 (2)
Inhibited	3 (4)	0	0	3 (4)
M1				
Excited	5 (6)	64 (79)	51 (63)	2 (2)
Inhibited	5 (6)	5 (6)	6 (7)	2 (2)
Monkey N				
S1				
Excited	—	5 (33)	5 (33)	1 (6)
Inhibited	—	0	1 (6)	1 (6)
M1				
Excited	—	9 (26)	8 (24)	1 (3)
Inhibited	—	3 (9)	5 (15)	1 (3)

Percentages represent proportions with respect to each area's neuronal sample. async, asynchronous; E1, epoch 1; sync, synchronous; V+P, virtual plus physical touch; Vonly, virtual touch only.

Table S2. Average responses response type, monkey, and cortical area

Monkey, cortical area, response type	sync			async	
	Vonly, E1	Vonly, E2	V+P, E2	Vonly, E1	Vonly, E2
Excited					
Monkey M					
S1, n = 44/64 (73%)					
Baseline rate	37.1 ± 3.0	34.9 ± 2.7	34.9 ± 2.7	30.9 ± 2.5	32.3 ± 2.6
Response rate	37.9 ± 3.0	39.0 ± 2.9	44.8 ± 3.5	32.1 ± 2.6	33.4 ± 2.6
ΔR	0.7 ± 3.0	4.2 ± 2.7	9.9 ± 2.7	1.2 ± 2.5	1.1 ± 2.6
Normalized ΔR	0.03 ± 0.01	0.14 ± 0.02	0.32 ± 0.01	0.04 ± 0.01	0.05 ± 0.01
M1, n = 64/82 (79%)					
Baseline rate	17.2 ± 2.0	17.1 ± 1.9	17.7 ± 2.0	18.9 ± 1.9	19.3 ± 2.1
Response rate	18.3 ± 2.1	22.6 ± 2.4	29.6 ± 2.9	20.0 ± 2.1	20.9 ± 2.1
ΔR	1.1 ± 2.0	5.5 ± 1.9	12.0 ± 2.0	1.0 ± 1.9	1.6 ± 2.1
Normalized ΔR	0.05 ± 0.01	0.23 ± 0.01	0.54 ± 0.01	0.04 ± 0.01	0.07 ± 0.01
Monkey N					
S1, n = 5/15 (33%)					
Baseline rate	—	15.8 ± 1.5	16.0 ± 1.4	—	13.6 ± 3.3
Response rate	—	22.2 ± 3.4	23.5 ± 4.0	—	13.8 ± 3.3
ΔR	—	6.5 ± 1.5	7.5 ± 1.4	—	0.2 ± 3.3
Normalized ΔR	—	0.34 ± 0.01	0.39 ± 0.01	—	0.00 ± 0.03
M1, n = 9/34 (26%)					
Baseline rate	—	24.9 ± 5.8	25.8 ± 6.1	—	20.8 ± 7.1
Response rate	—	33.7 ± 6.2	35.0 ± 6.2	—	21.7 ± 7.3
ΔR	—	8.9 ± 5.8	9.2 ± 6.1	—	0.9 ± 7.1
Normalized ΔR	—	0.41 ± 0.02	0.42 ± 0.02	—	0.06 ± 0.01
Inhibited					
Monkey M					
M1, n = 5/82 (6%)					
Baseline rate	15.8 ± 4.1	14.6 ± 3.7	14.8 ± 3.6	14.7 ± 2.8	14.0 ± 2.8
Response rate	15.0 ± 4.2	11.9 ± 3.4	10.2 ± 3.7	13.8 ± 2.6	12.5 ± 2.7
ΔR	−0.9 ± 4.1	−2.7 ± 3.7	−4.6 ± 3.6	−0.8 ± 2.8	−1.5 ± 2.8
Normalized ΔR	−0.06 ± 0.04	−0.17 ± 0.02	0.03 ± 0.02	−0.05 ± 0.03	−0.08 ± 0.03
Monkey N					
M1, n = 3/34 (9%)					
Baseline rate	—	21.3 ± 5.7	22.5 ± 5.5	—	29.7 ± 2.7
Response rate	—	19.7 ± 5.4	20.6 ± 5.2	—	28.9 ± 4.2
ΔR	—	−1.6 ± 5.7	−1.9 ± 5.5	—	−0.8 ± 2.7
Normalized ΔR	—	−0.07 ± 0.02	0.01 ± 0.01	—	−0.04 ± 0.02

Values presented as mean ± SEM. Only the neurons with significantly V+P responses were considered. Baseline rate was calculated for the period −1.2 to −0.2 s before the stimulus. Response rate was calculated for a 200-ms window centered at the response peak. Normalized ΔR represents the z-score of raw firing rate. async, asynchronous; ΔR, difference between response rate and baseline; E1, epoch 1; E2, epoch 2; sync, synchronous; V+P, virtual plus physical touch; Vonly, virtual touch only.