

## 1 Restored tactile sensation improves neuroprosthetic arm control

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16 **Summary paragraph:** The sense of touch is critical for skillful hand control<sup>1-3</sup>, but is largely missing for  
17 people who use prosthetic devices. Instead, prosthesis users rely heavily on visual feedback, even though  
18 state transitions that are necessary to skillfully interact with objects, such as object contact, are relayed  
19 more precisely through tactile feedback<sup>4-6</sup>. Here we show that restoring tactile sensory feedback,  
20 through intracortical microstimulation of the somatosensory cortex<sup>7</sup>, enables a person with a  
21 bidirectional intracortical brain-computer interface to improve their performance on functional object  
22 transport tasks completed with a neurally-controlled prosthetic limb. The participant had full visual  
23 feedback and had practiced the task for approximately two years prior to these experiments.  
24 Nevertheless, successful trial times on a commonly used clinical upper limb assessment task were  
25 reduced from a median time of 20.9 s (13.1 - 40.5 s interquartile range) to 10.2 s (5.4 - 18.1 s interquartile  
26 range) when vision was supplemented with microstimulation-evoked cutaneous percepts that were  
27 referred to different fingers and were graded in intensity based on real-time prosthesis contact forces.  
28 Faster completion times were primarily due to a reduction in the amount of time spent attempting to  
29 grasp objects. These results demonstrate the importance of tactile sensations in upper-limb control and  
30 the utility of creating bidirectional brain-computer interfaces to restore this stream of information using  
31 intracortical microstimulation.

32 We use our hands to interact with our environment, often by exploring and manipulating objects.  
33 Without tactile somatosensory feedback, even simple manipulation tasks become clumsy and slow<sup>1-3</sup>.  
34 Outside of investigational settings, this source of feedback is rarely provided for prosthetic devices<sup>8</sup>, and  
35 in the context of human brain-computer interfaces (BCIs), has only recently become possible<sup>7,9-11</sup>. These  
36 studies have begun to describe the perceptual characteristics of cortical stimulation, however, the  
37 potential benefits of a bidirectional BCI on function have remained unexplored. This is despite the fact  
38 that the need for somatosensory feedback in BCIs has long been suggested as the next step towards  
39 complete upper-limb restoration<sup>12-14</sup> and cited by amputees as a desired feature<sup>15-17</sup>. Here we show that  
40 a bidirectional BCI (Fig. 1) that provides these tactile percepts improves performance in functional object  
41 transport tasks using a BCI-controlled robotic arm. The percepts were driven in real-time by sensors in a  
42 prosthetic hand (Fig. 1c,d), evoked through intracortical microstimulation (ICMS) of area 1 of  
43 somatosensory cortex (S1) and experienced by a participant as originating from his own palm and  
44 fingers.

45 We used two tasks to evaluate performance: an object transfer task (Fig. 1f) and a modified version of  
46 the Action Research Arm Test (ARAT)<sup>18</sup> (Fig. 1g). Both tasks were completed using the Modular Prosthetic  
47 Limb (MPL)<sup>19</sup>. The robotic arm was controlled using neural activity recorded from two 88-channel  
48 microelectrode arrays implanted chronically in primary motor cortex (M1) (Fig. 1b) of a human  
49 participant with tetraplegia resulting from a cervical spinal cord injury. Five degrees-of-freedom (DoF),  
50 consisting of 3D endpoint translation, pronation/supination of the wrist, and hand grasp aperture (Fig.  
51 1a)—with the hand in a power grasp conformation—were continuously and simultaneously controlled by  
52 the participant during all tasks (Fig. 1e). Tactile feedback was delivered in the first four experimental  
53 sessions by ICMS through two 32-channel microelectrode arrays implanted in area 1 of S1 (Fig. 1b).  
54 Stimulation pulses were delivered at 100 pulses per second and pulse amplitude was modulated linearly  
55 by the reaction torques measured at the metacarpophalangeal joint of the fingers on the MPL (Fig. 1d).  
56 Pulse trains were delivered to electrodes which, when stimulated, evoked percepts on corresponding  
57 fingers (Fig. 1c).

58 We first tested the effect of providing ICMS-induced tactile feedback on functional performance using  
59 an object transfer task that was familiar to the participant. The goal was to transport a compliant object

60 across the workspace (Fig. 1f) as many times as possible in two minutes (Supplemental Video 1). We  
61 compared the number of transfers completed during four sessions with ICMS to four sessions without  
62 ICMS. Each session consisted of five two-minute trials. Across a total of 20 trials with ICMS, 352 transfers  
63 were completed compared to 315 transfers in the 20 trials without ICMS (Table 1). The number of  
64 transfers increased from  $15.8 \pm 3.8$  transfers per trial to  $17.8 \pm 2.4$  transfers per trial with ICMS, though  
65 this difference was not statistically significant ( $t_{38} = -2.02$ ,  $P = 0.050$ ,  $t$ -test). However, we observed  
66 qualitative improvements during the task that led us to examine the data in more detail.

67 The object transfer task can be broken up into grasp, transport and release phases. We defined these  
68 phases using the physical location of the MPL hand. The transport zone consisted of a region 22.5 cm  
69 wide and centered on the starting location of the hand at the beginning of a trial. The grasp zone was  
70 located to the left side of the transport zone, while the release zone was located to the right (Fig. 1f).  
71 We first examined the amount of time spent in each movement zone per transfer. We found that the  
72 time spent in the grasp zone decreased from  $3.3 \pm 1.2$  s per transfer without ICMS to  $2.3 \pm 0.4$  s per  
73 transfer with ICMS ( $t_{38} = 3.3$ ,  $P = 0.002$ ,  $t$ -test, Fig. 2a) while time spent in the release zone decreased  
74 from  $2.8 \pm 1.0$  s per transfer without ICMS to  $2.3 \pm 0.5$  s per transfer with ICMS ( $t_{38} = 2.0$ ,  $P = 0.048$ ,  $t$ -  
75 test, Fig. 2a). Time spent in the transport zone per transfer was no different with or without ICMS ( $2.1 \pm$   
76  $0.6$  s without ICMS,  $2.3 \pm 0.3$  s with ICMS,  $t_{38} = -1.3$ ,  $P = 0.206$ ,  $t$ -test, Fig. 2a). To uncover the reason  
77 behind the lower grasp times with ICMS, we examined the total distance travelled while the MPL was in  
78 the grasp zone. We found that there was significantly more movement in the grasp zone in trials without  
79 ICMS compared to trials with ICMS ( $44.2 \pm 13.1$  cm/transfer without ICMS,  $32.4 \pm 5.9$  cm/transfer with  
80 ICMS,  $t_{38} = 3.7$ ,  $P = 0.0007$ ,  $t$ -test, Fig. 2b). This suggests that in trials without ICMS, the additional time  
81 was used to move the hand into an ideal configuration to grasp the object. This effect is further  
82 illustrated by comparing the spatial distributions of time spent across the workspace per transfer (Fig.  
83 2c). With ICMS-evoked sensations, the participant spent less time in the immediate vicinity of the object.

84 We then compared performance on a modified version of the ARAT<sup>18</sup>, which is a clinically validated test  
85 of unilateral upper-limb function and one that has been used previously to assess arm control  
86 performance in BCI systems<sup>20,21</sup>. We placed different objects on the left side of the workspace, one at a  
87 time, and asked the participant to grasp the object and place it on a raised platform on the right side of

88 the table as quickly as possible (Fig. 1g and Supplemental Videos 2-4). A score of three was awarded if  
89 the task was completed in under five seconds, a score of two was awarded if the task was completed in  
90 under two minutes and a score of one was awarded if the object was touched but the task was not  
91 completed in two minutes. A score of zero was awarded otherwise. Each of the nine objects were  
92 attempted three times, for a total of 27 trials per ARAT session. The final score was the sum of the best  
93 score of the three attempts for each object.

94 Prior to these experiments, the participant had performed 23 ARAT sessions over a period of 23 months  
95 using several different control schemes, including four preliminary sessions with ICMS-driven tactile  
96 feedback (Fig. 3a). These four exploratory sessions included ICMS, but did not have consistent mapping  
97 between finger torque feedback and stimulation parameters. Further, these sessions were intermixed  
98 with sessions without ICMS rather than being performed consecutively with fixed parameters as in our  
99 final experimental design. Over these 23 sessions, performance had plateaued, with a median ARAT  
100 score of 18 and an interquartile range (IQR) of 16.25 – 19 (Fig. 3a). We then began collecting data to  
101 compare the effect of ICMS on ARAT performance. In the first block of four sequential sessions—which  
102 included ICMS, enabling our participant to feel tactile sensations perceived as originating from his own  
103 hand when the robotic hand grasped an object—his ARAT score increased significantly to a median of 21  
104 and a range of 20 – 21 ( $U = 5$ ,  $P = 0.005$ , Wilcoxon rank-sum test, Table 1, Fig. 3a). Performance with  
105 ICMS was also significantly better than the four subsequent matched control sessions without ICMS in  
106 which he achieved a median ARAT score of 17 with a range of 16 – 19 ( $U = 0$ ,  $P = 0.029$ , Wilcoxon rank-  
107 sum test, Fig. 3a). ARAT scores in these control sessions were no different than the 23 historical sessions  
108 ( $U = 39$ ,  $P = 0.65$ , Wilcoxon rank-sum test, Fig. 3a). Individual session scores are shown in Table 1. Despite  
109 the significantly improved scores in sessions with ICMS, there was no change in the total number of trials  
110 that were successfully completed ( $U = 7$ ,  $P = 0.83$ , Wilcoxon rank-sum, Table 1). Therefore, the improved  
111 ARAT scores occurred as a result of completing individual trials more quickly. In the ARAT scoring system,  
112 successfully transferring an object in less than five seconds, and achieving a score of three, is considered  
113 normal, unimpaired performance<sup>18</sup>. In the absence of tactile sensations evoked by ICMS, a score of three  
114 was achieved only once during the 4 sessions (108 trials). When tactile sensations were provided, a score  
115 of three was attained 15 times during the 108 trials.

116 Overall, we found that trials were consistently completed much more quickly when ICMS feedback was  
117 delivered (Fig. 3b, Supplemental Video 2); 14% of the trials with ICMS-evoked tactile feedback were  
118 completed more quickly than the fastest trial without ICMS. In fact, discounting the single trial that was  
119 completed in less than five seconds without ICMS, 25% of the trials with ICMS were completed more  
120 quickly than trials without ICMS (Fig. 3b). Successfully completed trial lengths decreased from a median  
121 time of 20.9 s (13.1 - 40.5 s IQR) to 10.2 s (5.4 - 18.1 s IQR) when tactile feedback was provided ( $U =$   
122  $1676$ ,  $P < 0.0001$ , Wilcoxon rank-sum test, Table 1, Fig. 3b and Supplemental Video 3). These faster  
123 completion times were the cause of the 3.5-point improvement in the ARAT score that occurred when  
124 ICMS was provided and can be interpreted as meaning that ICMS-induced tactile sensations allowed 3.5  
125 more objects, out of 9 possible, to be transported to the platform in a normal time ( $< 5$  seconds). The  
126 improved times were not due to differences in the commanded velocities. While the distributions of  
127 translation velocity commands measured at each time step were statistically different between  
128 conditions ( $D = 0.02$ ,  $P < 0.0001$ , 2-sample Kolmogorov-Smirnov test, Extended Data Fig. 1), the velocities  
129 were functionally equivalent. The median translation velocity was 16.7 cm/s (11.5 – 23.2 cm/s IQR) with  
130 ICMS and 16.4 cm/s (11.4 – 22.6 cm/s IQR) without ICMS. Similar results were observed for wrist rotation  
131 and grasp velocities (Extended Data Fig. 1).

132 The ARAT task can be broadly divided into reach, grasp, and transport phases (Supplemental Video 4).  
133 We separated the trials into these three sequential task phases: (1) reach, consisting of movement onset  
134 to first object contact; (2) grasp, consisting of first object contact to successful object liftoff; and (3)  
135 transport, consisting of object liftoff to object release. The median time spent reaching decreased from  
136 2.1 s (1.5 – 3.5 s IQR) without ICMS to 1.5 s (1.2 – 2.3 s IQR) when ICMS was provided, representing a  
137 27.8% improvement ( $n = 78$  without ICMS and  $n = 85$  with ICMS,  $U = 2204$ ,  $P = 0.0002$ , Wilcoxon rank-  
138 sum test, Fig. 3c). Likewise, the median time spent transporting the object decreased from 2.9 s (2.0 –  
139 4.0 s IQR) to 2.1 s (1.8 – 3.0 s IQR), representing a 22.3% improvement ( $n = 78$  without ICMS and  $n = 85$   
140 with ICMS,  $U = 2366.5$ ,  $P = 0.002$ , Wilcoxon rank-sum test, Fig. 3c). Most impressively, the amount of  
141 time spent attempting to grasp the object decreased from 13.8 s (7.2 – 35.4 s IQR) without ICMS to 5.8  
142 s (1.9 – 13.5 s IQR) with ICMS, resulting in a 44.7% improvement in performance ( $n = 78$  without ICMS  
143 and  $n = 85$  with ICMS,  $U = 1819.5$ ,  $P < 0.0001$ , Wilcoxon rank-sum test, Fig. 3c). We speculated that, much  
144 like in the object transfer task, the participant spent less time attempting to grasp the objects during

145 trials with ICMS-evoked tactile percepts because the percepts increased his certainty about object  
146 contact timing and his confidence that he had successfully grasped the object. Why the amount of time  
147 spent in the other two phases decreased is less clear. Since object contact and contact force cannot be  
148 felt without ICMS, he may have taken longer positioning the hand to improve the amount of information  
149 about object interaction he could extract visually, thus increasing the amount of time spent reaching.  
150 For the transport phase, the participant may have been less confident about his grasp stability, causing  
151 him to move more slowly during transport to avoid dropping the object.

152 By design, the objects in the ARAT task vary in size, shape, weight and, therefore, the overall difficulty in  
153 grasping them. As a result of the significant time spent practicing this task, the participant had classified  
154 the nine ARAT objects as being either easy (5 cm cube, 7.5 cm cube and sphere) or difficult (2.5 cm cube,  
155 10 cm cube, rock, small cylinder, large cylinder and water pouring) to complete. All of the objects that  
156 were rated as easy, as well as the 10 cm cube and large cylinder, were completed more quickly with  
157 ICMS than without ICMS (Fig. 3d, Extended Data Table 1). Including ICMS did not significantly improve  
158 performance with the rock, small cylinder or water pouring task although the median completion time  
159 did go down for all of the objects. Therefore, other factors, such as the controllable degrees of freedom  
160 or kinematic constraints in the robotic arm, may have limited performance on these objects. However,  
161 for those objects that could be completed more easily, adding ICMS feedback further improved  
162 performance.

163 Prior to conducting the functional tasks each session, BCI decoder performance was tested in the  
164 absence of ICMS-evoked tactile feedback using a random target sequence task<sup>22</sup>. This task explicitly  
165 measured how well the participant could independently control each DoF by moving to specific locations  
166 in the 5 DoF workspace. On the days when ICMS-evoked tactile feedback was not provided, sequence  
167 task performance was slightly higher, achieving a median score of 100% on all four days compared to a  
168 median of 95% (range 90-100%) on the days where ICMS was delivered during the functional tasks (12  
169 scores per condition,  $U = 40.5$ ,  $P = 0.025$ , Wilcoxon rank-sum test, median scores for individual sessions  
170 in Table 1). This suggests that decoder performance itself, and thus the participant's ability to control  
171 the robotic arm, did not favor the days on which ICMS was provided.

172 In many bidirectional upper-limb prosthetics studies where amputees receive restored sensory feedback  
173 through electrical stimulation of the peripheral nerves, the effect of artificial sensations on performance  
174 are measured without visual or auditory feedback<sup>12,23–25</sup>. Our approach differed from these studies in  
175 that our aim was to investigate the effect of providing artificial somatosensory feedback on tasks that  
176 were already possible with existing sensory modalities, namely vision. Here, we demonstrated that in  
177 highly-practiced tasks where normal visual feedback was available, adding artificial tactile feedback  
178 through ICMS enabled a person with spinal cord injury using a BCI to significantly improve their task  
179 scores, primarily by spending less time attempting to grasp the objects (Fig. 2a,c, 3b,c).

180 As with any single-subject study, it is uncertain whether these findings will generalize to future  
181 experiments. However, there are several reasons to believe that these results accurately represent the  
182 potential of restoring somatosensory percepts using ICMS. First, using the same fundamental neural  
183 decoding and control methods, we have demonstrated that two participants achieved similar scores on  
184 functional tasks with vision alone<sup>20,22</sup> and that these scores were only exceeded when ICMS-evoked  
185 tactile feedback was provided (Fig. 3a). This suggests that without artificial tactile feedback, control is  
186 impaired, much as it is when tactile sensations are absent in people with otherwise normal motor control  
187 capabilities<sup>3,26</sup>. Second, we found that performance improvements were driven primarily by reductions  
188 in the time taken to successfully grasp an object. State transitions, such as object contact<sup>5</sup> during the  
189 grasp phase, are uniquely encoded by tactile feedback in the intact nervous system. That the percepts  
190 signaled these state transitions with high temporal accuracy, and enabled him to grasp objects more  
191 quickly, suggests that ICMS delivered to area 1 of S1 can improve task performance in a way that is  
192 congruent to the way natural cutaneous feedback improves grasp performance. Finally, when ICMS-  
193 induced percepts were provided, performance improved significantly, and when they were removed,  
194 performance returned to pre-ICMS levels (Fig. 3a). Therefore, these observations suggest that the  
195 observed improvements were primarily due to the addition of reliable sensory information, rather than  
196 the result of additional practice. This immediate performance improvement also suggests that ICMS in  
197 S1 was not akin to sensory substitution cues that could have been provided by electrical or mechanical  
198 stimulation of intact skin or audio or visual cues, as the relationship between these cues and behavior  
199 must be learned<sup>27</sup>.

200 Ultimately, ICMS-induced tactile percepts improved task performance to levels not previously observed,  
201 decreased the time spent grasping in ways that were analogous to the role of natural tactile sensations  
202 during grasp state transitions, and do not appear to be the result of practice, suggesting that including  
203 naturalistic somatosensory feedback, like that induced with ICMS, could have a major impact on the  
204 future development and performance of dexterous prosthetic limb systems.

## 205 **Methods**

### 206 *Implantation and electrode arrays*

207 This study was conducted under an Investigational Device Exemption from the U.S. Food and Drug  
208 Administration and is registered at ClinicalTrials.gov (NCT01894802). The study was approved by the  
209 Institutional Review Boards at the University of Pittsburgh and the Space and Naval Warfare Systems  
210 Center Pacific. Informed consent was obtained before any study procedures were conducted.

211 A 28-year-old male participant with tetraplegia due to a C5 motor/C6 sensory ASIA B spinal cord injury  
212 was implanted with two sets of microelectrode arrays (Blackrock Microsystems, Inc., Salt Lake City, Utah,  
213 Fig. 1b). Two intracortical microelectrode arrays with 88 wired channels (10x10 array, 1.5 mm length  
214 platinum electrodes) were implanted in the hand and arm region of M1 in order to decode movement  
215 intent. Two additional microelectrode arrays with 32 wired channels were implanted in area 1 of S1  
216 (6x10 array, 1.5 mm length and coated with a sputtered iridium oxide film) in order to evoke sensations  
217 in the fingers of the right hand when stimulated<sup>7</sup>. The study sessions described here took place between  
218 717 and 738 days after the arrays were implanted.

### 219 *Neural Recording*

220 Voltage recordings from each electrode were band-pass filtered between 0.3 Hz and 7.5 kHz and  
221 digitized at 30,000 samples per second using a NeuroPort signal processor (Blackrock Microsystems, Inc.,  
222 Salt Lake City, Utah). Electrical artifacts induced by microstimulation were rejected using a combination  
223 of digital signal blanking and filtering. During each stimulus pulse the recorded signals were blanked  
224 using a sample-and-hold circuit. The signals were then high-pass filtered using a 750 Hz first-order  
225 Butterworth filter that minimized the effect of additional transient discontinuities in the signal, enabling  
226 fast settling of the wideband signal to baseline. A spike threshold was set at -4.5 times the root-mean-  
227 square of this high-pass filtered signal. Any transient threshold crossings that occurred in the sample



228 immediately after the blanking period were rejected in software. Using this approach, we were able to  
229 record single unit activity within 740  $\mu$ s of the end of a stimulus pulse<sup>28</sup>.

### 230 *Motor decoding*

231 To investigate the ability of the participant to use ICMS-evoked tactile percepts during continuous  
232 control of a prosthesis, we first created a mapping between population-level neural firing rates recorded  
233 in M1 and desired arm movements. A 5 DoF decoder was used in this study, comprising translation of  
234 the endpoint in 3D space, wrist pronation and supination, and flexion and extension of all fingers and  
235 the thumb, with the thumb always opposite the fingers. All 5 DoFs were controlled simultaneously. A 5  
236 DoF control scheme was chosen as it provided a balance between fast training times and a sufficient  
237 degree of dexterity to grasp the different objects used in these experiments.

238 To train the decoder, the participant observed a virtual version of the Modular Prosthetic Limb (MPL)<sup>19</sup>  
239 moving in a 3D environment, as has been described previously<sup>20</sup>. In this task, the participant was asked  
240 to observe and imagine performing the motions of the MPL as the hand was first translated, then  
241 oriented, and finally commanded to grasp targets that were randomly presented throughout the  
242 workspace using a combination of virtual objects and auditory cues. After observing the completion of  
243 27 trials, which took approximately 7 minutes, an optimal linear estimator decoder was derived using an  
244 encoding model that relates neural firing rates to arm kinematics. The encoding model was:

$$245 \quad f = b_0 + b_x v_x + b_y v_y + b_z v_z + b_\theta v_\theta + b_g v_g \quad (\text{Equation 1})$$

246 where  $f$  is the square-root transformed firing rate of a recorded unit,  $v$  is a kinematic velocity, and  $b$  is a  
247 regression coefficient for a given velocity dimension. The dimensions shown in Equation 1 are  $x$ ,  $y$ , and  $z$   
248 translation, wrist rotation ( $\theta$ ), and grasp ( $g$ ). The  $b$  coefficients were calculated using linear regression<sup>29</sup>.  
249 Decoder weights were then calculated using indirect optimal linear estimation (Fig. 1e)<sup>30</sup>.

250 The participant used the decoder trained from observation data to repeat the training task, however the  
251 computer constrained the decoded movement velocities to those that were on the ideal path<sup>31</sup>. Once  
252 this task was completed, a new decoder was trained using the data from the second training set. During  
253 task performance, all firing rates were scaled, prior to being decoded, by dividing them by the ratio  
254 between the population firing rate during the most recent 300 ms and the population firing rate during

255 decoder calibration. This method of scaling firing rates prior to decoding was developed to compensate  
256 for a correlated increase in firing rate across the recorded population that we observe when the  
257 prosthetic hand approaches objects<sup>32</sup>. This scaling allowed the participant to better stabilize the hand  
258 near objects in order to grasp them. Ultimately, this velocity decoder was then used, without computer  
259 assistance—that is the decoders and prosthetic arm control systems were naïve to the goal—to complete  
260 the tasks used to evaluate performance.

261 Decoder performance was evaluated using the physical MPL in a sequence task, where the goal was to  
262 acquire instructed combinations of hand endpoint position, wrist orientation and grasp posture<sup>20,22</sup>. A  
263 total of 3 sets of 10 trials were performed with the robotic limb without computer assistance to establish  
264 the baseline decoder performance accuracy in the absence of objects and ICMS. A trial was considered  
265 successful if the participant was able to place the robotic hand within a position target that was 5 cm in  
266 diameter, orient the wrist to within  $\pm 0.25$  radians and control the grasp aperture to be at least 80% of  
267 the way to maximum flexion or extension of the digits being used.

#### 268 *Intracortical microstimulation*

269 Stimulation pulse trains consisted of cathodal phase first, current-controlled, charge-balanced pulses  
270 delivered at a rate of 100 pulses per second. The cathodal phase was 200  $\mu$ s long, the anodal phase was  
271 400  $\mu$ s long, and the amplitude of the anodal phase was set to half the amplitude of the cathodal phase.  
272 The phases were separated by a 100- $\mu$ s interphase period. Detailed descriptions of sensory percepts  
273 evoked via ICMS of S1 have previously been reported<sup>7</sup>. Briefly, ICMS elicited percepts that were  
274 described by the participant as originating from the bases of the 2<sup>nd</sup> through 5<sup>th</sup> digits and up to the distal  
275 interphalangeal joint of the index finger. We selected the electrodes used to provide ICMS-evoked tactile  
276 percepts prior to the experiments and focused on electrodes that elicited easily detectable percepts with  
277 a clear projected location. One electrode, with a projected field in the proximal interphalangeal joint of  
278 the index finger, was mapped to the output of the torque sensor located at the index finger metacarpal  
279 phalangeal joint of the MPL. Four electrodes with projected fields in either the middle, ring or little finger  
280 were mapped to the torque sensor output from the middle finger of the MPL (Fig. 1c). Together, the  
281 projected fields from the selected electrodes spanned the index, middle, ring and little fingers.

282 For tasks with ICMS, torque sensors located in the motors controlling the MPL fingers provided the signal  
283 that was used to modulate ICMS pulse train amplitude according to the follow equation:

284 
$$A_t = \left( \frac{T_t - T_{min}}{T_{max} - T_{min}} \right) * (A_{max} - A_{min}) + A_{min}$$
 (Equation 2) where  $A_t$  refers to the commanded  
285 pulse train amplitude at time step  $t$ ,  $A_{min}$  and  $A_{max}$  refer to the electrode-specific range of stimulus  
286 amplitudes, and  $T$  represents the torque sensor data that was being used to relay grasp force. We also  
287 set values for the minimum and maximum torque readings,  $T_{min}$  and  $T_{max}$ , respectively, that  
288 corresponded to the minimum and maximum stimulation amplitudes. The selected torque thresholds  
289 were 0.1 Nm and 0.5 Nm, which corresponded approximately to light touch and strong grasp,  
290 respectively. These values were linearly mapped to stimulus amplitudes that ranged from 14 to 64  $\mu$ A  
291 in increments of 4 or 6  $\mu$ A (Fig. 1d). New torque values were sampled every 20 ms and used to update  
292 the pulse train amplitude in real time.

### 293 *Functional task descriptions and scoring metrics*

294 We used two different paradigms to quantify the effects of providing ICMS on the participant's ability to  
295 complete functionally relevant tasks. Both the object transfer task and Action Research Arm Test (ARAT)  
296 have been successfully performed with vision as the only source of feedback<sup>20,22</sup>. Here we directly  
297 compared performance with and without ICMS-evoked tactile percepts while vision was always present.

298 For the object transfer task, we asked the participant to reach to and grasp a cylindrical object (16 cm  
299 tall and 4.3 cm in diameter) with a weighted base placed on the left side of the table, lift the object off  
300 of the table, carry it to the target area on the right, and release the object (Fig. 1f). Two boundaries were  
301 marked on the table that defined a 22.5 cm region where the object was not allowed to touch the table  
302 (red area in Fig. 1f). If the object touched the table between these boundaries, the task could be  
303 continued by moving the object back to the left side of the table and continuing. Once the object was  
304 placed on the right side of the table, an experimenter returned the object to the start position and the  
305 participant repeated the process as many times as possible in two minutes (Supplemental Video 1).  
306 Performance on this task was measured as the number of times the object was successfully moved across  
307 the table in two minutes. This task was always completed prior to the ARAT task.

308 We also conducted a modified version of the Action Research Arm Test (ARAT)<sup>18,33</sup>, which consisted of  
309 moving eight different objects from the left side of a table to a raised platform located on the right side  
310 (Fig. 1g). These objects were selected from the suite of objects that are part of the standard ARAT task<sup>33</sup>  
311 and included four cubes (2.5 cm, 5 cm, 7.5 cm and 10 cm along each edge), a 7.5 cm diameter ball, a  
312 rock, and two cylinders (2.5 cm and 1 cm in diameter and 16 cm tall). Additional objects from the ARAT  
313 task were too small to be grasped by the MPL. The target platform was 34 x 20.5 cm and was elevated  
314 12 cm off the table surface. The objects started approximately 70 cm away from the target platform. A  
315 ninth object from the original ARAT task was also included in which a cup filled with small pieces of paper  
316 and plastic, as a proxy for water, was placed at the right side of the workspace, and an empty cup was  
317 placed 20 cm to the left of it. The participant's task was to empty the "water" from the cup on the right  
318 into the empty cup on the left and replace the originally grasped cup back on the table in an upright  
319 position. This task was considered a success if any "water" landed in the target cup and if the original  
320 cup was placed upright on the table.

321 In all cases, the participant was instructed to complete the task as quickly as possible. The participant  
322 had a maximum of two minutes per attempt, and three attempts per object. Each attempt at transferring  
323 the objects was considered a trial. Trials were timed by experimenters from movement onset to the  
324 object being successfully placed on the target platform. Each trial was scored on a 3-point system in  
325 which a score of zero was awarded if the object was never touched, a score of one was awarded if the  
326 object was touched but the participant was unable to complete the task, a score of two was awarded if  
327 the task was completed in less than two minutes but more than five seconds, and a score of three was  
328 awarded if the task was completed in under five seconds. The best score from the three attempts for  
329 each object was added together to create a single score for the test. Therefore, for the task with nine  
330 objects, a perfect score was 27.

331 The score, which is the validated metric of the ARAT task, fails to take into account other aspects of  
332 performance, such as the total number of completed attempts per object and the actual completion  
333 time. Therefore, we recorded video of all trials and measured the time spent reaching for, grasping, and  
334 transporting the object. All task phase calculations were done offline, marking individual video frames  
335 that spanned each event. Reaching was defined as the time from movement onset until the first object

336 contact. Grasping was defined as the period between object contact and successful object liftoff from  
337 the table. The transport phase spanned object liftoff until object release.

338 We tested the two feedback conditions in a block-design over the course of these experiments. For the  
339 first four sessions, ICMS feedback was delivered to five electrodes. Each experiment day, three blocks of  
340 the sequence task, five blocks of the object transfer task, and one ARAT session were completed. For the  
341 next four consecutive sessions, the same testing protocol was followed, but ICMS was not delivered.

#### 342 *Statistical analysis*

343 Statistical analyses were performed in MATLAB (The MathWorks). Data that were not normally  
344 distributed, as determined using Lilliefors test ( $\alpha = 0.05$ ), are reported as medians and interquartile  
345 ranges (IQR) and the Wilcoxon rank-sum test was used to assess significance for differences in the  
346 median unless otherwise stated. The Mann-Whitney U test statistic is reported for all Wilcoxon rank-  
347 sum tests. Normally-distributed data, as determined using Lilliefors test ( $\alpha = 0.05$ ), are reported as mean  
348  $\pm$  standard deviation and a two-tailed Student's t-test was used to assess significance for differences in  
349 the mean. Specific statistical tests are noted in the text. All object transfer data have  $n = 20$  trials per  
350 feedback condition.

#### 351 *Data availability*

352 Data supporting these findings as well as software routines to analyze these data are available from the  
353 corresponding author upon reasonable request.

354 **End Notes**

355 **Supplementary Information** is available in the online version of this paper.

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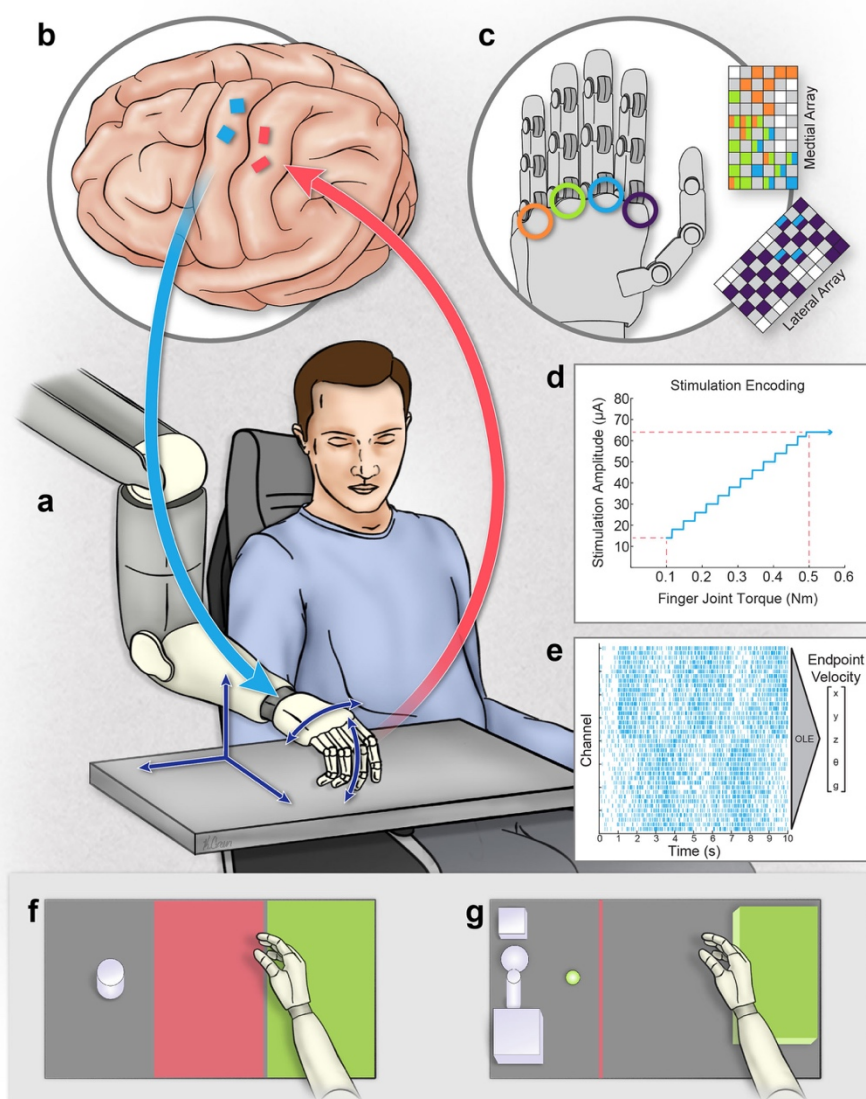
372 **Author Contributions** S.N.F., J.E.D., J.L.C., and R.A.G. designed the study. S.N.F., J.E.D., J.M.W., C.L.H.,  
373 A.J.H., J.L.C., and R.A.G. conducted the experiments. S.N.F. analyzed the data. All authors contributed to  
374 the interpretation of the results. S.N.F. wrote the paper with R.A.G. and J.L.C., and all authors provided  
375 critical review, edits, and approval for the final manuscript.

376 **Author Information** The authors declare that they have no competing interests. Correspondence and  
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378 **Table 1:** Performance metrics for each task per experiment day. The total number of object transfers is  
 379 the sum of all five 2-minute trials per day. ARAT scores were computed as the sum of the best score per  
 380 object, with a maximum score of 27. Each of the nine objects was attempted 3 times, so that the  
 381 maximum number of trials attempted per session was 27. The total median and IQR trial time for  
 382 successful ARAT trials was calculated by pooling trial times across all four sessions per feedback condition  
 383 and calculating the median and IQR from the aggregate distribution.

	Session	Object Transfer (transfers per day)	ARAT Score (out of 27)	ARAT Trials Completed (out of 27)	Median and IQR trial time for Successful ARAT Trials (s)	Median Sequence Task % Correct
With ICMS Feedback	1	97	21	19	11.9 (6.6 – 27.7)	90
	2	74	21	22	12.0 (5.6 – 38.9)	90
	3	93	21	21	8.8 (6.0 – 17.2)	100
	4	88	20	19	8.1 (4.6 – 11.9)	100
	<b>Total</b>	<b>352</b>	<b>83</b>	<b>81</b>	<b>10.2 (5.4 – 18.1)</b>	
Without ICMS Feedback	1	88	19	23	14.0 (11.1 – 30.9)	100
	2	55	16	19	27.6 (18.8 – 37.2)	100
	3	74	17	23	18.7 (12.3 – 41.7)	100
	4	98	17	13	40.5 (15.5 – 48.4)	100
	<b>Total</b>	<b>315</b>	<b>69</b>	<b>78</b>	<b>20.9 (13.1 – 40.5)</b>	

384

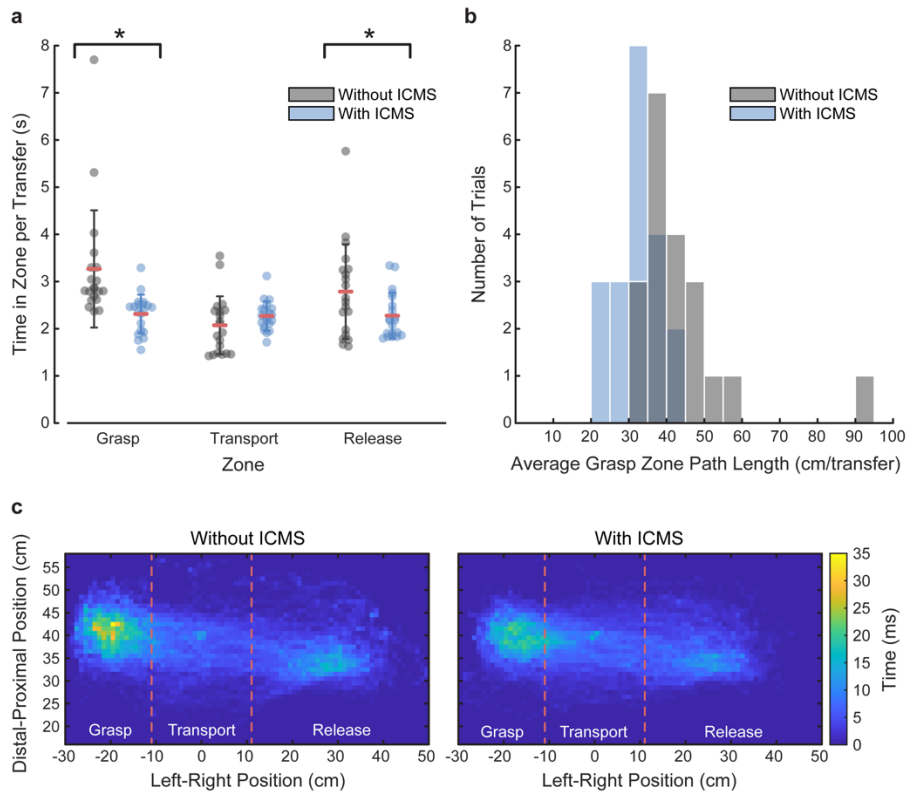


385

386 **Fig. 1:** Overview of bidirectional BCI system components, operation and tasks. **a**, The study participant  
387 used a bidirectional intracortical BCI to control a robotic prosthesis in real time. The arm was positioned  
388 near the participant to provide clear visual feedback, but physical contact was not possible. The  
389 participant controlled the prosthesis in five dimensions, illustrated by the dark blue arrows (3D  
390 translation, wrist rotation and grasp). **b**, Four microelectrode arrays were implanted in the left  
391 hemisphere. Arrays in primary motor cortex (blue) recorded signals which were used to control the  
392 modular prosthetic limb. Arrays in somatosensory cortex (red) delivered stimulation pulses, which  
393 artificially activated neurons, resulting in sensory percepts referred to the hand. **c**, Stimulation of the

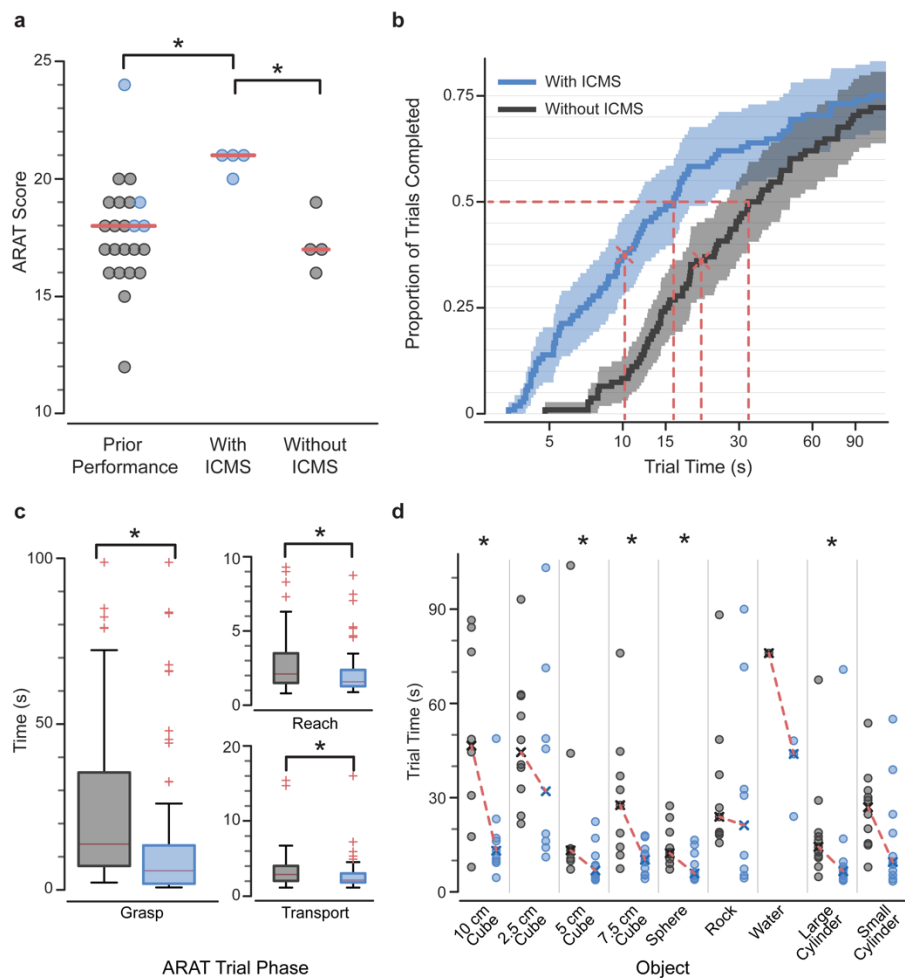


394 electrode arrays in the somatosensory cortex evoked percepts from the base of the fingers. Colored grids  
395 represent individual electrodes on the two microelectrode array and the locations on the hand where  
396 stimulation through each electrode evoked a percept (index finger = purple, middle finger = blue, ring  
397 finger = green, little finger = orange)<sup>7</sup>. Torque sensors in the robot fingers were used to drive selected  
398 electrodes in the somatosensory cortex with matching somatotopic fields (e.g. index finger torque  
399 sensor controlled electrodes evoking percepts in the index finger). **d**, The torque measured at the base  
400 of the fingers increased as more force was applied to the objects. Stimulation current amplitude was  
401 modulated by torque using a linear transformation. **e**, Threshold crossing events were detected from the  
402 multichannel neural recordings in the motor cortex. Each row represents an individual electrode and  
403 each mark represents a threshold crossing event. Using an optimal linear estimation decoding scheme,  
404 endpoint velocity ( $v_x$ ,  $v_y$ ,  $v_z$ ) as well as wrist pro/supination velocity ( $v_\theta$ ) and grasp velocity ( $v_g$ ) were  
405 simultaneously and continuously decoded. **f**, Overhead view of the object transfer task showing the grasp  
406 (gray area), transport (red area) and release (green area) zones. The cylindrical object was placed in the  
407 grasp zone by the experimenter, was grasped using the prosthesis, moved over the transport zone and  
408 placed in the release zone. This process was repeated as many times as possible in two minutes. **g**,  
409 Overhead view of the Action Research Arm Test (ARAT) showing the object presentation position (green  
410 dot) and the raised platform target (green box). Different objects (not all objects shown) were positioned  
411 at a standard location, grasped and then placed on the platform as quickly as possible. For all tasks, the  
412 arm was under full control of the user from the start to the end of a trial.



413

414 **Fig. 2:** Object transfer performance. **a**, Amount of time spent in each task zone, per transfer, by feedback  
415 condition ( $n = 20$  trials per feedback condition). Data for all trials are shown with red lines indicating the  
416 mean value and the whiskers indicating one standard deviation. The amount of time spent in the grasp  
417 and release zones decreased significantly with ICMS feedback ( $*P = 0.002$  and  $0.048$ ,  $t$ -test, respectively),  
418 but the amount of time in the transport zone per transfer was not affected. **b**, Distribution of average  
419 path lengths in the grasp zone per trial for the two feedback conditions, computed as the total path  
420 length divided by the number of transfers. The longer path lengths ( $*P = 0.0007$ ,  $t$ -test) without ICMS  
421 suggest that the extra time spent in the grasp zone was to adjust the endpoint position, rather than to  
422 hold the robot still while attempting to issue a grasp command. **c**, Spatial map of the amount of time  
423 spent in each location in the workspace per transfer. Each individual square represents a  $1 \times 1$  cm region.  
424 Without stimulation, there was substantially more time spent near the object in the grasp zone as shown  
425 by the increase in the number of locations colored yellow in the grasp zone. Red lines indicate zone  
426 boundaries. Color indicates the amount of time spent in each location per transfer.

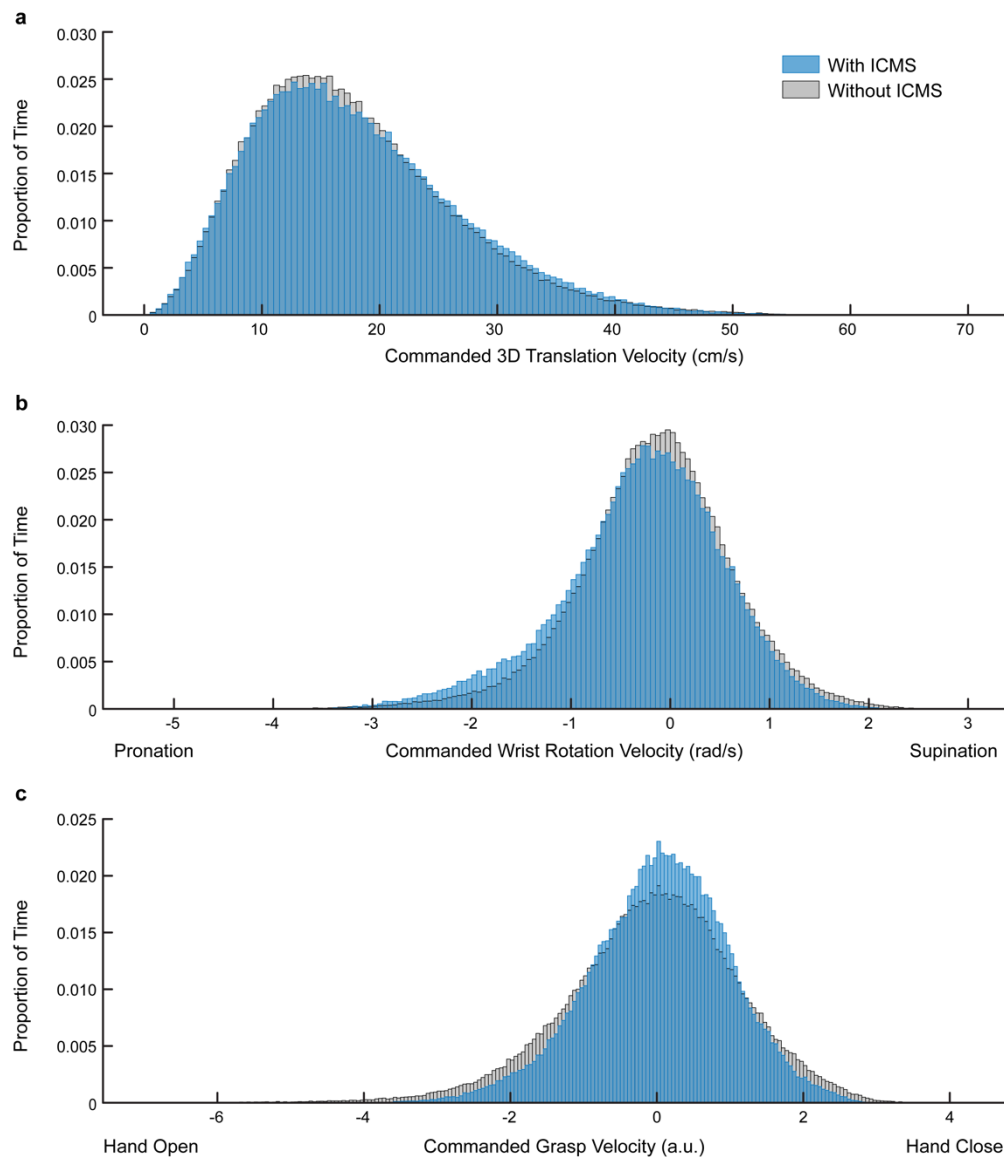


427

428 **Fig. 3:** Effect of ICMS on ARAT task performance. **a**, Comparison of ARAT scores before experiment onset,  
 429 which spanned a range of controlled degrees of freedom and occasionally employed ICMS feedback  
 430 (blue dots), to data from the current experiment with ICMS feedback (blue) and without (gray). ARAT  
 431 scores with ICMS feedback were significantly higher than historic performance ( $*P = 0.005$ , Wilcoxon  
 432 rank-sum test) as well as control tests ( $*P = 0.029$ , Wilcoxon rank-sum test) conducted without ICMS.  
 433 Red lines indicate the median score per paradigm. **b**, Cumulative distribution of individual trial times,  
 434 including failed trials, shown on a log-normalized axis. Trials for all four sessions for each feedback  
 435 condition were combined to compute the empirical cumulative distribution. The horizontal red line and  
 436 connected vertical red lines indicate the times at which 50% of all attempted trials were completed for  
 437 each condition. Vertical dashed lines connected to red X's indicate when 50% of successful trials were  
 438 completed. Shading indicates the 95% confidence bounds, calculated with Greenwood's formula. **c**,  
 439 Amount of time spent in each phase of the ARAT task. Red lines are medians, box outlines are

440 interquartile ranges, and whiskers are the range of the data excluding outliers which are shown as red  
441 '+' symbols. All task phases were faster when ICMS feedback was provided (\*P < 0.01, Wilcoxon rank-  
442 sum test). For this analysis we included trials containing a successful reach, grasp and transport phase.  
443 Water pouring trials were not included as the transport phase is not defined. n = 78 trials for all phases  
444 without ICMS feedback and n = 85 trials for all phases with ICMS feedback. **d**, Effect of ICMS feedback  
445 on completion times for individual objects. Gray dots indicate trial times without ICMS feedback while  
446 blue dots are individual trial times with ICMS. Median trial times are marked for each object/feedback  
447 paradigm with an X. Medians for each object are connected with a red line for visualization. Trial times  
448 were significantly lower for five of the nine objects when ICMS feedback was provided (\*P < 0.05,  
449 Wilcoxon rank-sum test).

## 450 Extended Data



451

452 **Extended Data Fig. 1:** Distribution of commanded robot velocities for each timestep during all ARAT  
453 trials with (blue) and without ICMS (gray) **a**, Commanded 3D translation velocity. The distribution of  
454 commanded translation velocities were different for trials with and without ICMS ( $D = 0.02$ ,  $P < 0.001$ ,  
455 2-sample Kolmogorov-Smirnov test). **b**, Commanded wrist rotation velocity. The distributions of  
456 commanded wrist rotation velocities were different for trials with and without ICMS ( $D = 0.055$ ,  $P <$   
457  $0.0001$ , Kolmogorov-Smirnov test). The median wrist rotation velocity was  $-0.22$  rad/s ( $-0.74 - 0.26$  rad/s  
458 IQR) with ICMS and  $-0.13$  rad/s ( $-0.61 - 0.33$  rad/s IQR) without ICMS. **c**, Commanded grasp velocity. The

459 distributions of commanded grasp velocities were different for trials with and without ICMS ( $D = 0.058$ ,  
460  $P < 0.0001$ , Kolmogorov-Smirnov test). The median grasp velocity was 0.074 a.u. (-0.571 – 0.680 a.u. IQR)  
461 with ICMS and -0.001 a.u. (-0.763 – 0.711 a.u. IQR) without ICMS.

462 **Extended Data Table 1:** Successful ARAT trial times by object. All successful water pouring attempts are  
 463 listed as there were not enough successfully completed trials to calculate the median and IQR.

Object	Median (s)	IQR (s)	n	Mann-Whitney U Statistic	Significance (p-value, Wilcoxon rank-sum test)
10 cm cube – no ICMS	46.6	24.2 – 80.3	8	13	0.027
10 cm cube – ICMS	13.1	9.8 – 18.6	9		
2.5 cm cube – no ICMS	44.5	32.8 – 62.4	10	30	0.408
2.5 cm cube – ICMS	32.0	15.1 – 60.1	8		
5 cm cube – no ICMS	13.2	10.3 – 29.0	8	17	0.043
5 cm cube – ICMS	6.8	4.3 – 11.5	10		
7.5 cm cube – no ICMS	27.6	13.7 – 38.9	9	15	0.010
7.5 cm cube – ICMS	10.2	6.0 – 13.3	11		
Sphere – no ICMS	12.3	10.9 – 17.8	11	22.5	0.024
Sphere – ICMS	5.9	4.4 – 12.3	10		
Rock – no ICMS	23.9	18.7 – 40.1	9	29	0.541
Rock – ICMS	21.2	6.3 – 52.2	8		
Large Cylinder – no ICMS	14.4	11.2 – 18.3	12	27.5	0.019
Large Cylinder – ICMS	6.6	4.5 – 9.2	11		
Small Cylinder – no ICMS	27.0	15.4 – 32.3	10	29.5	0.078
Small Cylinder – ICMS	9.5	5.7 – 23.2	11		
Water – no ICMS (all times)	76			n/a	
Water – ICMS (all times)	24, 43.9, 48.1				

464

465 **Supplementary Information**

466 **Supplemental Video 1:** Object transfer example trials with and without ICMS feedback. In the full trial,  
467 the task lasts for two minutes. The first minute from a trial with the median number of transfers for each  
468 feedback condition is used to illustrate performance.

469 **Supplemental Video 2:** Fastest ARAT trials for each object and feedback condition.

470 **Supplemental Video 3:** ARAT trials for the median completion time for each object and feedback  
471 condition. In cases where there were an even number of completed trials, the faster trial is shown in the  
472 video.

473 **Supplemental Video 4:** Example ARAT trial with ICMS feedback, annotated to indicate task state  
474 transitions and illustrate ICMS delivery.



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