

1 **Title:** Neuronal control of the fingertips is socially configured in touchscreen smartphone
2 users

3

4

5

6 **Authors:** Myriam Balerna and Arko Ghosh

7

8

9 **Affiliation:** Institute of Neuroinformatics, University of Zurich and ETH Zurich,

10 Winterthurerstr. 190, 8400 Zurich, Switzerland

11

12

13 **Corresponding author:** Arko Ghosh, Institute of Neuroinformatics, University of Zurich and

14 ETH Zurich, Winterthurerstr. 190, 8400 Zurich, Switzerland. Email: arko@ini.uzh.ch; Phone:

15 044 63 53098

16

17

18 **Author Contributions:** MB acquired the data, participated in data analysis, and edited this

19 manuscript. AG designed the study, helped in data acquisition, analyzed the data, and drafted

20 this manuscript.

21

22

23 **Abstract**

24

25 As a common neuroscientific observation, the more a body part is used, the less variable the
26 corresponding computations become. We here report a more complicated scenario concerning
27 the fingertips of smartphone users. We sorted 21-days histories of touchscreen use of 57
28 volunteers into social and non-social categories. Sensorimotor variability was measured in a
29 laboratory setting by simple button depressions and scalp electrodes (electroencephalogram,
30 EEG). The ms range trial-to-trial variability in button depression was directly proportional to
31 the number of social touches and inversely proportional to non-social touches. Variability of
32 the early tactile somatosensory potentials was also proportional to the number of social touches,
33 but not to non-social touches. The number of Apps and the speed of touchscreen use also
34 reflected this variability. We conclude that smartphone use affects elementary computations
35 even in tasks not involving a phone and suggest that social activities uniquely reconfigure the
36 thumb to touchscreen use.

37

38

39

40

41 **Introduction**

42
43 Smartphones enable a remarkably broad range of activities. From the perspective of higher
44 cognition, smartphone behavior engages complex computations for decision-making, language,
45 and social interactions. From the perspective of lower-level sensorimotor control, the thumb
46 and the fingertips are repeatedly applied on the touchscreen to essentially either tap or swipe.
47 The observation that even toddlers can easily operate a touchscreen underscores the simplicity
48 of its sensorimotor control (1). According to a series of experiments, a repeated use of the hand
49 in either skillful or simple actions enhances the corresponding representation in the
50 sensorimotor cortex (2–6). Sensorimotor alterations have been observed in trained laboratory
51 monkeys, athletes, Braille readers, and concert string instrument players (3, 5, 7–9). A
52 prominent notion underlying these observations is that the sensorimotor cortex keeps track of
53 the amount of activity generated by the corresponding body part but the exact nature of this
54 tracking is unclear. For instance, in terms of touchscreen use, the cortex may keep track of the
55 number, frequency, and/or behavioral context of touchscreen actions.

56 In real-world observations, the role of the behavioral context in use-dependent plasticity
57 is difficult to establish, partly because of a poor quantification of human actions. For instance,
58 it is common to assess the extent of deliberate practice in elite musicians by using
59 questionnaires (6, 10, 11). Such qualitative approaches do not provide a measure of the amount
60 of activity nor do they capture the activity context. Under well-controlled laboratory conditions,
61 the precise extent of plasticity depends on whether the sensory information presented at the
62 fingertip is used towards a behavioral task or not (4). In general, the cortical plasticity can be
63 modulated by artificially stimulating neuromodulators, such as dopamine or serotonin, that are
64 naturally released according to the behavioral relevance (12). Social behavior strongly engages
65 such neuromodulators and the touchscreen smartphone is prominently used towards social
66 activities (13–15). Therefore, the use-dependent configuration of fingertips in touchscreen users

67 might not be a simple function of sensorimotor activity (16). In particular, touchscreen touches
68 used towards social activities may be distinctly weighted towards use-dependent plasticity of
69 the sensorimotor cortex. Social activities are well compartmentalized within specific Apps,
70 allowing us to quantitatively address use-dependent plasticity in distinct behavioral contexts.

71 In this report, we focused on the elementary property of neuronal variability, or noise,
72 in the sensorimotor system. Substantial theoretical and empirical support exists for the notion
73 that an increased use of a body part reduces the sensorimotor noise (17–21). According to one
74 prominent theory, the brain actively learns to suppress motor variability as if to eliminate
75 unwanted noise, albeit a different theory has been put forward on how the brain may exploit the
76 inherent noise towards learning (18, 22). Sensorimotor variability of the fingertips is diminished
77 with musical practice, by typing on the keyboard, or by deliberately practicing laboratory-
78 designed tasks (18, 23–25). Therefore, a clear-cut prediction would be that the sensorimotor
79 variability of the fingertips is diminished with increased touchscreen use, irrespective of the
80 actions being social or non-social. Alternatively, the complexity, neuromodulation, and the
81 overall significance of social activities may distinctly shape the sensorimotor variability.

82 To address these possibilities, we performed a multiple regression analysis to assess
83 the relationship between (a) Social App usage in the real world and sensorimotor variability
84 measured in the laboratory, and (b) Non-social App use and sensorimotor variability measured
85 in the laboratory. We also examined other variables that were likely to influence sensorimotor
86 variability. To alleviate the effect of development or aging on our measurements, we restricted
87 the analysis to a young adult population (26). Gender-associated differences exist in
88 sensorimotor processing from the fingertips and in the performance variability of a simple task
89 (27, 28). Therefore, we included a dummy variable representing the gender of participants in
90 the regression analysis. Since an accurate control of motor timing is important for rapid actions,
91 fast touchscreen operators may develop a more precise sensorimotor system (29). Therefore, a
92 typical rate of touchscreen touches was added as an explanatory variable. Finally, practicing

93 motor skills in various contexts leads to better performance in a previously not experienced
94 context (30). Since each App on the phone is associated with a distinct context, we quantified
95 the number of Apps in use as an explanatory variable. In summary, type of touchscreen activity
96 (social or non-social), the gender, a typical rate of touchscreen activity, and the number of Apps
97 may all impact sensorimotor computations measured in the laboratory. Incorporating these
98 factors in a single regression model allowed us to address if and how they are separately
99 weighing in on the sensorimotor variability.

100

101

102

103 **Results**

104

105 *Basic features of touchscreen use*

106

107 We quantified touchscreen use for a period of 21 d in a young adult population using a custom-
108 designed software operating in the background to record every touchscreen event and the App
109 targeted by the event. Social activity generated on the touchscreen was sorted based on the App
110 in use. We considered Apps that primarily enabled the communication of personal messages or
111 opinions to a circle of friends or acquaintances as “Social”, and Apps that did not fulfill these
112 functions as “Non-social” (for a sample of Social and Non-social Apps in the database see
113 *Supplementary List 1*). The usage statistics were as follows: the volunteers touched the screen
114 from 1540.3 (20th percentile) to 5562.3 (80th percentile) times per day, and generated between
115 429.1 (20th percentile) and 2486.9 (80th percentile) touches per day on the Social Apps.
116 Importantly, the number of social touches was only partly correlated with the number of non-
117 social touches [variables Log_{10} normalized, $R^2 = 0.29$, $f(1,55) = 22$, $p = 1.9 \times 10^{-6}$, robust linear
118 regression]. Furthermore, volunteers ranked the fingers used according to their preference.
119 Confirming previous findings for smartphone usage, the thumb was ranked by 73% of the users
120 as most preferred on the touchscreen; 16% preferred the index finger; and 10% preferentially
121 used both the thumb and the index finger (16, 31). Remarkably, only one user preferred their
122 middle finger to all the other fingers.

123

124 *Motor variability of the thumb, but not of the middle finger, is associated with touchscreen*
125 *use*

126

127 At the end of the touchscreen recording period, the volunteers performed a simple tactile
128 reaction task in the laboratory where the reaction involved micro switch press-down and
129 release-up actions (*Figure 1a,b*). In theory, the time taken to trigger the press-down action

130 (reaction time) reflects the sensory decision processes, and the time taken to complete the motor
131 act, from pressing down to releasing upwards (movement time), reflects the lower cognitive
132 levels of sensorimotor execution (32–35). The trial-to-trial variability was parametrized using
133 ex-Gaussian fits. Specifically, we estimated the variability of Gaussian curve region lacking
134 very slow actions driven by attention lapses (36, 37). In agreement with the notion that the
135 reaction and movement times reflect distinct neuronal computations, the corresponding
136 variabilities were unrelated to each other [$R^2 = 0.02$, $f(1,53) = 1.1$, $p = 0.299$, robust linear
137 regression]. Since we were interested in the low-level sensorimotor variability, we focused on
138 the movement time.

139 In our multiple linear regression analysis of movement time variability, we treated the
140 number of daily touches on the Social, Non-social, and Uncategorized Apps (all Log_{10} -
141 normalized), gender (dummy variable, female = 1), typical rate of touchscreen touches, and the
142 number of Apps used during the recording period, as explanatory variables. First, let us
143 elaborate on the thumb use analysis data (the thumb was most preferred for touchscreen
144 interactions). The full regression model was highly significant [$R^2 = 0.45$, $f(6,48) = 6.5$, $p =$
145 4.43×10^{-5} , robust multiple linear regression; for variation inflation factors see *Supplementary*
146 *Figure 1*]. The maximum variation inflation factor was 2.7, indicating that the regression model
147 was not affected by multicollinearity (38). According to the simple prediction of use-dependent
148 reduction in sensorimotor variability, the regression coefficient for social touches was expected
149 to be either zero, suggesting that social actions are not distinctly tracked by the brain, or
150 negative, suggesting that social actions are distinctly tracked but a higher number of social
151 touches leads to lower sensorimotor variability. Contrary to these predictions, we found that
152 higher number of social touches led to increased movement time variability [$t(1,48) = 3.96$, p
153 $= 0.00024$, *Figure 1c*]. The case for non-social touches was anticipated, with higher number
154 linked with smaller variability [$t(1,48) = -2.66$, $p = 0.011$, *Figure 1d*]. The same was observed
155 for uncategorized touches [$t(1,48) = -2.45$, $p = 0.018$].

156 To what extent does the social behavior-movement time variability relationship (*Figure*
157 *1c*) depend on App classification? We addressed this by repeating our analysis 10^5 times using
158 randomly shuffled categories. The relationship uncovered for social touches was well separated
159 from the distribution of relationships obtained by quantifying random category touches (*Figure*
160 *1e*). This result further supported the notion that the type of touchscreen behavior determines
161 how neuronal processes responsible for the thumb are configured.

162 To address whether the touchscreen behavior-movement time variability relationship
163 was specific to the thumb, a subset of volunteers also performed the task with their middle
164 finger (which was rarely indicated as the preferred finger for touchscreen use). We found a
165 strong association between the explanatory variables and movement time variability for the
166 thumb [$R^2 = 0.79, f(6,10) = 6.43, p = 0.0053$, robust linear regression], similarly to data for the
167 full set of volunteers. Importantly, here too the number of social touches was significantly
168 related with movement variability [$t(1,10) = 2.70, p = 0.022$, *Supplementary Figure 2*].
169 However, the results for the middle finger were strikingly different. We found no correlation
170 between the explanatory variables and movement time variability [$R^2 = 0.28, f(6,10) = 0.66, p$
171 $= 0.683$, robust linear regression]. Moreover, the regression coefficient associated with the
172 number of social touches was non-significant [$t(1,10) = -0.30, p = 0.77$, *Supplementary Figure*
173 *2*]. These results suggested that the putative impact of touchscreen use on movement time
174 variability is specific to the finger that is repeatedly engaged on the touchscreen.

175
176 *Social keypad touches distinctly impact on motor variability*
177

178 In the analyses conducted above, the touchscreen touches consisted of different gestures, i.e.,
179 keypad taps, swipes, and pinches. One interesting possibility was that the correlations identified
180 for social touches were driven by the different gestures used for Social Apps. Therefore, we
181 next restricted our analysis to pop-up keypad touches. It is safe to assume that for sensorimotor
182 control, i.e., the degrees of freedom for motor control and visuomotor coordination, keypad

183 touches for Social Apps are the same as the ones for Non-social Apps. The difference concerns
184 the specific content typed. Full regression model based on the keypad touches was significantly
185 related to motor time variability [$R^2 = 0.60, f(6,25) = 6.36, p = 0.0004$, robust linear regression].
186 We noted that the higher the number of social touches on the keypad, the larger the movement
187 time variability [$t(1,25) = 3.76, p = 0.0009$, **Supplementary Figure 3**]. This suggested that
188 gestures cannot simply account for the distinct imprint of social activities on motor time
189 variability.

190

191 *Social and non-social touches show distinct patterns of correlations as a function of time*

192

193 The continuously recorded touchscreen behavior made prior to the laboratory measurements
194 allowed us to address the question of whether the touchscreen-movement time variability
195 relationship changes as a function of time. Should the relationship be driven by rapid plasticity,
196 then it would simply decay as a function of time. However, if slow mechanisms were
197 operational, then the relationship would peak with older rather than the most recent touchscreen
198 experiences, as if indicating a delayed impact of touchscreen behavior. F-values, describing the
199 relationship strength, revealed a simple decay trend for non-social touches. This was well
200 described ($R^2 = 0.82$, **Figure 1f**) by:

201

$$\begin{aligned} 202 \quad & Y_{\text{Non-social touches vs. motor variability relationship strength}} \\ 203 \quad & = 8.6 \times e^{\text{Number of non-social touches} \times 0.15} \end{aligned}$$

204

205 The relationship for social touches was more complicated, consisting of both an initial decay
206 and a strong relationship with older data. This dynamic was well described ($R^2 = 0.81$, **Figure**
207 **1f**) by:

208

209 $Y_{\text{Social touches vs. motor variability relationship strength}}$

210 $= [24.53 \times e^{-\left(\frac{\text{Number of social touches} + 17.06}{1.97}\right)^2}] + [2.06 \times 10^{15} \times e^{-\left(\frac{\text{Number of social touches} - 655.2}{114.7}\right)^2}]$

211

212

213 The distinct pattern of time-dependent relationships for social vs. non-social touches suggested
214 that they engage different forms of plasticity.

215 We also revealed the dynamics of other explanatory variables that were significantly
216 related to touchscreen use recorded over the 21-d period. In brief, as anticipated, variability was
217 smaller with a higher typical rate of touchscreen touches [$t(1,48) = -5.10, p = 5.73 \times 10^{-6}$,
218 *Supplementary Figure 4*] and with a larger number of Apps used [$t(1,48) = -3.29, p = 0.002$,
219 *Supplementary Figure 4*]. Time-dependent dynamics for the typical rate of touchscreen
220 touches indicated slow plasticity but the “number of Apps” variable dynamics indicated both
221 rapid and slow plasticity (*Supplementary Figure 4*). The gender of the user was not
222 significantly associated with the motor time variability [$t(1,48) = -0.90, p = 0.37$].

223

224 *Social touches distinctly affect the reaction time variability*

225

226 We opportunistically explored the variability of higher cognitive levels captured by the reaction
227 time. For the reaction time variability, the full regression model was significant but weak [$R^2 =$
228 $0.26, f(6,49) = 2.86, p = 0.02$, robust linear regression]. Similarly to the results for movement
229 time variability, we observed that a higher number of social touches was associated with greater
230 reaction time variability [$t(1,49) = 2.72, p = 0.009$, *Supplementary Figure 5*]. The only other
231 explanatory variable that significantly contributed to the regression model was the participant
232 gender, such that the females showed less variability [$t(1,49) = -3.25, p = 0.0002$] than the
233 males. Since the reaction and movement times measure different aspects of cognition, taken

234 together, they suggested that the putative impact of social touches is not restrained to the lower-
235 levels of sensorimotor cognition.

236

237 *The signal-to-noise ratio of the early somatosensory evoked potentials from the thumb strongly*
238 *corresponds with touchscreen use*

239

240 To address the neurophysiological predictions of use-dependent plasticity, we measured the
241 cortical potentials in response to tactile stimulation of the fingertips using
242 electroencephalography (EEG). The EEG signals were noisy at a single trial level and an
243 averaging method across several trials revealed an event-related potential (**Figure 2a**) (39). We
244 used the ratio between the average response and a trial-to-trial deviation from the average as a
245 measure of putative signal-to-noise ratio. Based on the observations from an electrode showing
246 the strongest response (according to the grand average), a distinctive rise in the signal-to-noise
247 ratio was observed, with a peak at 55 ms (latencies are reported from the onset of stimuli, **Figure**
248 **2b**).

249 We were interested in both the direction and timing of neuronal correlates of
250 touchscreen use. Based on the simplistic prediction of use-dependent plasticity, we anticipated
251 that the more the fingertips are used on the touchscreen (irrespective of the social category of
252 the activity), the larger the signal-to-noise ratio (6, 16, 40). Measurements at different latencies
253 reflect distinct stages of the cortical somatosensory processing, with the potentials between 40
254 and 100 ms dominated by the primary somatosensory cortex, and those between 100 and 200
255 ms dominated by the secondary somatosensory and frontal cortices (41, 42).

256 Multiple regression analysis included all time points from -30 to +200 ms and was
257 conducted across all electrodes. Significant relationships with social and non-social touches
258 were largely restricted to the electrodes above the contralateral sensorimotor cortex
259 (contralateral to the stimulated hand), i.e., the electrodes that also showed the highest signal-to-

260 noise ratio (*Figure 2c-f*). Our analysis revealed that the number of social touches was
261 correlated with the thumb-associated signal-to-noise ratio at time points between 70 and 100
262 ms, and then again between 125 and 150 ms (*Figure 2c*). Notably and contrary to the simplistic
263 prediction, the direction of the correlation was such that the higher the number of social touches,
264 the lower the signal-to-noise ratio (*Figure 2c*). In contrast, the history of non-social touches
265 was significantly related to the cortical signals in a narrow window between 135 and 150 ms,
266 so that the higher the number of touches, the larger the signal-to-noise ratio (the relationships
267 with other explanatory variables are presented in *Supplementary Figure 6*). These results
268 suggested that social touches were tracked by the somatosensory cortex separately from non-
269 social touches, and that the social touches were encoded at multiple stages of somatosensory
270 processing.

271 To verify whether the uncovered relationship between the number of social touches on
272 the phone and signal-to-noise ratio for the thumb was based on the social category per se, we
273 once again employed random category shuffling. Based on the maximum signal-to-noise ratio,
274 for the signal-to-noise ratio at the chosen electrode, the distribution of relationships for the
275 number of touches on random categories was well separate from the relationship based on
276 touches on Social Apps (*Figure 2g*). We also explored the relationships between the number
277 of social touches on the phone and the somatosensory signal-to-noise ratios for the index and
278 middle fingers, in addition to the thumb (*Figure 2h*). In comparison with the thumb, the
279 relationships were substantially weaker for the index finger and absent for the middle finger. In
280 summary, these results suggested that engaging in social activity on the touchscreen diminishes
281 the cortical signal-to-noise ratio associated with the thumb, contrary to the anticipated
282 consequences based on a simplistic view of use-dependent plasticity.

283

284

285

286 *Neuronal correlates of social touches on the keypad*

287

288 The neuronal correlates of social touches described above were based on all touchscreen
289 gestures, leaving open the possibility that the correlates reflected the underlying differences in
290 the gestures used on Social vs. Non-social Apps. We matched the gesture type by restricting
291 the analysis to pop-up keypads. A near-identical pattern of correlates was observed as in the
292 original analysis that included all gestures. Briefly, with an increasing number of social touches
293 on the keypad, the signal-to-noise ratio associated with the thumb between 70 and 100 ms
294 decreased (*Supplementary Figure 7*).

295

296 *Social touches vs. somatosensory signal-to-noise ratio correlations as a function of time*

297

298 According to the results presented above, the signal-to-noise ratio at early stages of the cortical
299 somatosensory processing was significantly correlated with the number of social touches on the
300 touchscreen but not with the number of non-social touches. Touchscreen behavior was
301 continuously recorded prior to the EEG measurements. We leveraged this continuity to
302 establish the temporal dynamics in terms of the time elapsed between the touchscreen behavior
303 and the EEG measurement. Using the observations from the chosen electrode, we found the
304 following complex temporal dynamics: the relationships were strong when examining recent
305 social touches, followed by complex relationships decay, and the relationships picked up again
306 with older touches (*Figure 2i*). The dynamics, although apparently more complicated than what
307 was observed for the social touches vs. movement time variability relationships, were well
308 captured using the following formula ($R^2 = 0.83$):

309

310

311

312 $Y_{\text{Social touches vs. signal-to-noise ratio relationship strength}}$

$$\begin{aligned} 313 &= (24.1 \times e^{-\left(\frac{\text{Number of social touches} + 6.68}{1.1}\right)^2}) \\ 314 &+ (21.3 \times e^{-\left(\frac{\text{Number of social touches} + 2.01}{3.3}\right)^2}) \\ 315 &+ (22.5 \times e^{-\left(\frac{\text{Number of social touches} + 24.76}{12.1}\right)^2}) \end{aligned}$$

316

317

318 This relationship pattern suggested that a complex mix of both fast and slow mechanisms of
319 plasticity is employed when configuring the cortex according to the history of social touches.

320

321 *Increased trial-to-trial variability in neuronal response amplitude is associated with social*
322 *touches on the touchscreen*

323

324 A reduction in somatosensory cortical signal-to-noise ratio associated with a larger number of
325 social touches may be associated with two entirely different attributes of neuronal activity. First,
326 the reduction may genuinely reflect an alteration in the amount of neuronal activity; and second,
327 the reduction may reflect increased trial-to-trial temporal jitter, so that averaging of responses
328 across trials results in a smaller amplitude (43). In theory, it would be possible to address these
329 two possibilities by focusing on the shape of the evoked potentials at a single trial level to
330 estimate the variability in peak amplitude separately from peak latency. However, in practice,
331 the EEG signals intensely fluctuate at the single trial level, precluding facile analysis of the
332 shape of the evoked potentials. To partly smooth the signals, we averaged a subset of 25 trials.
333 Next, we detected the amplitude and latency of local maxima that immediately followed the
334 temporal landmarks placed at 50 and 85 ms (**Figure 3a**). The landmarks were set so as to focus
335 on the initial stages of somatosensory processing that did not encode the number of social
336 touches according to the signal-to-noise ratio analysis (50 ms) and later stages that did (85 ms,

337 at the center of the correlated range of 70–100 ms). We repeated this with a different subset of
338 25 trials, 10^5 times for each volunteer, to estimate the trial-to-trial variability of the
339 corresponding latencies and amplitudes (**Figure 3b,c**).

340 The variability of cortical signal amplitudes detected by the 50 ms landmark was
341 unrelated to the explanatory variables that included movement time variability in addition to
342 the original set of variables derived from the touchscreen and gender [$R^2 = 0.31, f(7,33) = 2.11,$
343 $p = 0.07$, robust linear regression]. In particular, amplitude variability was clearly unrelated to
344 the number of social touches [$t(1,33) = 0.68, p = 0.5$] and non-social touches [$t(1,33) = -0.02,$
345 $p = 0.98$, **Supplementary Figure 8**]. The variability of signal latencies at this temporal landmark
346 was also unrelated to the social touches [$t(1,33) = 0.60, p = 0.6$] and non-social touches [$t(1,33)$
347 $= -0.23, p = 0.8$, **Supplementary Figure 8**]. In contrast, the variability of signal amplitudes
348 detected by the 85 ms landmark was strongly related to the explanatory variables [$R^2 = 0.45, f$
349 $(7,33) = 3.9, p = 0.003$, robust linear regression]. We observed that the higher the number of
350 social touches, the larger the variability [$t(1,33) = 4.62, p = 5.6 \times 10^{-5}$, **Figure 3d**]. There was
351 a weak trend linking the number of non-social touches and neuronal variability, such that the
352 higher the number, the lower the variability [$t(1,33) = -1.9, p = 0.07$, **Figure 3e**]. In terms of
353 variability of signal latencies at this landmark, a weak relationship with the explanatory
354 variables was observed [$R^2 = 0.34, f(7,33) = 2.5, p = 0.04$, robust linear regression], and the
355 higher the number of social touches, the larger the neuronal temporal variability [$t(1,33) = 2.3,$
356 $p = 0.03$, **Supplementary Figure 8**]. Finally, we did not find any significant links between
357 movement time variability and neuronal response variability [latency dispersion at 85 ms: $t(33)$
358 $= -1.8, p = 0.08$; amplitude dispersion at 85 ms: $t(33) = -1.91, p = 0.06$]. This raised the
359 possibility that although both movement time variability and neuronal variability increased with
360 social touches, the two measures themselves reflected largely separate neuronal process.

361 In summary, the results were consistent with the notion that trial-to-trial variability of
362 both, the degree and timing of neuronal activity, increased according to the number of social

363 touches. However, it must be noted that the evidence for increased temporal variability was
364 rather weak in contrast with the evidence for increased amplitude variability.

365

366 *Time-dependent structure of the relationships between touchscreen use and neuronal*
367 *variability*

368

369 As with the preceding time-dependent analyses, we reasoned that the putative plasticity
370 attributes could be studied by sampling touchscreen behavior at various times before laboratory
371 measurements. Since a tendency was observed linking non-social touches over the entire
372 recording period with neuronal variability, we first studied temporal dynamics of the
373 phenomenon using F-values associated with non-social touches. The relationship strength
374 simply decayed as a function of time and was well described by the following formula ($R^2 =$
375 0.81 , **Figure 3f**):

376

$$377 \quad Y_{\text{Non-social touches vs. variability relationship strength}} = 9.9 \times e^{\text{Number of non-social touches} \times 0.34}$$

378

379 The social touches showed more complex dynamics, such that the relationship was
380 strong when using recent touchscreen data, weakening over time. The relationship was also
381 strong when using older data. This was well captured by the following equation ($R^2 = 0.72$,
382 **Figure 3f**):

383

$$384 \quad Y_{\text{Social touches vs. variability relationship strength}}$$

385

$$386 \quad = (11.04 \times e^{-\left(\frac{\text{Number of social touches} + 16.6}{7.47}\right)^2}) + (1.2 \times 10^{15}$$

$$387 \quad \times e^{-\left(\frac{\text{Number of social touches} - 203.6}{36.3}\right)^2})$$

388

389 Time-dependent neuronal variability dynamics of the correlates were qualitatively
390 similar to what we observed for motor time variability. Overall, these results indicated that
391 social touches are distinctly integrated to reconfigure the cortical circuits associated with the
392 thumb and both rapid and slow forms of use-dependent plasticity are employed towards this
393 putative reconfiguration.

394

395

396

397

398

399

400 **Discussion**

401

402 One striking finding of this report was that the individuals who generated a larger number of
403 social touches on the touchscreen were more variable in their response times when performing
404 a simple task with the thumb. The somatosensory cortical activity also exhibited more
405 variability associated with social touches. The dense digitization of behavior on the smartphone
406 allowed us to quantify and contrast these relationships with the history of non-social touches.
407 The results based on social touches data were contrary to the simplistic view of use-dependent
408 plasticity, which predicted more stable sensorimotor computations corresponding to an
409 increased touchscreen use. Even when placed outwith the framework of use-dependent
410 plasticity, these results suggested that the understanding of inter-individual differences in
411 elementary sensorimotor control is deeply inter-connected with the details of behavior
412 expressed in the real world.

413 We interpret these results as indicative that social activities on the touchscreen lead to
414 increased sensorimotor variability. However, the correlational nature of our findings precludes
415 us from discarding an alternative possibility that a higher sensorimotor variability leads to more
416 social touches, or that a common factor determines both these variables. Based on the current
417 knowledge, a reasonable case for the former cannot be made but the latter must be seriously
418 considered. Extraverted individuals are characterized by higher usage of Social Apps than
419 introverts and extraversion is associated with diminished somatosensory cortical activity
420 evoked by the fingertips (44, 45). The extraversion-based relationship is specific to the left hand
421 and is absent for the right hand (45). In contrast, our study focused on the right hand. Moreover,
422 the extraversion-based relationship is not specific to particular fingertips, in contrast to the
423 thumb-specific correlates of touchscreen use uncovered here and in our previous study (16). In
424 addition to the personality factor, cognitive states that lead to enhanced attention or arousal may
425 influence both the touchscreen behavior and neuronal measures in the laboratory (46). This

426 state-dependent view does not account for the observation that touchscreen-based correlates
427 were largely restricted to the thumb. It also does not account for how the 1-2 weeks old
428 touchscreen data could strongly correlate with the laboratory measurements. Given these
429 evidences, the framework of use-dependent plasticity may be the most appropriate for
430 considering our findings.

431 Neuronal correlates uncovered here suggest that low-level sensorimotor processing, at
432 the primary somatosensory cortex, encodes the history of social touches on the touchscreen.
433 This observation is consistent with the notion that the primary sensory areas do not exclusively
434 represent the incoming sensory inputs but integrate these inputs into behavioral context (47).
435 For the somatosensory cortex, this is supported by laboratory observations that the cortex
436 participates in multi-sensory integration and that factors, such as attention, modulate its activity
437 and plasticity (4, 48, 49). Our findings provide a real-world example that the behavioral context
438 of an experience is a key factor in configuring the cortex.

439 The temporal dynamics of the associations uncovered herein provide some insights into
440 the nature of processes engaged in the putative use-dependent plasticity. For both, trial-to-trial
441 movement time variability and neuronal variability, we observed a complex fall and then rise
442 in the relationships strength with older data from the Social Apps. This pattern suggests that
443 social touches trigger both rapid and slow mechanisms of plasticity. Rapid mechanisms may
444 include such processes as alteration in excitatory-inhibitory balance or the unmasking of pre-
445 existing circuits (8, 50). Slow mechanisms may include the formation of entirely new pathways,
446 comprising changes of the underlying white matter that may take weeks to complete (5). The
447 relationship with older data from the Non-social Apps simply decayed, suggesting exclusive
448 deployment of rapid mechanisms.

449 It is not clear how the sensorimotor cortex sorts the touches on Social Apps separately
450 from Non-social Apps. One possibility is that the social touches are sorted based on top-down
451 information flow via neuromodulators or feedback from high-level neuronal networks engaged

452 in social behavior (14, 51). Another possibility is that the touches are sorted in a bottom-up
453 manner based on distinct sensory features that accompany the social touches. We tested this
454 possibility by restricting our analysis to pop-keypad touches, only to discover that even when
455 the gestures were apparently matched, the social touches showed a distinct sensorimotor
456 correlate. Other relevant but unexplored differences in the input statistics of Social vs. Non-
457 social Apps may exist in terms of the length of the words typed or the complexity of language
458 used. Nevertheless, a previous study on typing skills suggested that greater experience was
459 associated with smaller sensorimotor variability (23). Therefore, the increased variability
460 associated with social touches cannot be easily explained using the widely held notions on use-
461 dependent plasticity.

462 Why does sensorimotor variability increase with social touches on the touchscreen? We
463 propose that the increased variability is an inevitable consequence of repeated engagement of
464 the thumb in social cognition. Essentially, social touches on the touchscreen are accompanied
465 by an array of neuronal processes associated with language, anticipation, and social status (13).
466 Presumably, using Hebbian-like mechanisms of plasticity, the thumb becomes increasingly
467 connected with this broad array of processes. It is this enhanced embedding of sensorimotor
468 processing in a broad array of neuronal processes that may lead to increased noise in low-level
469 circuits (52).

470 In the population of young adults sampled here, the median number of touchscreen
471 touches generated per day was 2.7×10^3 and the most active individual generated 1.1×10^4
472 touches per day. These numbers reflect the dominance of touchscreen events in modern human
473 actions, comparable in magnitude with the number of steps (1×10^4) or eye blinks per day (1.2
474 $\times 10^4$) (53, 54). Therefore, it should not be surprising that the neuronal sensorimotor processing
475 is reconfigured by touchscreen behavior (16). The nature of the touchscreen behavior-neuronal
476 relationships uncovered by leveraging seamless quantifications on the smartphone warrants a
477 more in-depth examination on how social activities on the touchscreen reconfigure the brain.

478 These links also highlight the complex nature of neurobehavioral relationships in elementary
479 sensorimotor control, such that the history of social and non-social touches, the rate of
480 touchscreen activity, and number of different Apps used are all independently encoded to
481 impact future computations. Addressing how the quantitative history of touchscreen behavior
482 relates to elementary neuronal functions will help bridge the large gap between inherently
483 artificial laboratory experiments and the behavior expressed in the real world.

484

485

486

487

488

489

490

491

492

493

494 **Materials and Methods**

495

496 *Subjects*

497

498 Volunteers (n = 57) were recruited using campus-wide announcements at the University of
499 Zurich and ETH Zurich between December 2014 and August 2015. The sample consisted of
500 subjects within a narrow age group [26 females; 23 (20th percentile) to 28 (80th percentile)
501 years old]. The age at which the volunteers reportedly began using the phone was also narrowly
502 distributed [19 (20th percentile) to 25 (80th percentile) years old]. Previous reports on inter-
503 individual variability in cortical somatosensory signal-to-noise ratio, touchscreen use-
504 dependent plasticity and use-dependent reduction in sensorimotor variability employed a
505 sample size between 15 – 28 (16, 18, 23, 55). Essentially we anticipated a weaker impact of the
506 social touches on the touchscreen than the explanatory variables studied before, i.e., deliberate
507 laboratory practice, touchscreen use in general and the presence of autism spectrum disorder.
508 Therefore, we doubled the sample size and employed more regression parameters than the
509 previous studies to increase the sensitivity of our analysis. All experimental procedures were
510 conducted according to the Swiss Human Research Act approved by the cantons of Zurich and
511 Vaud. The procedures also conformed to the Declaration of Helsinki. The volunteers provided
512 written and informed consent before participating in the study. Reasonable health, right-
513 handedness, and ownership of a non-shared touchscreen smartphone were pre-requisites for
514 participation. The handedness was further verified by a questionnaire (55). The fingers used on
515 the touchscreen were analyzed using a pictorial survey where the volunteers ranked each finger
516 on a scale 1–10 (1, least preferred; 10, most preferred).

517

518 *Smartphone data collection and analysis*

519

520 A custom-designed background App was installed on the volunteers' smartphones to quantify
521 the touchscreen behavior (see the Supplementary Methods for in-depth description of the design
522 and performance specifications of the App). Briefly, the App recorded the timestamps of
523 touchscreen events and the label of the App on the foreground. The App recorded the
524 touchscreen events with an interquartile error range of 5 ms. Data were stored locally and
525 transmitted by the user at the end of the observation period via secure email. Smartphone data
526 were processed using custom written scripts on MATLAB (MathWorks, Natick, USA). In
527 smartphones with more relaxed permission settings, the pop-up keypad touches were
528 additionally labeled. The number of touches on each App category ("Social", "Non-social", or
529 "Uncategorized") was divided by the length of the recording period to determine the number of
530 touches per day. Apps that functioned to enable social interactions between a circle of friends
531 or acquaintances were labeled as "Social" and Apps that clearly did not feature this functionality
532 were labeled as "Non-social". Apps whose label was poorly registered by the operating system,
533 untraceable on Google Play, or that contained both social and non-social properties, e.g.,
534 gaming Apps with social messaging, were labeled as "Uncategorized". The touches that were
535 separated by less than 50 ms were eliminated from further analysis. The rate of touchscreen
536 events was determined as $\frac{1}{\text{Median inter-touch interval}}$. A recording period of up to 21 d was used
537 for the main regression analysis. The number of Apps that were used over the recording period
538 was counted.

539

540

541 *Simple reaction time task and analysis*

542

543 Volunteers responded to a brief (10 ms) tactile pulse by depressing and releasing a button
544 mounted on a micro switch. The tactile pulse was presented by using a computer-controlled
545 solenoid tactile stimulator (Heijo Research Electronics, London, UK). The stimulating
546 magnetic rod (2 mm in diameter) generated a supra-threshold 2-mN contact. The thumb or the
547 middle finger was stimulated. The micro switch (extracted from RX-300 optical mouse,
548 Logitech, Lausanne, Switzerland) was operated by press-downwards and release-upwards
549 movements of the thumb or the middle finger. All volunteers performed the task with the thumb
550 (n = 57) and a subset of randomly chosen volunteers performed the task with the middle finger
551 in addition to the thumb (n = 17).

552 The task was repeated 500 times (for each fingertip) within an experimental session,
553 with 2 min break in the middle of the session. The pulses were delivered with 3 ± 1 s gap and
554 the button presses generated analogue signals that were digitized at 1 kHz. In two volunteers,
555 the micro switch off-state measurements malfunctioned; in one other volunteer, the on-state
556 measurements malfunctioned. The corresponding measurements were subsequently eliminated
557 from further analysis. The reaction time and movement time (the time taken to execute button
558 depression) were fitted with three ex-Gaussian parameters. This form of fitting separates
559 skewed reaction time data into a Gaussian region and an exponential region. Mean of the
560 Gaussian region was captured by parameter μ , and variability of the Gaussian region by
561 parameter σ . The exponent τ captured unusually slow responses. The parameters were estimated
562 using previously described MATLAB scripts (36).

563

564 *EEG data acquisition and analysis*

565

566 A subset of volunteers (n = 43) participated in EEG experiments. The volunteers were seated

567 upright for the EEG and the right, stimulated, hand was concealed by a baffle. Computer-
568 controlled solenoid tactile stimulator (see above) was attached to the right thumb tip and to the
569 right index and middle finger tips. To ease the tedium of the hours-long measurements required
570 for gathering the tactile evoked potentials data (SSEPs), volunteers were allowed to view a
571 movie (David Attenborough's Africa series); white noise, played to mask the sound generated
572 by the stimulator, was mixed with the movie soundtrack and delivered through headphones.
573 The number of trials was set to 1000 for each fingertip, randomized for the tips, and the stimuli
574 were separated for each fingertip by 2–4 s. A non-alcoholic and caffeine-free drink break was
575 offered every 10 min, for a maximum of 10 min. To record the EEG signals, 64 electrodes were
576 used (62 equidistant scalp electrodes and two ocular ones), against a vertex reference (EasyCap,
577 Herrsching, Germany), as previously reported (16). The electrode locations were digitized in a
578 3D nasion-ear coordinate frame (ANT Neuro and Xensor software, Netherlands) for a
579 representative volunteer. The signals were recorded and digitized by BrainAmp (Brain Products
580 GmbH, Gilching, Germany) at 1 kHz. Offline data processing was accomplished using
581 EEGLAB, a toolbox designed for EEG analysis on MATLAB (56). The data were referenced
582 to the average of all scalp electrodes and band-pass filtered between 1 and 80 Hz. "Epoched"
583 trials over 80 μ V were eliminated to remove large signal fluctuations, e.g., from eye blinks. The
584 data were further processed using independent component analysis. Components dominated by
585 eye movements and other measurement artifacts were eliminated by using the EEGLAB plug-
586 in SASICA (57). The signal-to-noise ratio was estimated using the linear modeling toolbox
587 LIMO EEG (EEGLAB plug-in) (58). In this toolbox, R^2 values were estimated for each
588 volunteer based on single trials, as a sum of squares of the putative signal divided by the sum
589 of squares of the residuals. Essentially, the predominant notion in the sensory evoked potential
590 research field is that the average over multiple trials extracts a signal that is otherwise hidden
591 in the measurement noise and background neuronal processes (39). The signal-to-noise ratio in
592 this case captures how well the estimated mean (putative signal) represents the data. To

593 normalize the data across the sampled population, the square root of the putative signal-to-noise
594 ratio was used for subsequent analyses using multiple linear regression.

595 The trial-to-trial variations in EEG responses were estimated based on the rectified
596 event-related waveforms of 25 randomly sampled samples. The resampling was reiterated 10^5
597 times for each individual. The first local maxima above 50 and 85 ms were estimated for each
598 iteration. The maxima were estimated using a MATLAB add-on function (“EXTREMA”). This
599 form of bootstrapping was used to recover the distribution of signal timings and amplitudes,
600 and these distributions were subsequently used to derive the coefficient of dispersion for each
601 individual ($\frac{\text{Inter quartile range}}{\text{Median}}$) at marked time points.

602

603 *Correlational statistics*

604

605 All analyses involving the reaction and movement times were conducted by robust–bi-square–
606 multiple linear regression analysis (implemented in MATLAB). The fitted model was evaluated
607 using ANOVA with a level of significance set at $p = 0.05$. The following main regression
608 equation was used:

609

$$\begin{aligned} 610 \quad Y = & \beta_0 + \beta_1 X_{\text{Touches on Non-social Apps}} + \beta_2 X_{\text{Touches on Social Apps}} \\ 611 & + \beta_3 X_{\text{Touches on Uncategorized Apps}} + \beta_4 X_{\text{Rate of touchscreen touches}} \\ 612 & + \beta_5 X_{\text{Number of Apps on the touchscreen}} + \beta_6 X_{\text{Gender (female=1)}} \end{aligned}$$

613

614 Where Y took the form of $Y_{\text{Movement time variability}}$ or $Y_{\text{Reaction time variability}}$, or
615 $Y_{\text{Somatosensory putative signal-to-noise ratio}}$. For $Y_{\text{Coefficient of dispersion in peak latency}}$ and
616 $Y_{\text{Coefficient of dispersion in peak amplitude}}$, the explanatory variable $\beta_7 X_{\text{Movement time variability}}$
617 was added to the original equation. $\beta_{1 \text{ to } n}$ comprised regression coefficients estimated by robust

618 regression, and β_0 the intercept. The explanatory variables quantifying the touchscreen behavior
619 were based on 21 d of recording made prior to the laboratory measures.

620 To analyze the time-dependent structure of regression parameters associated with the
621 number of touchscreen touches, we used the following approach. The parameters
622 $X_{Touches\ on\ Non-social\ Apps}$, $X_{Touches\ on\ Social\ Apps}$, and $X_{Touches\ on\ Uncategorized\ Apps}$ were re-
623 estimated over the span of 21 d with 12-h steps and 72-h windows. Other parameters were
624 unchanged and, as in the main regression equation, were based on the data spanning the entire
625 21-d period. To describe the time-dependent fluctuation of F-values, the relationship was
626 iteratively fitted by comparing linear, exponential, and Gaussian equations with a maximum of
627 three terms. The fit with the highest R^2 was used to describe the relationships.

628 Similarly, to assess the temporal structure of the variable typical rate of touchscreen use
629 or the number of Apps used, the variables X_{Rate} or $X_{Number\ of\ Apps\ on\ the\ touchscreen}$ were re-
630 estimated with 12-h steps and 72-h windows while other parameters remained unchanged.

631 As a control, we repeated the analysis with shuffled App categories. Essentially, for the
632 original analysis, the Apps were labeled as “Social”, “Non-social”, and “Uncategorized”
633 according to a fixed criterion, i.e., Social Apps were those that enabled the communication of
634 a message or an opinion to a circle of friends or acquaintances. The list of all Apps in the
635 database and their classifications were randomly shuffled (10^5 iterations). These shuffled lists
636 were then used to estimate the number of touches in each of the action categories. Note that the
637 total number of Apps in each category was constant during shuffling.

638 Plots for displaying multiple linear regression results in two dimensions (adjusted
639 response plots) were generated using a built-in MATLAB function (plotAdjustedResponse).
640 Formulation of this plotting method and its advantages are described elsewhere (59).

641 The EEG data were correlated with touchscreen parameters using robust regression,
642 iterative least squares method (implemented in LIMO EEG). The correlation coefficients were
643 estimated across all electrodes and for the time period from -30 to 200 ms relative to the

644 stimulation onset. When focusing the analysis on keypad use, due to the smaller number of
645 samples, the variables were restricted to parameters X_{Rate} , $X_{Number\ of\ touches\ on\ Social\ Apps}$, and
646 $X_{Number\ of\ touches\ on\ Non-social\ Apps}$. The regression statistics were corrected for multiple
647 comparisons by using 1000 bootstraps and spatiotemporal clustering, as implemented in LIMO
648 EEG.
649

650 **Acknowledgements**

651

652 The data collection was made possible by the assistance of Ciara Shortiss and Magali Chytiris.

653 We thank Enea Ceolini for helping in the design and implementation of the behavioral tracking

654 software. This research was funded by Holcim Stiftung and the Society in Science Branco

655 Weiss Fellowship. The authors would like to thank Eric Rouillier, Anne-Dominique Gindrat,

656 Kevan Martin, and Valerio Mante for discussions. The authors thank Joanna Mackie for help

657 in editing this manuscript.

658 **References**

659

- 660 1. Hourcade JP, Mascher SL, Wu D, Pantoja L (2015) Look, My Baby Is Using an iPad! An Analysis of
661 YouTube Videos of Infants and Toddlers Using Tablets. *Proceedings of the 33rd Annual ACM Conference*
662 *on Human Factors in Computing Systems*, CHI '15. (ACM, New York, NY, USA), pp 1915–1924.
- 663 2. Herholz SC, Zatorre RJ (2012) Musical Training as a Framework for Brain Plasticity: Behavior, Function,
664 and Structure. *Neuron* 76(3):486–502.
- 665 3. Byl NN, Merzenich MM, Jenkins WM (1996) A primate genesis model of focal dystonia and repetitive
666 strain injury I. Learning-induced dedifferentiation of the representation of the hand in the primary
667 somatosensory cortex in adult monkeys. *Neurology* 47(2):508–520.
- 668 4. Jenkins WM, Merzenich MM, Ochs MT, Allard T, Guic-Robles E (1990) Functional reorganization of
669 primary somatosensory cortex in adult owl monkeys after behaviorally controlled tactile stimulation. *J*
670 *Neurophysiol* 63(1):82–104.
- 671 5. Zatorre RJ, Fields RD, Johansen-Berg H (2012) Plasticity in gray and white: neuroimaging changes in
672 brain structure during learning. *Nat Neurosci* 15(4):528–536.
- 673 6. Elbert T, Pantev C, Wienbruch C, Rockstroh B, Taub E (1995) Increased cortical representation of the
674 fingers of the left hand in string players. *Science* 270(5234):305–307.
- 675 7. Hamilton RH, Pascual-Leone A (1998) Cortical plasticity associated with Braille learning. *Trends Cogn*
676 *Sci* 2(5):168–174.
- 677 8. Donoghue JP (1995) Plasticity of adult sensorimotor representations. *Curr Opin Neurobiol* 5(6):749–754.
- 678 9. Pascual-Leone A, Amedi A, Fregni F, Merabet LB (2005) The plastic human brain cortex. *Annu Rev*
679 *Neurosci* 28:377–401.
- 680 10. Kleber B, Veit R, Birbaumer N, Gruzelier J, Lotze M (2010) The Brain of Opera Singers: Experience-
681 Dependent Changes in Functional Activation. *Cereb Cortex* 20(5):1144–1152.
- 682 11. Münte TF, Altenmüller E, Jäncke L (2002) The musician's brain as a model of neuroplasticity. *Nat Rev*
683 *Neurosci* 3(6):473–478.
- 684 12. Moucha R, Kilgard MP (2006) Cortical plasticity and rehabilitation. *Prog Brain Res* 157:111–389.
- 685 13. Adolphs R (1999) Social cognition and the human brain. *Trends Cogn Sci* 3(12):469–479.
- 686 14. Crockett MJ, Fehr E (2014) Social brains on drugs: tools for neuromodulation in social neuroscience. *Soc*
687 *Cogn Affect Neurosci* 9(2):250–254.
- 688 15. Smith A (2015) *US Smartphone Use in 2015*. *Pew Research Center*.
- 689 16. Gindrat A-D, Chytiris M, Balerna M, Rouiller EM, Ghosh A (2015) Use-Dependent Cortical Processing
690 from Fingertips in Touchscreen Phone Users. *Curr Biol* 25(1):109–116.
- 691 17. Krakauer JW, Mazzoni P (2011) Human sensorimotor learning: adaptation, skill, and beyond. *Curr Opin*
692 *Neurobiol* 21:1–9.
- 693 18. Cohen RG, Sternad D (2009) Variability In Motor Learning: Relocating, Channeling and Reducing Noise.
694 *Exp Brain Res Exp Hirnforsch Exp Cerebrale* 193(1):69–83.
- 695 19. Slifkin AB, Newell KM (1998) Is Variability in Human Performance a Reflection of System Noise? *Curr*
696 *Dir Psychol Sci* 7(6):170–177.

- 697 20. Schmidt RA, Zelaznik H, Hawkins B, Frank JS, Quinn Jr. JT (1979) Motor-output variability: A theory for
698 the accuracy of rapid motor acts. *Psychol Rev* 86(5):415–451.
- 699 21. Davids K, Bennett S, Newell KM (2006) *Movement System Variability* (Human Kinetics).
- 700 22. Herzfeld DJ, Shadmehr R (2014) Motor variability is not noise, but grist for the learning mill. *Nat*
701 *Neurosci* 17(2):149–150.
- 702 23. Gentner DR (1983) The acquisition of typewriting skill. *Acta Psychol (Amst)* 54(1–3):233–248.
- 703 24. Wöllner C, Cañal-Bruland R (2010) Keeping an eye on the violinist: motor experts show superior timing
704 consistency in a visual perception task. *Psychol Res* 74(6):579–585.
- 705 25. McMorris T, Keen P (1994) Effect of exercise on simple reaction times of recreational athletes. *Percept*
706 *Mot Skills* 78(1):123–130.
- 707 26. Sosnoff JJ, Newell KM (2011) Aging and Motor Variability: A Test of the Neural Noise Hypothesis. *Exp*
708 *Aging Res* 37(4):377–397.
- 709 27. Dykiert D, Der G, Starr JM, Deary IJ (2012) Sex differences in reaction time mean and intraindividual
710 variability across the life span. *Dev Psychol* 48(5):1262–1276.
- 711 28. Peters RM, Hackman E, Goldreich D (2009) Diminutive Digits Discern Delicate Details: Fingertip Size
712 and the Sex Difference in Tactile Spatial Acuity. *J Neurosci* 29(50):15756–15761.
- 713 29. Ivry RB (1996) The representation of temporal information in perception and motor control. *Curr Opin*
714 *Neurobiol* 6(6):851–857.
- 715 30. Schmidt RA, Bjork RA (1992) Paradigms Suggest New Concepts for Training. *Psychol Sci* 3(4):207–217.
- 716 31. Xiong J, Muraki S (2014) An ergonomics study of thumb movements on smartphone touch screen.
717 *Ergonomics* 57(6):943–955.
- 718 32. Henry FM (1961) Reaction time-movement time correlations. *Percept Mot Skills* 12:63–66.
- 719 33. Fitts PM, Peterson JR (1964) Information capacity of discrete motor responses. *J Exp Psychol* 67(2):103–
720 112.
- 721 34. Houlihan M, Campbell K, Stelmack RM (1994) Reaction time and movement time as measures of
722 stimulus evaluation and response processes. *Intelligence* 18(3):289–307.
- 723 35. Carlson JS, Mark C (1982) Reaction time, movement time, and intelligence: A replication and extension.
724 *Intelligence* 6(3):265–274.
- 725 36. Lacouture Y, Cousineau D (2008) How to use MATLAB to fit the ex-Gaussian and other probability
726 functions to a distribution of response times. *Tutor Quant Methods Psychol* 4(1):35–45.
- 727 37. Kofler MJ, et al. (2013) Reaction time variability in ADHD: A meta-analytic review of 319 studies. *Clin*
728 *Psychol Rev* 33(6):795–811.
- 729 38. O'brien RM (2007) A Caution Regarding Rules of Thumb for Variance Inflation Factors. *Qual Quant*
730 41(5):673–690.
- 731 39. Makeig S, Debener S, Onton J, Delorme A (2004) Mining event-related brain dynamics. *Trends Cogn Sci*
732 8(5):204–210.
- 733 40. Huber R, et al. (2006) Arm immobilization causes cortical plastic changes and locally decreases sleep
734 slow wave activity. *Nat Neurosci* 9(9):1169–1176.

- 735 41. Allison T, McCarthy G, Wood CC (1992) The relationship between human long-latency somatosensory
736 evoked potentials recorded from the cortical surface and from the scalp. *Electroencephalogr Clin*
737 *Neurophysiol Potentials Sect* 84(4):301–314.
- 738 42. Onishi H, et al. (2010) Neuromagnetic activation of primary and secondary somatosensory cortex
739 following tactile-on and tactile-off stimulation. *Clin Neurophysiol Off J Int Fed Clin Neurophysiol*
740 121(4):588–593.
- 741 43. Nicoletis MAL, et al. (1998) Simultaneous encoding of tactile information by three primate cortical areas.
742 *Nat Neurosci* 1(7):621–630.
- 743 44. Montag C, et al. (2015) Smartphone usage in the 21st century: who is active on WhatsApp? *BMC Res*
744 *Notes* 8:331.
- 745 45. Schaefer M, Heinze H-J, Rotte M (2012) Touch and personality: extraversion predicts somatosensory
746 brain response. *NeuroImage* 62(1):432–438.
- 747 46. Coull JT (1998) Neural correlates of attention and arousal: insights from electrophysiology, functional
748 neuroimaging and psychopharmacology. *Prog Neurobiol* 55(4):343–361.
- 749 47. Gilbert CD, Sigman M (2007) Brain States: Top-Down Influences in Sensory Processing. *Neuron*
750 54(5):677–696.
- 751 48. Cardini F, Longo MR, Haggard P (2011) Vision of the Body Modulates Somatosensory Intracortical
752 Inhibition. *Cereb Cortex* 21(9):2014–2022.
- 753 49. Mima T, Nagamine T, Nakamura K, Shibasaki H (1998) Attention Modulates Both Primary and Second
754 Somatosensory Cortical Activities in Humans: A Magnetoencephalographic Study. *J Neurophysiol*
755 80(4):2215–2221.
- 756 50. Dayan E, Cohen LG (2011) Neuroplasticity Subservicing Motor Skill Learning. *Neuron* 72(3):443–454.
- 757 51. Carmichael ST, Price JL (1995) Sensory and premotor connections of the orbital and medial prefrontal
758 cortex of macaque monkeys. *J Comp Neurol* 363(4):642–664.
- 759 52. Shadlen MN, Newsome WT (1998) The Variable Discharge of Cortical Neurons: Implications for
760 Connectivity, Computation, and Information Coding. *J Neurosci* 18(10):3870–3896.
- 761 53. Bohannon RW (2007) Number of pedometer-assessed steps taken per day by adults: a descriptive meta-
762 analysis. *Phys Ther* 87(12):1642–1650.
- 763 54. Barbato G, et al. (2000) Diurnal variation in spontaneous eye-blink rate. *Psychiatry Res* 93:145151.
- 764 55. Oldfield RC (1971) The assessment and analysis of handedness: The Edinburgh inventory.
765 *Neuropsychologia* 9(1):97–113.
- 766 56. Delorme A, Makeig S (2004) EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics
767 including independent component analysis. *J Neurosci Methods* 134(1):9–21.
- 768 57. Chaumon M, Bishop DVM, Busch NA (2015) A practical guide to the selection of independent
769 components of the electroencephalogram for artifact correction. *J Neurosci Methods* 250:47–63.
- 770 58. Pernet CR, Chauveau N, Gaspar C, Rousselet GA (2011) LIMO EEG: A Toolbox for Hierarchical Linear
771 MOdeling of ElectroEncephaloGraphic Data. *Comput Intell Neurosci* 2011:e831409.
- 772 59. DuMouchel W (1988) Graphical representation of main effects and interaction effects in a polynomial
773 regression on several predictors. *Proc. 20th Symp. on the Interface: Computer Science and Statistics*, pp
774 127–134.
- 775

776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795

796 **Figure Legends**

797
798
799
800
801
802
803
804

Figure 1. The history of unconstrained touchscreen behavior reflects on the performance of a simple task. (a) Touchscreen activity was recorded for 21 d and followed by laboratory measurements of sensorimotor variability. (b) The task required responding to tactile stimuli by pressing and releasing a micro switch, as fast as possible, with the thumb. (c-d) Adjusted response plots. (c) Movement time variability (σ) was directly proportional to the number of touches generated on the Social Apps (social touches). (d) The movement time variability was inversely proportional to the number of touches generated on the Non-social Apps (non-social

805 touches). (e) The distribution of relationships for randomly categorized Apps (10^4 iterations)
806 in comparison to the relationship uncovered for social touches. (f) Parsing the touchscreen
807 recordings in 12 h steps (72 h bin) revealed that the relationship involving non-social touches
808 simply decayed as a function of time, whereas the relationship involving social touches showed
809 a more complex pattern. The statistical tests and the details of the fits are reported in the main
810 text.

811

812 **Figure 2.** Early cortical somatosensory processing reflects the history of Social App usage. (a)
813 We estimated the signal-to-noise ratio in the cortical responses upon a brief tactile stimulus
814 presented to the right thumb tip, the hand was in a resting position during the recording. The
815 head plot shows the electrode location with the best response (red) (b) Putative signal-to-noise
816 ratio (SNR) at the electrode (SS, sum of squares). Individual volunteers (gray lines) and
817 population mean (black). (c) Event related coefficients with the SNR as dependent variable and
818 touchscreen parameters based on the entire 21 d recordings as explanatory variables.
819 Statistically significant coefficients (thickened lines, $p < 0.05$, corrected for multiple
820 comparisons, ANOVA). (d) Head plot of the population mean of the SNR at a latency of 80
821 ms. (e,f) The event related coefficients and the corresponding statistics at 80 ms. (g) At the
822 chosen electrode and at 80 ms, the distribution of the relationship strength based on randomly
823 categorized Apps (10^4 iterations) in comparison to the relationship uncovered for social
824 touches. (h) The relationship with social touches was the strongest for the thumb, followed by
825 the index finger, and, finally, the middle finger. (i) Parsing the touchscreen recordings in 12 h
826 steps (72 h bin) revealed that the relationship between social touches and the signal-to-noise
827 ratio evoked from the thumb at 80 ms latency fluctuated in a complex manner through the
828 recording period. The details of the fit is reported in the main text.

829

830 **Figure 3.** The trial-to-trial variability in the degree of cortical responses is proportional to
831 Social App usage. **(a–c)** Depiction of the analysis method to separately estimate the trial-to-
832 trial variability in the cortical signal latency and the amplitude. **(a)** Rectified event related
833 potentials based on a random sample of 25 trials was generated 10^5 times. The rectified potential
834 based on all the trials in one volunteer is drawn in grey. The first local maxima encountered on
835 10^3 iterated potentials after the set temporal landmarks of 50 and 85 ms are indicated (colored
836 dots). The distribution of latencies **(b)** and amplitudes **(c)** of the first maxima in the same
837 volunteer based on which the corresponding coefficient of dispersion (CD) was estimated. **(d-
838 e)** Adjusted response plots. **(d)** The greater the number of social touches in the 21-d recording
839 period, the larger the variability in signal amplitudes at the 85 ms landmark (measured in terms
840 of CD). **(e)** The relationship between the number of non-social touches and the variability was
841 not significant. **(f)** Parsing the touchscreen recordings in 12 h steps (72 h bin) revealed that the
842 relationship for non-social touches simply decayed with older touchscreen data and a more
843 complex pattern was apparent for the social touches.

844 **Supplementary Information Index**

845

846 Supplementary Methods: Description of the App used to track touchscreen behavior.

847

848 Supplementary List: A sample of all the Apps in the database to illustrate the App categorization
849 used in this study in Social and Non-social Apps.

850

851 Supplementary Figure 1: The plot matrix of the explanatory variables and the corresponding
852 variation inflation factors.

853

854 Supplementary Figure 2: The social touches do not reflect on movement time variability when
855 the task is performed with the middle finger. (a) Adjusted response plot showing the link

856 between the number of social touches generated on the touchscreen and the movement-time
857 variability when the task was performed by using the thumb. Specifically, higher the number
858 of social touches the higher the movement time variability (b) When the same volunteers
859 performed the task with the middle finger the relationship was absent.

860

861 Supplementary Figure 3: Social touches on the keypad is related to movement time variability.
862 (a-b) Adjusted response plots. (a) Higher the number of social touches on the touchscreen pop-
863 up keypad the higher the movement time variability. (b) The non-social touches on the keypad
864 were not related to the variability.

865

866 Supplementary Figure 4: Analysis of explanatory variables other than the number of social and
867 non-social touches. (a-b) Adjusted response plots. (a) The link between the typical rate of
868 touchscreen usage and movement time variability and (b) the number of Apps used and the
869 variability. (c) The analysis of the relationships to movement time variability after parsing the
870 touchscreen recordings in 12 h steps (72 h bin).

871

872 Supplementary Figure 5: The reaction time variability is related to the number of social touches.
873 (a) Adjusted response plot displaying that higher the number of social touches the larger was
874 the reaction time variability. (b) The non-social touches were unrelated to the reaction time
875 variability. (c) The relationship discovered for the social touches was well apart from the
876 distribution of relationships obtained by using randomly shuffled categories.

877

878 Supplementary Figure 6: The links between somatosensory cortical signal-to-noise ratio and
879 the touchscreen-based explanatory variables. (a) Multiple regression analysis was conducted to
880 explain the inter-individual variability in response to tactile stimulation at the thumb. The
881 regression coefficients for the signal-to-noise ratio measured at the electrode with the strongest

882 response. The sold lines depict $p < 0.05$ (corrected for multiple comparisons, ANOVA). (b-e)
883 Head plot of the regression coefficients and the corresponding statistics. (f-g) The relationships
884 for the number of non-social touches and the typical rate on the touchscreen were the strongest
885 for the thumb followed by the index and then the middle finger.

886

887 Supplementary Figure 7: The neuronal correlates of the number of social touches on the
888 touchscreen keypad. When we restricted our analysis to the pop-up keypad touches, we found
889 that higher the number of social touches on the keypad smaller the signal-to-noise ratio as in
890 the original analysis including all types of touchscreen events. The legend is identical to Figure
891 2 panels a-f.

892

893 Supplementary Figure 8: The neuronal variability determined from the early temporal landmark
894 set at 50 ms was unrelated to the number of touches. (a-d) Data by using the 50 ms temporal
895 landmark. Adjusted response plots showing the non-significant regressions between social or
896 non-social touches and neuronal variability in terms of amplitude or latency. (e,f) Latency data
897 by using the 85 ms temporal landmark shows a weak relationship between social touches (and
898 not for non-social touches) and trial-to-trial temporal variability.

899

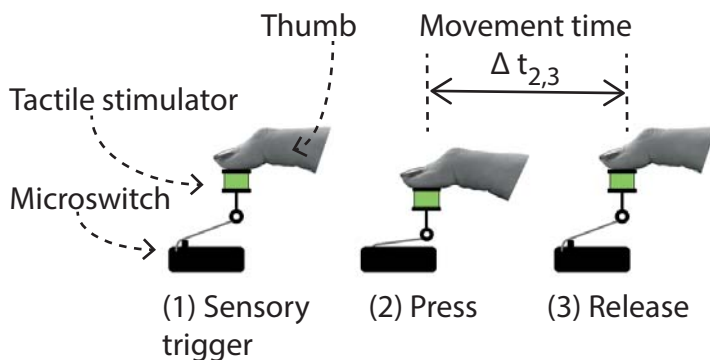
a

Phone behavior

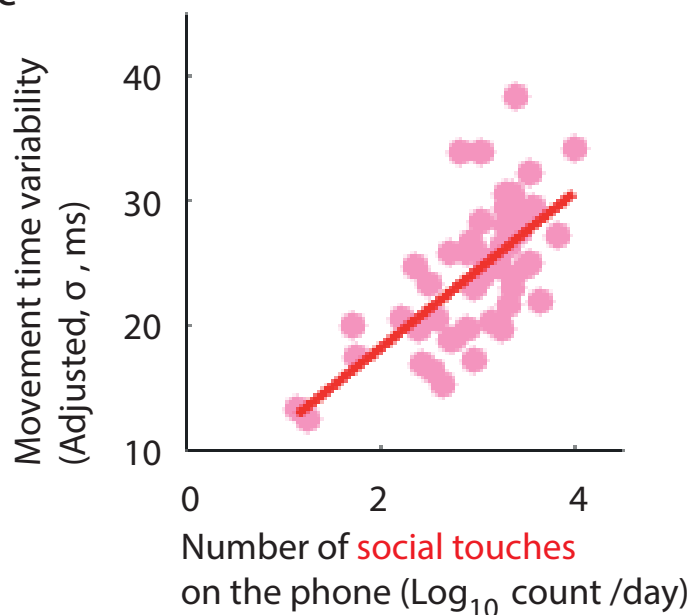


Social: Twitter, Facebook, WhatsApp etc.
Non-social: AccuWeather, Dictionary etc.

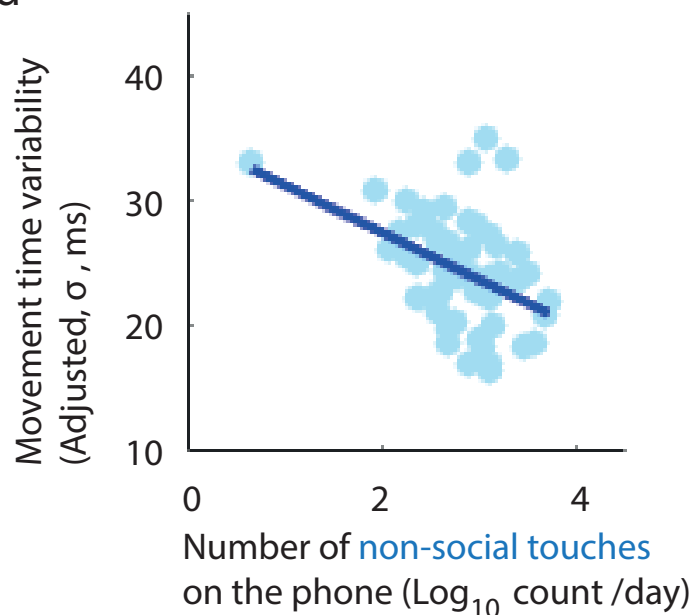
Motor variability



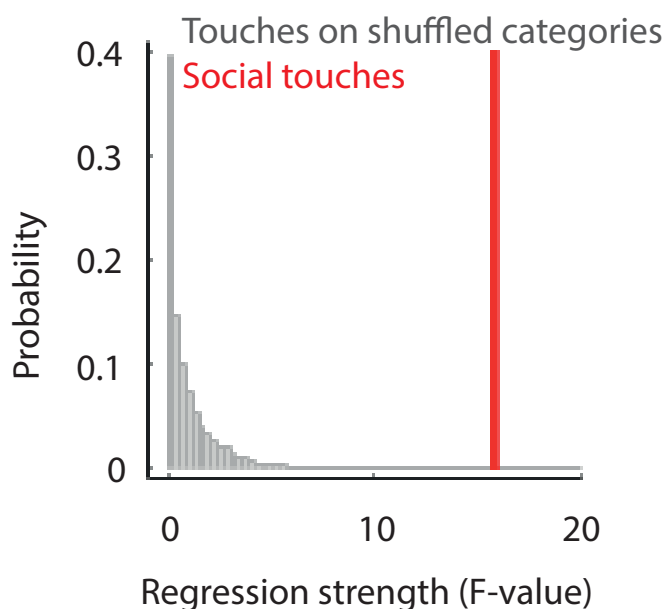
c



d



e



f

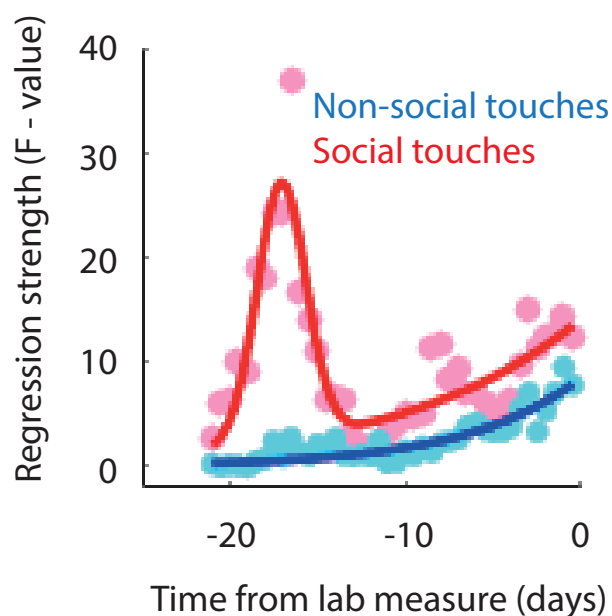


Figure 1. The history of unconstrained touchscreen behavior reflects on the performance of a simple task. (a) Touchscreen activity was recorded for 21 d and followed by laboratory measurements of sensorimotor variability. (b) The task required responding to tactile stimuli by pressing and releasing a micro switch, as fast as possible, with the thumb. (c-d) Adjusted response plots. (c) Movement time variability (σ) was directly proportional to the number of touches generated on the Social Apps (social touches). (d) The movement time variability was inversely proportional to the number of touches generated on the Non-social Apps (non-social touches). (e) The distribution of relationships for randomly categorized Apps (10^4 iterations) in comparison to the relationship uncovered for social touches. (f) Parsing the touchscreen recordings in 12 h steps (72 h bin) revealed that the relationship involving non-social touches simply decayed as a function of time, whereas the relationship involving social touches showed a more complex pattern. The statistical tests and the details of the fits are reported in the main text.

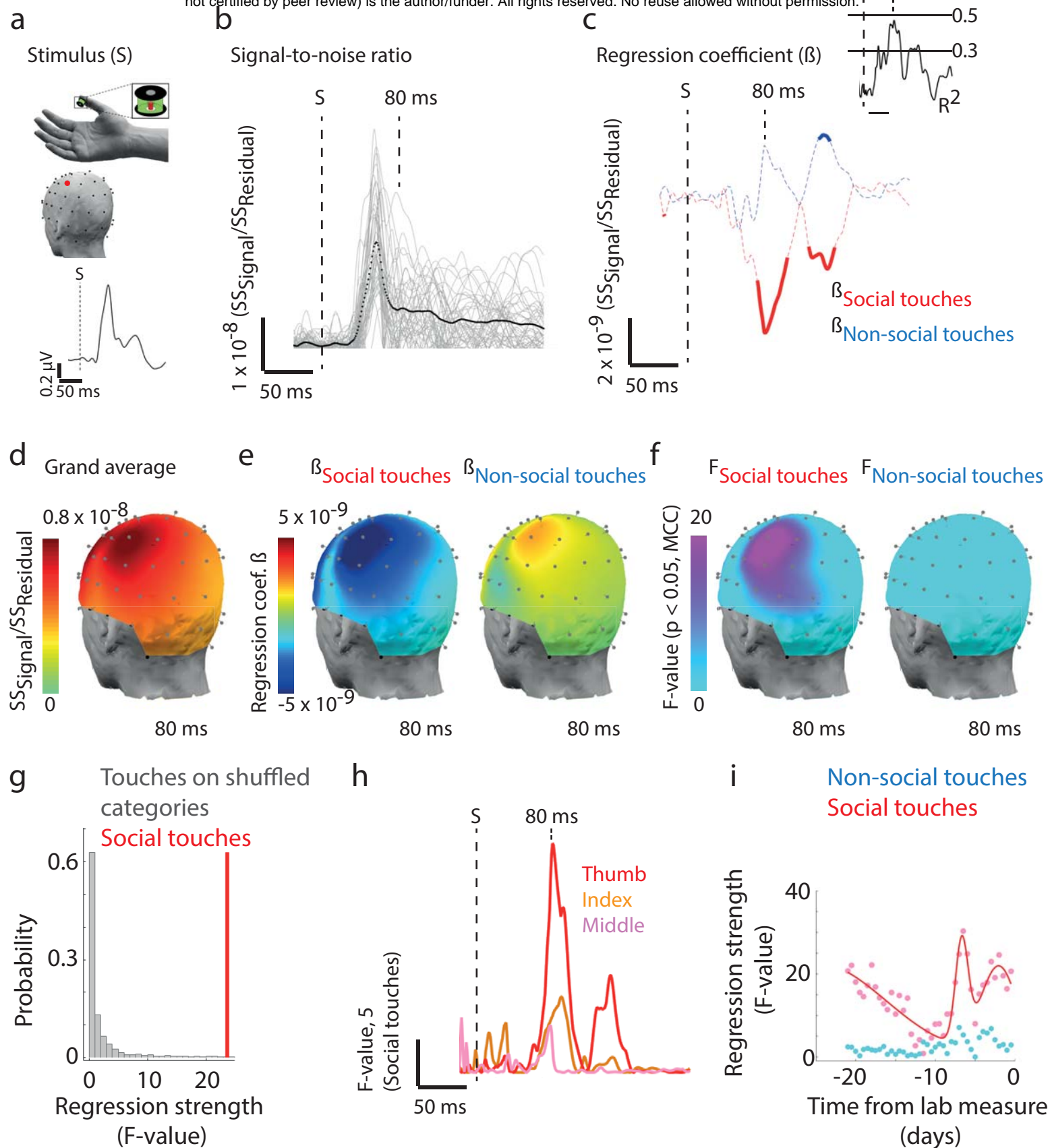


Figure 2. Early cortical somatosensory processing reflects the history of Social App usage. (a) We estimated the signal-to-noise ratio (SNR) in the cortical responses upon a brief tactile stimulus presented to the right thumb tip, the hand was in a resting position during the recording. The head plot shows the electrode location with the best response (red) (b) SNR at the electrode (SS, sum of squares). Individual volunteers (gray lines) and population mean (black). (c) Event related coefficients with the SNR as dependent variable and touchscreen parameters based on the entire 21 d recordings as explanatory variables. Statistically significant coefficients (thickened lines, $p < 0.05$, corrected for multiple comparisons, ANOVA). (d) Head plot of the population mean of the SNR at a latency of 80 ms. (e,f) The event related coefficients and the corresponding statistics at 80 ms. (g) At the chosen electrode and at 80 ms, the distribution of the relationship strength based on randomly categorized Apps (10^4 iterations) in comparison to the relationship uncovered for social touches. (h) The relationship with social touches was the strongest for the thumb, followed by the index finger, and, finally, the middle finger. (i) Parsing the touchscreen recordings in 12 h steps (72 h bin) revealed that the relationship between social touches and the SNR at 80 ms latency fluctuated in a complex manner through the recording period. The details of the fit is reported in the main text.

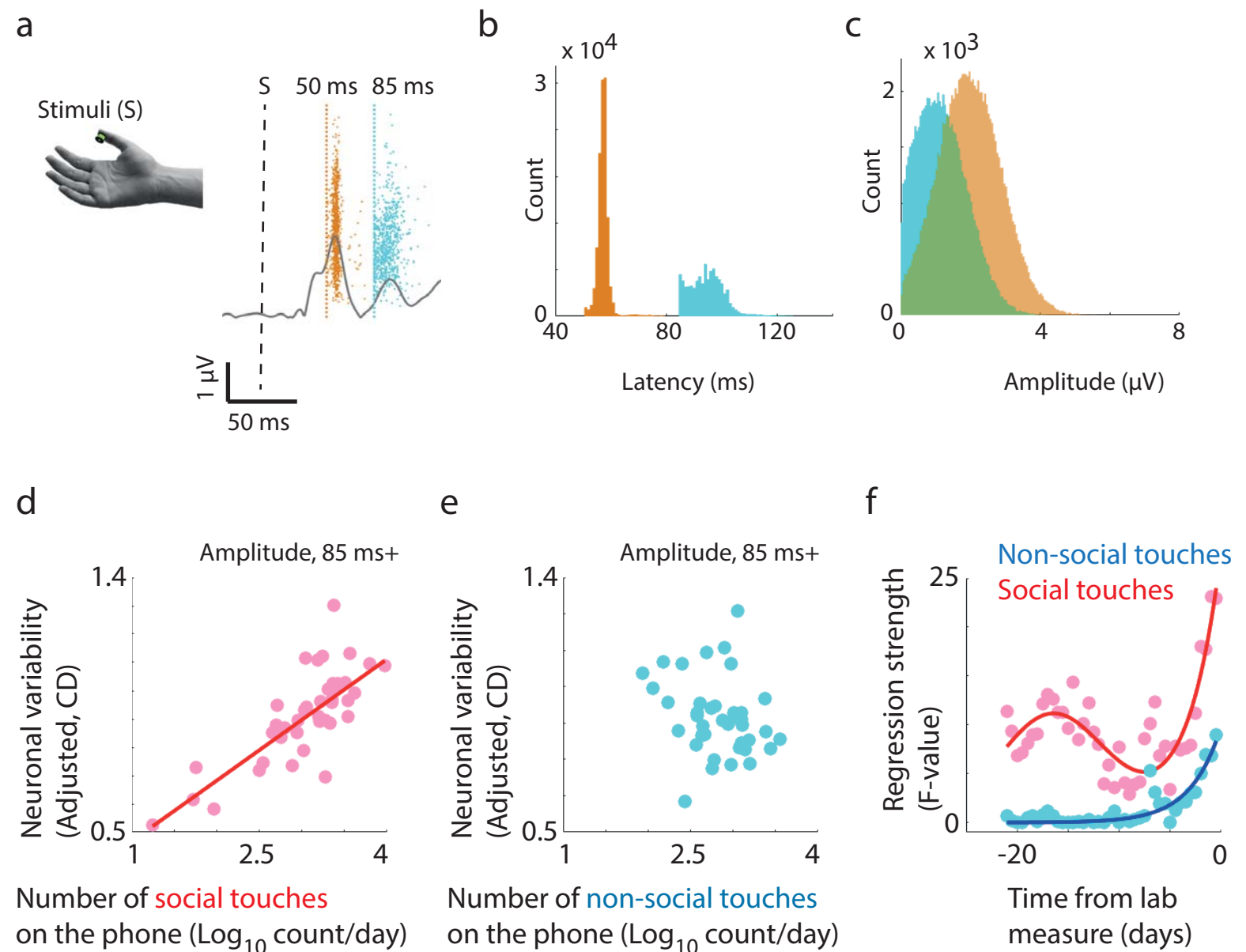


Figure 3. The trial-to-trial variability in the degree of cortical responses is proportional to Social App usage. (a–c) Depiction of the analysis method to separately estimate the trial-to-trial variability in the cortical signal latency and the amplitude. (a) Rectified event related potentials based on a random sample of 25 trials was generated 10^5 times. The rectified potential based on all the trials in one volunteer is drawn in grey. The first local maxima encountered on 10^3 iterated potentials after the set temporal landmarks of 50 and 85 ms are indicated (colored dots). The distribution of latencies (b) and amplitudes (c) of the first maxima in the same volunteer based on which the corresponding coefficient of dispersion (CD) was estimated. (d–e) Adjusted response plots. (d) The greater the number of social touches in the 21-d recording period, the larger the variability in signal amplitudes at the 85 ms landmark (measured in terms of CD). (e) The relationship between the number of non-social touches and the variability was not significant. (f) Parsing the touchscreen recordings in 12 h steps (72 h bin) revealed that the relationship for non-social touches simply decayed with older touchscreen data and a more complex pattern was apparent for the social touches.