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Holmes, N.P. and Tamè, Luigi (2018) Locating primary somatosensory cortex in human brain stimulation studies: systematic review and meta-analytic evidence. *Journal of Neurophysiology* 121 (1), pp. 152-162. ISSN 0022-3077.

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or alternatively

1 Title: **Locating primary somatosensory cortex in human brain stimulation**
2 **studies: Systematic review and meta-analytic evidence**

3

4 Running head: Locating S1 in human brain stimulation studies

5

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14 Author contributions:

15 Collected data, analysed data, wrote the paper: NPH

16 Wrote and commented on the paper: LT

17

18 **Abstract**

19 Transcranial magnetic stimulation (TMS) over human primary somatosensory cortex
20 (S1), unlike over primary motor cortex (M1), does not produce an immediate,
21 objective output. Researchers must therefore rely on one or more indirect methods to
22 position the TMS coil over S1. The 'gold standard' method of TMS coil positioning is
23 to use individual functional and structural magnetic resonance imaging (F/SMRI)
24 alongside a stereotactic navigation system. In the absence of these facilities,
25 however, one common method used to locate S1 is to find the scalp location which
26 produces twitches in a hand muscle (e.g., the first dorsal interosseus, M1-FDI), then
27 move the coil posteriorly to target S1. There has been no systematic assessment of
28 whether this commonly-reported method of finding the hand area of S1 is optimal. To
29 do this, we systematically reviewed 124 TMS studies targeting the S1 hand area, and
30 95 functional magnetic resonance imaging (fMRI) studies involving passive finger
31 and hand stimulation. 96 TMS studies reported the scalp location assumed to
32 correspond to S1-hand, which was on average 1.5 to 2cm posterior to the
33 functionally-defined M1-hand area. Using our own scalp measurements combined
34 with similar data from MRI and TMS studies of M1-hand, we provide the estimated
35 scalp locations targeted in these TMS studies of the S1-hand. We also provide a
36 summary of reported S1 coordinates for passive finger and hand stimulation in fMRI
37 studies. We conclude that S1-hand is more lateral to M1-hand than assumed by the
38 majority of TMS studies.

39

40

41 **New and noteworthy**

42 Non-invasive methods of human brain stimulation involve applying electromagnetic
43 stimuli to the scalp. To target a brain area, brain imaging or other measurement
44 methods are used. Here, we systematically review the methods used to target
45 transcranial magnetic stimulation onto the hand area of primary somatosensory
46 cortex. We relate these targeted locations to our own scalp measurements and to a
47 systematic review of functional magnetic resonance imaging data. We find that the
48 most widely-used heuristic to locate the hand area of S1 is not optimal.

49

50 Keywords: S1, SI, TMS, TDCS, MRI

51 **1. Introduction**

52 In December 1908, the brain surgeon Harvey Cushing operated on the exposed
53 postcentral gyrus of his patient, a 44 year old man who had recently developed
54 epilepsy. Electrical stimulation to the cortex just posterior to the middle genu (now
55 referred to as the 'hand knob', Yoursy et al. 1997) elicited sensations which the
56 patient, wide awake and fully cooperative, described “*as though someone had*
57 *touched or stroked the [right index] finger*” (Cushing 1909, p50).

58

59 More than a century after these remarkable and pioneering experiments, the
60 localization of somatosensory function in the human cerebral cortex is still under
61 study in neurosurgical patients (Hiremath et al. 2017). In non-clinical experiments
62 with healthy participants, researchers can use non-invasive brain stimulation
63 techniques such as transcranial magnetic stimulation (TMS, Barker et al. 1985) to
64 study the human primary somatosensory cortex (S1).

65

66 S1 covers a large territory along the central sulcus and postcentral gyrus. While ‘S1
67 proper’ is restricted to BA3b, we consider three distinct somatosensory cortical areas:
68 BA3b, BA1, and BA2 (Geyer et al. 1999), collectively referring to them here as ‘S1’.
69 Within S1 there are several topographically-organized maps of the body, representing
70 the genitalia, feet, and legs medially, the upper arms superiorly, the forearms and
71 hands laterally, and the face and internal organs laterally and ventrally. While the
72 precise location of each body part representation, as well as the gross anatomy and
73 folding of the pre- and postcentral sulci, may vary between people, the overall
74 topography remains remarkably similar to the classic 'homunculus' as drawn by

75 Penfield and Boldrey (1937; Tamè et al. 2016). The topography in S1 is more finely-
76 grained and more organized than that of neighboring M1 (Hlustik et al. 2001).

77

78 This within- and between-person consistency in the locations of different body part
79 representations in S1 allows neuroscientists to aggregate and map the results from
80 different people in studies of cortical somatosensory function. Functional magnetic
81 resonance imaging (fMRI) data can, for example, provide reasonable estimates of
82 the relative locations of body part representations in small samples of healthy
83 participants, even when the data are transformed into the same, standard, coordinate
84 frames (i.e., warping the shape and size of the brain image), and when averaging
85 data over participants (Nelson and Chen, 2008). Likewise, studies using transcranial
86 electrical, magnetic, or direct current stimulation (TES, TMS, TDCS) can rely on the
87 topography of the neighboring primary motor cortex for stimulator placement over the
88 'core region' of a given muscle (e.g., Weiss et al. 2013). Due to this reliable
89 stimulation of the motor areas, along with clear, immediate and objective outputs in
90 the form of stimulation-evoked body movement and muscle activity, good progress
91 has been made in studying the human primary motor cortex in healthy participants
92 (e.g., Raffin et al. 2015).

93

94 Progress has been slower, however, in understanding the electrical excitability of
95 primary somatosensory cortex and its function in healthy participants. This is likely
96 due, in part, to the lack of direct, immediate, and objective consequences of S1
97 stimulation. While some early studies reported that TMS over M1 or S1 elicited
98 'paraesthesias' or 'sensations of movement' in healthy participants (Amassian et al.

99 1991; Sugishita and Takayama, 1993), this phenomenon has not received systematic
100 experimental attention (though see, e.g., Ragert et al. 2003; Tegenthoff et al. 2005,
101 for anecdotal and pre-experimental evidence). The lack of immediate objective
102 consequences following TMS over S1 means that researchers cannot be sure that
103 the stimulating coil is correctly positioned, or that the stimulating current is sufficiently
104 strong or properly oriented to activate the targeted neurons in S1. Reliable coil
105 positioning is critical both to ensure stimulation of the correct brain area, but also to
106 ensure adequate control of TMS-related side-effects (Meteyard & Holmes, 2018;
107 Holmes & Meteyard, under review).

108

109 In previous work (Tamè & Holmes, 2016), we used individual fMRI neuronavigation
110 to locate S1-hand in 20 healthy participants during a TMS study of tactile detection
111 and discrimination. We noticed that, in every participant, the scalp location of S1-
112 hand (specifically, the index and middle finger representations) was lateral to the
113 scalp location of M1-hand (specifically, the first dorsal interosseus muscle
114 representation, M1-FDI). This surprised us, as almost all the TMS literature that we
115 were aware of had moved the TMS coil posteriorly to M1-FDI rather than laterally.
116 Further, fMRI studies in which both M1 and S1 were measured in the same
117 participants also showed that the S1 representation was lateral to the M1
118 representation of the hand (Blatow et al. 2011).

119

120 The purpose of the present systematic review was therefore to summarize the
121 available evidence concerning the location on the human scalp which researchers
122 stimulate in TMS studies of S1, in particular the S1 representation of the hand and

123 fingers (S1-hand). We did this in several ways. First, we summarized all the available
124 scalp measurements that we have collected during 35 previous TMS experiments
125 conducted in our own laboratory. Specifically, we summarised those data pertaining
126 to head size and the likely scalp coordinates overlying the representation of M1-FDI,
127 which is often used as a reference-point for TMS studies of S1, along with the
128 location of the C3/C4 electrode location in the 10:20 system (Jasper, 1954), another
129 commonly-used reference. The purpose of systematically measuring the scalp in our
130 prior work is to relate our TMS data to the 10:20 system, to measure between-
131 participants variability in head size and shape, to provide informative prior estimates
132 to assist future localizations, and to provide a check for measurement errors that may
133 arise during neuronavigation. Second, we systematically reviewed the methods used
134 to locate human S1-hand in previous TMS studies, focusing on the scalp locations
135 targeted. Third, we reviewed previous attempts to relate positions on the scalp to the
136 underlying positions in the brain. Finally, we systematically reviewed the brain
137 locations activated following passive finger and hand stimulation in FMRI studies.
138 These four components of the present work allowed us to relate the scalp locations
139 stimulated in prior TMS studies of S1-hand, to the likely location of S1-hand in FMRI
140 studies.

141

142 **Materials and methods**

143 All experimental studies received approval from local research ethics committees,
144 and were conducted in accordance with international safety guidelines (Rossi et al.
145 2009), and with the Declaration of Helsinki (2008 version, which does not require
146 study pre-registration). Throughout the manuscript, we refer to scalp and brain

147 coordinates using the following convention: ORIGIN(lateral,anterior). For example,
148 5cm left and 1cm anterior to the vertex origin, Cz, is written: Cz(-5,1), and 2cm
149 posterior to the FDI muscle location is FDI(0,-2). Standard MNI neuroimaging
150 coordinates are given as MNI(X,Y,Z), in mm. MRI data reported in Talairach and
151 Tournoux (1988) coordinates were converted to MNI coordinates using Matthew
152 Brett's tal2mni.m script implemented in several Matlab functions
153 (http://eeg.sourceforge.net/doc_m2html/bioelectromagnetism/mni2tal.html). All data
154 and analysis scripts are available at <https://osf.io/c8nhj/>.

155

156 *Head size and 10:20 locations*

157 The Hand Laboratory has been recording scalp locations during TMS experiments
158 since 2012, and more thoroughly and systematically since 2016 (Protocol sheet
159 available at <https://osf.io/c8nhj/>). Researchers measured the distance between
160 nasion and inion, and between the pre-auricular points of the two ears. The
161 intersection of these lines is marked as the vertex. For sites relatively close to the
162 vertex and/or close to the pre-auricular axis (e.g., M1, S1), a rectangular coordinate
163 frame (x-axis = right of vertex, y-axis = anterior to vertex) is suitable. For areas
164 further away from vertex, this system would break down with the curvature of the
165 skull, and a polar coordinate scheme is required. The lateral coordinate of a scalp
166 location is always measured first, and the anterior coordinate second, measuring
167 perpendicularly forwards or backwards from the vertex-preauricular line. The data are
168 noted first on the protocol sheet, and transferred later to an electronic database
169 (MySQL, accessed via custom web-based software ARM and LabMan,
170 <https://github.com/TheHandLab>). As these scalp location data accumulate, they will

171 be made freely available via the TMS-SMART website (<http://tms-smart.info>). The
172 HandLab database was queried for all available head measurements (N=284),
173 aggregated by participant (N=101). Mean and SD within and between participants
174 was calculated. The standard 10:20 system electrode locations C3/C4, often used in
175 transcranial stimulation studies of S1-hand, were converted into distances measured
176 along the scalp from the vertex by dividing the inter-preauricular distance by 5 (i.e.
177 20%). Note that head size and shape is likely to vary widely across participants,
178 probably more so than brain size and shape (Zilles et al. 2001; Xiao et al. 2018).

179

180 *TMS over M1-FDI*

181 The HandLab database was queried for the mean scalp location stimulated during
182 our TMS studies of primary motor cortex, specifically the contralateral representation
183 of the FDI (N=127), aggregating the data by participant (N=65) and hemisphere.
184 Measurements from the same participant were averaged prior to averaging across
185 participants.

186

187 *Systematic review of TMS over S1-index*

188 PubMed (<https://www.ncbi.nlm.nih.gov/pubmed/>) was searched with the query
189 “(somatotop* OR somatosens* OR tact* OR touch OR cutan*) AND (TMS OR TDCS
190 OR transcranial stimulation)” on 2nd January 2018, and again on 30th July 2018. The
191 primary variables assessed were the methods used to locate the TMS coil over S1,
192 including the body part targeted, anatomical reference points, coordinate system, and
193 distances measured along the scalp or in the brain.

194

195 The reference sections of relevant articles were checked for additional articles, and
196 citations between included articles were recorded. 1384 initial results were
197 decreased to 299 (22%) potential articles on the basis of titles and abstracts. PDFs of
198 291/299 (97%) were retrieved and inspected for relevant methods.

199

200 Inclusion criteria were experimental reports including TMS targeted over human S1.
201 We restricted the analyses to TMS studies which either explicitly targeted the hand
202 area of S1, used the hand area of M1 as a reference-point, or did not explicitly say
203 which body part was targeted, but used the same methods as those studies which
204 did target the hand area. For example, studies which positioned the TMS coil relative
205 to a facial or foot muscle representation in M1 were excluded, but studies which
206 positioned the TMS coil, for example over C3/C4, or over C3'/C4', or 2cm behind
207 C3/C4, and which stated that this was over the 'somatosensory cortex' were included.

208

209 We excluded 12 review articles, 23 studies which targeted TMS over M1 or mapped
210 M1, 48 studies which targeted other brain areas, 14 studies which did not report
211 scalp coordinates, 41 studies which used other brain stimulation methods, 7 for other
212 reasons, and 8 studies for which we could not access the full article. 14 additional
213 studies from this search were excluded from the systematic review, but were relevant
214 to the review of scalp-to-brain measurements, described below. 124/291 (43%)
215 identified studies were included. 96/124 (77%) reported numerical coordinates for
216 locating S1, met all other inclusion criteria, and are included in the analyses. We did
217 not include or exclude studies based on the type of TMS equipment, experiment
218 protocol, or participants tested – the purpose of the review was to identify the scalp

219 locations stimulated, not the effects of stimulation on the brain or somatosensory
220 perception.

221

222 *Review of studies relating scalp and cortical anatomy*

223 During the systematic reviews, fourteen articles were found which provided methods
224 of relating scalp locations for the EEG electrode locations C3/C4 or TMS over M1, to
225 anatomical landmarks or coordinates. No systematic search or review was
226 attempted, however the reference sections of these articles was searched and
227 followed for additional potential articles.

228

229 *Systematic review of FMRI of S1-hand*

230 PubMed was searched with the query “(primary somatosensory cortex OR S1 OR SI)
231 AND (FMRI OR functional magnetic resonance imaging) AND (hand OR finger OR
232 digit)” on the 7st January, 2018, and again on 31st July, 2018. 1252 search results
233 were combined with 28 additional articles found in the previous search. This was
234 reduced to 389 (31%) potential articles on the basis of titles and abstracts, searching
235 for any neuroimaging methods and any somatosensory stimuli. A second, more
236 thorough, review checked abstracts and/or full papers for inclusion criteria, which
237 were: a) used FMRI, b) reported atlas coordinates in a standardized space (Talairach
238 and Tournoux, 1988, or Montreal Neurological Institute, MNI), c) tested healthy adult
239 human participants, d) applied somatosensory stimulation to the digit(s) or hand(s),
240 and e) reported activation in the central sulcus, post-central gyrus, and/or any part of
241 S1, using a statistical contrast between passive stimulation and no stimulation.

242 139/389 (36%) of studies were deemed relevant, but the full articles (.pdfs) were only

243 available for 95 (68%) of the relevant articles. Of the 293 excluded articles, 142
244 (49%) did not report coordinates in 3 dimensions or reported coordinates only relative
245 to other coordinates, 31 (11%) involved active hand movement, 30 (10%) did not use
246 fMRI, 27 (9%) did not stimulate the hand, 25 (9%) contained data only from patients,
247 children, or monkeys. The data from 4 further articles had been published elsewhere
248 previously, 3 were purely anatomical studies, 3 were not in English, and 2 were not
249 empirical studies. 26 (9%) were excluded because we could not access the full text.

250

251 The primary variable extracted from 95 selected articles was the reported 3D location
252 of BOLD signal (peak voxel in group analysis, or mean across participants of peak
253 voxel in individual analyses) in S1, including the body part targeted, the coordinate
254 system used, and any anatomical or functional labels assigned to the coordinate.

255 Means and standard deviations (SD) across participants were recorded or calculated
256 where individual data were available. Coordinates reported using the Talairach and
257 Tournoux reference system (most often, studies using BrainVoyager software) were
258 transformed into MNI space. During analysis, and following advice from reviewers,
259 we further restricted the analysis to coordinates which were labeled as being in
260 BA3b, BA1, or BA2, and which were within the 50% cytoarchitectural probability
261 maps of these three areas. The on-line data and analysis scripts include additional
262 variables not explored in the present work, including stimulus modality (i.e.,
263 thermo/nociceptive, electrical, vibrotactile, brushing, and punctate stimulation).

264

265 *Limitations*

266 Due to limitations on time and resources, we did not use multiple independent

267 databases for the systematic reviews, and we did not use multiple independent
268 coders to select articles from the 2,636 identified records or to extract the stimulation
269 and activation data from the 219 included papers. For the TMS literature search, we
270 tracked the citations of all articles identified in order to locate studies not found by the
271 initial searches. This did not lead to any additional articles. We did not, therefore,
272 repeat this search for the fMRI literature. Because we included all stimulus sub-
273 modalities in our fMRI literature search, the resulting mean coordinates for S1-hand
274 may not be sufficiently precise for future researchers interested in only one
275 somatosensory sub-modality. To address these limitations, we have provided all our
276 data and analysis scripts in supplementary on-line materials. We encourage other
277 researchers to validate, extend, and improve our work, for example by implementing
278 a more thorough literature search with multiple independent searchers (e.g.,
279 Hayward et al. 2016), or by repeating the analyses using only their preferred sub-
280 modality of stimulation.

281

282 *Analysis*

283 For all reported and measured scalp locations (lateral and anterior to the given
284 reference point), and for reported fMRI coordinates (x, y, z), the means and standard
285 deviations across studies were calculated, aggregating data across conditions where
286 relevant. For fMRI studies which reported individual participants' coordinates, the
287 mean across the individual coordinates was calculated within each study, separately
288 for different brain areas (BA3b, BA1, BA2). Coordinates that were reported in
289 Talairach (& Tournoux) space were converted into MNI space. Coordinates which
290 were not reported as being in Talairach or MNI spaces were assigned to the most

291 likely space, according to the software used (e.g., MNI for SPM, Talairach for
292 BrainVoyager), or else plot in 3D alongside all other MNI coordinates, both before
293 and after applying the Talairach-to-MNI transform to identify the most likely space. If
294 unsure, the data were assumed to be in MNI space. For calculation of 'weighted
295 means' across studies, we multiplied the reported means by the reported number of
296 participants, then divided the sum of these values across all studies by the grand
297 total of all participants across all studies, to give a weighted mean location, either on
298 the scalp or in MNI coordinates.

299

300 ***Results and statistical analyses***

301 ***Measurements of scalp size and 10:20 locations***

302 Across 101 participants, the mean \pm SD head size was 35.9 \pm 2.1cm (range: 31-41cm)
303 from nasion toinion, and 35.9 \pm 1.5cm (range: 33-40cm) between left and right pre-
304 auricular points. This places the mean \pm SD C3/C4 electrode sites, on average,
305 7.2 \pm 0.3cm (range: 6.6-7.8cm) lateral to the vertex (Figure 1). Forty-four participants'
306 heads were measured more than once (range 2-23 measurements;
307 mean \pm SD=5.1 \pm 4.7 measurements per participant). Of these, the head
308 measurements varied within-participants and between-sessions, by as much as 5cm
309 for nasion toinion (mean \pm SD within-participants range=1.8 \pm 1.4cm), and 4cm for pre-
310 auricular distances (mean \pm SD=1.3 \pm 0.9cm). The large range of these measurements
311 is likely due to human error.

312

313 ***TMS over M1-FDI***

314 *Across 108 measurements from 56 participants, the mean \pm SD left hemisphere scalp*

315 *location of M1-FDI was $5.2\pm0.8\text{cm}$ left of, and $0.4\pm0.9\text{cm}$ anterior to the vertex*
316 *(Figure 1). In 19 measurements from 14 participants, the mean \pm SD right hemisphere*
317 *M1-FDI location was $5.2\pm0.9\text{cm}$ right of, and $0.5\pm0.9\text{cm}$ anterior to the vertex.*

318

319 **Systematic review of TMS over S1-index**

320 TMS studies targeting S1-hand have used three main localization strategies. The first
321 study (Cohen et al. 1991) applied the border of a round coil, or the center of a figure-
322 of-eight coil over the C3/C4 electrode location. This method was followed by Seyal et
323 al. (1992, 1993), Pascual-Leone and Torres (1993), Siebner et al. (1998) and Harris
324 et al. (2002). Starting with Enomoto et al. (2001), other studies also used C3/C4 as a
325 reference point, but moved the coil posteriorly by between 2 and 3.6cm. In total, 16
326 studies used C3/C4 as a reference, and positioned the coil a mean \pm SD of $1.5\pm1.2\text{cm}$
327 posterior to C3/C4 (Table 1).

328

329 The second, and most common, strategy was to use the functionally-defined scalp
330 location for a muscle in the hand (typically FDI, abductor pollicis brevis, APB, or
331 opponens pollicis, OP) as a reference point. Starting with Sugishita and Takayama
332 (1993), 43 such studies used MEPs to localize M1-FDI, then moved the coil
333 posteriorly from that point on the scalp, by between 0 and 3cm
334 (mean \pm SD= $1.9\pm0.9\text{cm}$). 16 additional studies used thenar muscles (APB, OP) to
335 locate S1 (mean \pm SD= $2.1\pm1.0\text{cm}$ posterior). 21 studies did not report using MEPs,
336 but relied instead on visible twitches in the muscles of the hand (e.g., Amemiya et al.
337 2017). These studies moved the coil a mean \pm SD of $1.6\pm1.2\text{cm}$ posterior to the M1
338 hand area. In most studies, the researchers reported moving directly posterior

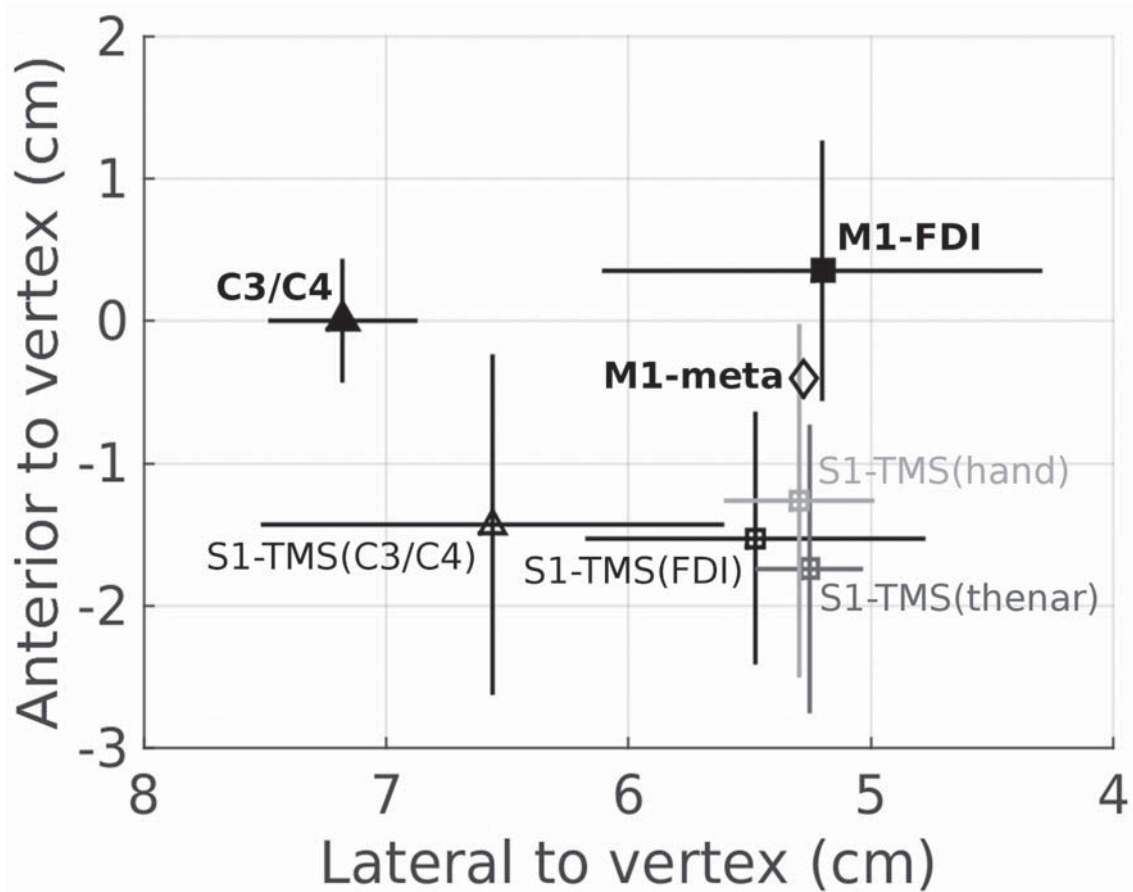
339 (parasagittally) to the motor location, while other researchers moved at an oblique
340 angle away from the midline, reasoning that the central sulcus is oriented at
341 approximately 45 degrees to the midline (e.g., Balslev et al. 2004). The estimated
342 mean locations stimulated under these different strategies are depicted in Figure 1.
343 These estimates used data about the likely scalp locations of M1-FDI and C3/C4
344 obtained in our laboratory. These data are described below.

345

346

[FIGURE 1 ABOUT HERE]

347



348 *Figure 1. Systematic review of the locations stimulated in transcranial magnetic*
349 *stimulation (TMS) studies of the hand area of primary somatosensory cortex (S1).*

350 *The grid shows locations lateral to the vertex, Cz(0,0) on the x-axis, and anterior to*
351 *the vertex on the y-axis. The data points show mean±standard deviation (SD)*
352 *locations measured or stimulated across the included studies (Table 1). Filled black*
353 *square: Scalp location of primary motor cortex (M1) representation of the first dorsal*
354 *interosseus (FDI) muscle of the hand, obtained from the HandLab database. Filled*
355 *black triangle: Scalp location of the C3/C4 electroencephalographic electrode*
356 *location obtained from the HandLab database. Black open triangle: Scalp location*
357 *stimulated in TMS studies of S1 which use C3/C4 as a reference point (Table 2).*
358 *Black open diamond: Scalp location of M1-FDI/thenar representation, obtained from*
359 *non-systematic review (Table 3). Black open square: Scalp location stimulated in*
360 *TMS studies of S1 which use the M1-FDI location as a reference point. Dark grey*
361 *open square: Scalp location stimulated in TMS studies of S1 which use the M1-*
362 *thenar location as a reference point. Light grey open square: Scalp location*
363 *stimulated in TMS studies of S1 which use the M1 hand location (in general, usually*
364 *without electromyography) as a reference point.*

365

366 A third approach to locate S1-hand has been to use MRI-guided neuronavigation.
367 This was done in three main ways: Using a standard head and brain template and
368 registering each participant's head to the template head (4 studies, e.g., Ruzzoli and
369 Soto-Faraco, 2014), using individual structural MRI scans obtained from each
370 participant (7 studies, e.g., Romaguère et al. 2005), using individual structural MRI
371 scans with additional individual fMRI data (3 studies, e.g., Valchev et al. 2015).
372 Seven additional studies reported using neuronavigation, but it was either not clear
373 which of these three categories they used, or multiple approaches were used across

374 different sub-groups of participants. Only one study that used neuronavigation also
375 reported coordinates of S1 relative to M1 (Tamè and Holmes, 2016).

376

377 ***Review of studies relating scalp and cortical anatomy***

378 In an appendix to a report on clinical EEG methods, Jasper (1958) reviewed four
379 existing systems of EEG electrode positioning, and consolidated them into the 'Ten
380 twenty' system of the International Federation. Cadavers and X-ray were used to
381 register the EEG locations to the underlying brain anatomy. Positions C3/C4 are
382 shown lying over the Rolandic fissure (see figure 6 in Jasper, 1958). Using MRI in 4
383 participants, Towle and colleagues (1993) found C3/4 to be anterior to the central
384 sulcus in five hemispheres, and posterior in three. They reported that the location
385 C3'/C4' (also called CP3/CP4), which is several centimeters posterior to C3, was
386 posterior to the central sulcus in all participants. Three later studies (Lagerlund et al.
387 1993; Vitali et al. 2002; Okamoto et al. 2004) used MRI in 10 or more participants. All
388 found that the brain underneath the C3/C4 location corresponded to the range of
389 coordinates MNI($\pm 51:57, -13:-23, 54:58$), with a left hemisphere weighted mean of
390 MNI(-53,-18,57). The grey matter closest to this coordinate (e.g., MNI(-53,-17,55))
391 corresponds in the Harvard-Oxford and Juelich (e.g., Eickhoff et al. 2005)
392 probabilistic atlases to postcentral gyrus (62%), BA1 (88%), BA2 (4%), BA3b (2%),
393 BA4p (1%), and BA4a (1%). Finally, Xiao et al. (2018) published the most detailed
394 and systematic mapping study to date, involving 114 Chinese and 24 Caucasian
395 participants. C3/C4 is positioned just posterior to the central sulcus, over the
396 postcentral gyrus. These studies are summarised in Table 2.

397

398 Seven studies were found that mapped the locations of M1-FDI or M1-APB to the
399 scalp and/or cortical surface. Excluding a single case study which produced a very
400 different localization, the M1-FDI/ABP location was found to be at Cz(-5.9:-4.8,-
401 0.8:0.5), approximately 5cm lateral to the vertex (Figure 1). Three studies registered
402 the optimal location for M1-FDI/APB to the cortical surface, finding the cortical
403 projection point at MNI(-40:-31,-22:-14,52:59), with a weighted left hemisphere mean
404 of MNI(-38,-15,58). This coordinate corresponds in the Harvard-Oxford and Juelich
405 probabilistic atlases to precentral gyrus (38%), postcentral gyrus (2%) BA6 (50%),
406 BA4a (38%), BA3b (19%), BA1 (9%), and BA4p (4%). These studies are summarised
407 in Table 3.

408

409 ***Systematic review of FMRI of S1-hand***

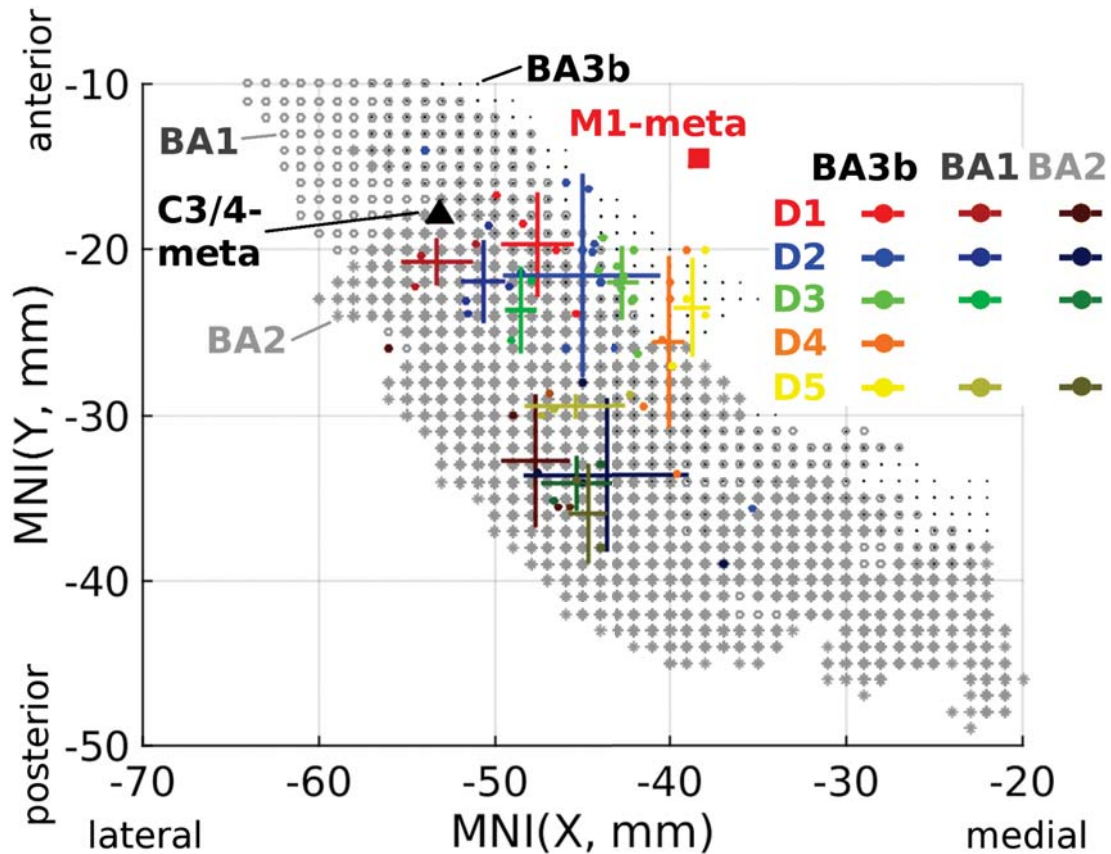
410 Of ninety-five studies reviewed, there were 216 reported coordinates relating to
411 passive stimulation of the fingers, hand, and median nerve at the wrist. Some studies
412 labeled the coordinates according to the likely Brodmann's areas (BA3b, BA1, BA2),
413 but the majority used labels S1, SI, or postcentral gyrus. Juelich probabilistic atlases
414 for BA3b, BA1, and BA2, in 1mm isotropic resolution in MNI152 space, were
415 imported into Matlab. These maps had been thresholded at 50% likelihood for each
416 brain area. The coordinates of the included studies were plot in 3D to check the
417 distribution of data. Datapoints that were more than 2mm outside the 50% probability
418 volumes were excluded. All remaining data were included. Averages for different
419 hemispheres and reported Brodmann's areas are provided in Table 4, and a visual
420 representation of the data is given in Figure 2. A full list of included studies, 3D
421 figures, and all analysis data and scripts is available at <https://osf.io/c8nhj/>.

422

423

424

[FIGURE 2 ABOUT HERE]



425 Figure 2. Systematic review of the locations activated in functional magnetic
426 resonance imaging (fMRI) studies of the hand area of primary somatosensory cortex
427 (S1-hand). The data show locations in the standard Montreal Neurological Institute
428 (MNI) coordinates, with mm right of the origin shown on the x-axis, and mm anterior
429 to the origin on the y-axis. The small background symbols show the 50% probability
430 volumes of the Juelich cytoarchitectural maps for S1: Black dots: Brodmann's area
431 (BA) 3b, open dark grey circles: BA1, light grey asterisks: BA2. Large filled symbols
432 show the locations of C3/C4 (filled black triangle) and primary motor cortex (M1)
433 representation of the first dorsal interosseus (FDI) or thenar muscle (filled red

434 square), obtained from the systematic reviews. Filled colored circles show the
435 reported MNI coordinates of individual studies included in the review, separated by
436 cytoarchitectural area. Different colors show different digits (D1: red, D2: blue, D3:
437 green, D4: orange, D5: yellow). The lightest tones are for BA3b data, mid-tones for
438 BA1, and darkest tones for BA2. Horizontal and vertical colored lines show the
439 means±standard deviations (SD) of the data, by digit and cytoarchitectural area.
440 Data for the ring finger (D4) were reported only for BA3b. The key result is that the
441 blue crosses are lateral to the red square – that S1-index is lateral, not directly
442 posterior, to M1-FDI.

443

444 **Relationship between TMS locations and FMRI locations of S1-hand**

445 Review of previous attempts to relate scalp and cortical anatomy revealed that the
446 C3/C4 electrode location overlies the central sulcus, precentral gyrus, or postcentral
447 gyrus, with a weighted mean coordinate for the cortical projection site of MNI(-53,-
448 18,57). This site is 8mm lateral, 4mm anterior, and 7mm superior to the BA3b
449 representation of S1-index, as determined by the systematic review. The scalp
450 location of M1-FDI/APB across four studies was Cz(-5.3,0.0), and the likely cortical
451 projection site was MNI(-38,-15,58). This is 7mm medial, 7mm anterior, and 8mm
452 superior to the BA3b representation of S1-index.

453

454 The systematic reviews revealed very consistent strategies used to locate S1-index
455 in TMS studies, namely moving an average of approximately 2cm posterior from M1-
456 FDI. The systematic reviews also revealed that the cortical location of the index finger
457 in FMRI studies of BA3b is likely 7mm lateral, 7mm posterior, and 8mm inferior to the

458 cortical location of M1-FDI. The representation of the index finger in BA1 is likely
459 13mm lateral, 6mm posterior, and 8mm inferior to M1-FDI; and the index finger in
460 BA2 is likely 5mm lateral, 18mm posterior, and 4mm inferior to M1-FDI. These
461 distances are all measured within the brain. It is not yet known how these distances
462 will convert to measurements taken from the scalp, nor how they relate to the optimal
463 TMS coil position required to target S1-hand. These questions will be answered in a
464 separate report.

465

466 **Discussion**

467 We systematically reviewed studies using transcranial magnetic stimulation and
468 functional magnetic resonance imaging that targeted the hand area of the primary
469 somatosensory cortex (S1-hand). Of 124 published TMS studies, the majority have
470 used a heuristic to find S1-hand that involved finding the optimal location for
471 stimulating the hand muscles (M1-hand), then moving the coil posteriorly, by a mean
472 of approximately 2cm. Our own data, along with a review of similar studies (e.g.
473 Sparing et al. 2008), shows that the optimal location for stimulating the M1
474 representation of intrinsic hand muscles is approximately 4-6cm lateral and 0-1cm
475 anterior or posterior to the vertex. For primary somatosensory cortex, on average,
476 TMS studies targeting the hand area of S1 have therefore stimulated a location ~6cm
477 lateral, and ~1.5cm posterior to the vertex (Figure 1).

478

479 FMRI studies have localised the index finger representation of Brodmann's BA3b in
480 the left hemisphere at MNI(-45,-22,50), and of BA1 approximately 6mm lateral to
481 that, at MNI(-51,-21,51). By co-registering data on the scalp position of M1-hand (M1-

482 meta in Figure 2) and C3/C4 into the same coordinate frame (i.e., the MNI template),
483 the estimated locations of M1-hand and S1-hand can be compared. There is an
484 orderly progression of the mean representation of the digits, with the little (D5) and
485 ring finger (D4) representations in BA3b approximately 15mm posterior to M1-hand,
486 and the thumb representation (D1) approximately 9mm lateral and 5mm posterior to
487 M1-hand. These meta-analytic locations correspond well with the orderly
488 topographies found within individual participants (e.g., Nelson & Chen 2008).

489

490 The heuristic of moving the TMS coil directly posterior to the M1 representation of the
491 intrinsic hand muscles to locate the S1-hand representation therefore seems to be
492 sub-optimal. This strategy is likely to be approximately correct if the TMS target is the
493 BA3b representation of the little and ring fingers, but these digits are rarely targeted
494 (only two out of the 87 reviewed studies that presented tactile stimuli to the fingers
495 targeted these digits – Amassian et al. 1991; Knecht et al. 2003). By contrast, the
496 largest number of studies used the M1 representation of intrinsic hand muscles to
497 target the S1 representation of the index finger (36 of the 87 studies presented tactile
498 stimuli on the index finger). Despite the predominance of this strategy, the systematic
499 review data suggest that S1-index is lateral and slightly posterior to M1-hand.

500

501 The conclusion that S1-hand is lateral to M1-hand is supported by studies in which
502 both M1 and S1 representations are measured together. Blatow and colleagues
503 (2011) applied passive pneumatic stimulation to the index finger and thumb of 16
504 participants, as well as asking them to make finger-thumb opposition movements for
505 digits 1-5. The peak BOLD response in their active movement task (after converting

506 their coordinates to MNI space) puts M1-hand at MNI(-39,-29,58), and S1-hand in the
507 sensory task 11mm laterally, 2mm anteriorly, and 6mm inferiorly, at MNI(-50,-27,52).
508 Their figure 2b clearly shows S1-hand lateral to M1-hand. Similar conclusions were
509 reached by Schellekens et al. (2018) using population receptive field methods, and
510 by Tamè & Holmes (2016), who reported that the S1-index representation was 11mm
511 lateral, 7mm posterior, and 11mm inferior to the M1 representation of FDI, as
512 measured using TMS-evoked MEPs in that muscle.

513

514 Given that moving the TMS coil posterior to the M1-hand representation does not
515 seem optimal to target S1-hand, the question arises as to why this method seems to
516 have become the default. Indeed, this method is still commonly relied upon, with one
517 recent paper stating: “*A large body of evidence shows that the hand area in the*
518 *somatosensory cortex can be successfully targeted by positioning the coil 1–4 cm*
519 *posterior to the motor hotspot*” (Gallo et al. 2018, p19). The earliest TMS studies of
520 S1 (e.g., Cohen et al. 1991; Seyal et al. 1992, 1993) positioned the TMS coil over the
521 C3/C4 electrode position. These studies presumably relied on evidence showing that
522 the C3/C4 location lay approximately over the central sulcus (Jasper, 1958; Towle et
523 al. 1993; Table 2). Indeed, studies relating the C3/C4 position to the underlying brain
524 surface gave an estimated location of the C3/C4 projection point of MNI(-53,-18,57)
525 (Figure 2). This cortical projection point of C3/C4 is just 6.6mm from the BA1
526 representation of the thumb.

527

528 Since the C3/C4 projection point is so close to the likely representation of thumb and
529 index fingers in BA1 and BA3b, and the available evidence suggests that finger

530 representations in S1 are lateral to those in M1, why is *2cm posterior to the M1-hand*
531 *location* the dominant reference point for TMS studies of S1-hand? While the
532 literature is not clear on this point, one possibility is that, following Towle et al. (1993),
533 who reported that the C3'/C4' electrode location was posterior to the central sulcus in
534 all four of their participants, subsequent researchers have used C3'/C4' to ensure that
535 they were on the posterior side of the central sulcus. C3'/C4' (also labeled CP3/CP4)
536 is halfway between C3 and P3, which, from our scalp measurements is about 3.6cm
537 posterior to C3/C4. Relatively few studies have used a site as posterior as this to
538 target S1 (e.g., McKay et al. 2003; Restuccia et al. 2007). Other researchers have
539 located C3'/C4' only about 1.5cm posterior to C3/C4 (Pascual-Leone & Torres, 1993).
540 Some researchers state that the C3/C4 location is several centimeters posterior to
541 the optimal location to stimulate M1 (Feurra et al. 2011; Koch et al. 2006; McKay et
542 al. 2003; Nardone et al. 2015, 2016), which from our scalp measurements does not
543 seem correct. Other researchers state that C3/C4 is the approximate scalp location of
544 the M1-hand representation (e.g., Fiorio & Haggard 2005; McKay et al. 2003). It
545 seems that, at some point, the original heuristic of 'posterior to C3/C4' has changed
546 into the heuristic 'posterior to M1-hand'. We did not find an empirical justification for
547 this change. At present, then, selective citation of the literature can be used to justify
548 a number of different strategies. In systematically reviewing this literature, it is clear
549 that there is very little agreement among researchers about the relative scalp
550 locations of C3/C4, C3'/C4', and their relationship to the underlying representations of
551 M1-hand, and S1-hand. The data reviewed here show that these areas are all
552 several centimeters apart. In the following, we consider two additional reasons why
553 researchers might have chosen to move the TMS coil posteriorly from M1-hand to

554 target S1-hand.

555

556 Using TMS to evoke MEPs in hand muscles provides a potentially very reliable
557 functional localiser for M1-hand. Localising M1-hand functionally is likely better than
558 relying on scalp measurements alone. Once M1-hand has been localised,
559 researchers have often justified moving the coil posteriorly to M1-hand in order to
560 ensure that muscle twitches evoked by stimulating over M1 would not interfere with
561 the intended effects of TMS over S1 (e.g., Convento et al. 2018; see also Holmes &
562 Tamè, 2018). This strategy can be criticized on two grounds.

563

564 First, M1 and S1 are adjacent and anatomically contiguous in the brain. For the
565 purposes of TMS, stimulation of the posterior bank of the precentral sulcus (e.g.,
566 BA4p, primary motor cortex) and the anterior bank of the postcentral sulcus (e.g.,
567 BA3b, primary somatosensory cortex) is very likely to occur simultaneously. Selective
568 stimulation of particular sub-areas of primary sensory (e.g., BA3a vs. BA3b) or motor
569 cortex (BA4a vs. BA4p) is likely to require detailed and careful work to optimise
570 precisely the necessary location, orientation, intensity, and TMS pulse pattern (e.g.,
571 Hamada et al., 2012). By comparison to the strategy for selectively stimulating S1 but
572 not M1, TMS studies focusing on M1 (or other brain areas) have not argued for
573 moving the coil anteriorly in order to prevent simultaneous stimulation of S1, even
574 though it is likely that S1 stimulation directly affects M1 activity, for example, as
575 shown by the short-afferent-inhibition paradigm (Tamè et al. 2015; Turco et al. 2018).
576 Rather, specific stimulation of M1 must be deduced from the effects of TMS, and
577 these may depend on the timing, intensity, orientation, or pattern of TMS impulses,

578 on connectivity with other areas, or on other factors that allow M1 involvement to be
579 determined.

580

581 Second, in our previous experiments using fMRI-guided neuronavigated TMS over
582 S1, while TMS has indeed evoked muscle twitches in many participants, the
583 amplitude of these twitches did not correlate with the effects of TMS on tactile
584 perception (Tamè and Holmes, 2016). We suggest that there is no necessary reason
585 to attempt to avoid the side-effects of M1 stimulation when targeting S1. Rather,
586 researchers should stimulate S1 as directly as possible, measure any muscle
587 contractions that result, and test whether these contractions interfere or correlate with
588 somatosensory perception or other measures. To this end, it may be that different coil
589 orientations should be used to stimulate S1-hand as compared to M1-hand (e.g.,
590 Pascual-Leone et al. 1994; Raffin et al. 2015). Future studies will need to follow-up
591 on these reports of the optimal coil orientation for interfering with somatosensory
592 perception. Once we are more certain about the location of S1-hand, we can then
593 begin to study how S1-hand and somatosensory perception respond in detail to
594 systematic changes in TMS coil position and orientation, and TMS pulse intensity,
595 frequency, and pattern.

596

597 It may also be argued that, by moving the TMS coil 2cm posterior to M1-hand,
598 researchers were specifically targeting the little or ring finger representations in BA3b
599 or BA1, or the largely-overlapping finger representations in BA2 (Figure 2). 2cm
600 directly posterior to M1-hand (i.e., MNI(-38,-35,58) – compare the location stimulated
601 by Ku et al. 2015: MNI(-34,-36,51)) is likely on the posterior bank of the postcentral

602 gyrus (cytoarchitectural probability: 39%) or superior parietal lobule (17%), and may
603 include parts of BA3b (52%), BA2 (46%), BA1 (21%), BA7 (20%), BA4p (12%) BA5
604 (5%) or BA4a (4%). BA1 and BA2 are less clearly somatotopically organized than
605 BA3b (Martuzzi et al. 2014; see Figure 2). It is therefore possible that TMS over a
606 region approximately 2cm behind M1-hand may be sufficient for targeting higher-
607 order and less topographic representations of the hand in S1. Although we have not
608 done the necessary systematic review or experiments to determine which part of S1
609 is 2cm posterior to the M1-hand location, it is most likely to be a part of S1 that
610 represents the forearm, upper arm, and/or shoulder (e.g., Blankenburg et al., 2006;
611 Figure 2).

612

613 *Scope and recommendations*

614 This review was limited to assessing the scalp locations that previous TMS studies
615 have assumed to correspond to S1-hand, as well as the brain locations activated
616 during passive somatosensory stimulation of the hand. Explicitly relating the TMS
617 scalp measurements and the fMRI brain measurements is beyond the scope of this
618 review. In an accompanying experimental paper (Holmes et al., under review), we
619 systematically map the effect of TMS on tactile perception, provide a probabilistic
620 atlas of the central sulcus, and systematically measure the location of S1-hand using
621 individual fMRI-guided neuronavigation. From the systematic reviews reported here,
622 we can make three general recommendations.

623

624 First, we recommend that all TMS studies should use as much of the available
625 evidence as possible to guide and justify their choice of target scalp locations,

626 including systematic review, meta-analysis, FMRI, M/EEG, scalp measurements, and
627 behavioral data. By selectively citing the literature, quite a wide range of strategies
628 for localising a TMS target can appear evidence-based. In the reviewed literature, we
629 were unable to find any empirical evidence to support the most commonly-reported
630 strategy for localising S1-hand in TMS studies, that is, moving 2cm posterior from the
631 M1-hand representation. While the distances involved are relatively small (i.e., 2cm,
632 relative to a typical TMS coil diameter of 7cm), researchers studying MEPs elicited by
633 TMS over M1 know just how sensitive the measurements can be to relatively small
634 changes in TMS coil position and orientation. More accurate positioning of the TMS
635 coil should increase the effect sizes of the phenomena we set out to measure.

636

637 Second, we recommend that all TMS studies systematically measure and report their
638 participants' head measurements and the scalp locations stimulated, using a
639 common reference frame. Very few studies reported scalp measurements. For sites
640 close to the vertex, measurements lateral and anterior in a Cartesian system relative
641 to the vertex may be sufficient, although a polar system may be superior. For sites
642 further from the vertex, the reference point could be relative to another 10:20
643 electrode location (e.g., C3/C4; Pz). If a functional localiser is available, such as
644 MEPs elicited from M1-FDI, then careful mapping of that functional location is
645 required prior to reporting the target location relative to that reference.

646

647 Finally, from the evidence presented here, we suggest that the representation of the
648 index finger in BA3b and BA1 is likely to be around 1cm lateral, and 0.5cm posterior
649 to M1-FDI, as measured in the brain. These distances, particularly the lateral

650 distance, are likely to be underestimates relative to the equivalent distances
651 measured along the scalp, due to the distance between the scalp and the brain, and
652 the curvature of the scalp. The scalp localisation of S1-index is addressed by Holmes
653 et al. (under review).

654 **Online data**

655 Raw data, supplementary results, data sheet, (<https://osf.io/c8nhj/>).

656

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Table 1: Systematic review of approximate scalp locations stimulated in 117 TMS studies of S1-hand

Reference	N*	Relative to Reference (cm)		Relative to Cz (cm)†	
		Lateral	Anterior	Lateral	Anterior
C3/C4	16	0.0±0.0 (0.0:0.0)	-1.5±1.2 (-3.6:0.0)	-6.6±0.9 (-7.2:-5.2)	-1.4±1.2 (-3.6:0.4)
FDI	43	-0.3±0.7 (-3.0:0.0)	-1.9±0.9 (-3.0:0.0)	-5.5±0.7 (-8.2:-5.2)	-1.5±0.9 (-2.7±0.4)
Thenar	16	-0.1±0.2 (-0.9:0.0)	-2.1±1.0 (-4.0:0.0)	-5.3±0.2 (-6.1:-5.2)	-1.7±1.0 (-3.7:0.4)
Hand/other	21	-0.1±0.3 (-1.0:0.0)	-1.6±1.2 (-4.0:0.0)	-5.3±0.3 (-6.2:-5.2)	-1.3±1.2 (-3.7:-0.4)
Navigated‡	21	-	-	-	-

Data are Means±SD (min:max). * Number of studies. Location data are not weighted by study sample-size. † Approximate measures, based on estimated population means reported below; ‡ Most neuronavigated studies did not report any coordinates, so no summary data are available.

Table 2: Nonsystematic review of C3/C4 location

Study	Methods	N	C3/C4*
Jasper 1958	Cadavers, X-rays	?	Over CS
Towle et al. 1993	MRI-EEG	4	Anterior to CS (5 hemispheres) Posterior to CS (3 hemispheres)
Lagerlund et al. 1993	MRI-EEG	10	45.6° lateral from Cz
Vitali et al. 2002	MRI-EEG	10†	M=MNI(-57,-13,54) SD=MNI(5,13,6)
Okamoto et al. 2004	MRI-EEG	17	M=MNI(-53,-16,58) SD=8; over postcentral gyrus
Koessler et al. 2009	MRI-EEG	16	MNI(-51,-23,57)‡
Cutini et al. 2011	MRI-EEG	(model)	MNI(-53,-11,49)
Xiao et al. 2018	MRI-EEG	114+24	Postcentral gyrus

C3/C4: anatomical location(s) of this electrode position; CoG: center of gravity; CS: central sulcus; Cz: vertex; M: Mean; MNI: Montreal Neurological Institute 152 template brain; N: Number of participants or brains; SD: Standard Deviation. * Right hemisphere X-coordinates, if given, were inverted and averaged with left hemisphere (left-right differences were minimal); † Patients with epilepsy. ‡ Converted from Talairach and Tournoux coordinates.

Table 3. Non-systematic review of M1-Hand scalp and brain location

Study	TMS Methods	N	M1*
Wilson et al 1993	M1-APB CoG M1-ADM CoG	10	Cz(-5.9,0.5) Cz(-5.4,0.4)
Ruohonen et al 1996	MRI-MEG-TMS M1-APB M1-ADM	1	Precentral gyrus Cz(-3.0,2.0)
Boroojerdi et al 1999	FMRI-TMS M1-APB/FDI	4	Cz(-5.5,0.25)
Borghetti et al 2008	M1-ADM Median M1-ADM CoG	10	Cz(-4.5,0.0) Cz(-4.9,-0.8)
Sparing et al 2008	(Meta-analysis) M1-FDI Max	10	MNI(-31,-22,52) Cz(-4.8,-0.8)
Niskanen et al 2010	M1-APB	59	MNI(-38,-14,58)
Raffin et al 2015	MRI, M1-FDI	13	M=MNI(-40,-17,59) SD=MNI(10,7,24)

Cz: vertex; M: Mean; MNI: Montreal Neurological Institute 152 template brain; N: Number of participants or brains; SD: Standard Deviation. * Right hemisphere X- coordinates, if given, were inverted and averaged with left hemisphere (left-right differences were minimal); CoG: Centre of Gravity

Table 4: Weighted mean±SD reported S1 MNI coordinates across the reviewed studies

Body	BA	Hem	N datapoints				MNI Coordinate means and SDs								
			Studies		People		X			Y			Z		
			Ms	SDs	Ms	SDs	M	SD _M	SD _P	M	SD _M	SD _P	M	SD _M	SD _P
Thumb (D1)	3b	L	4	4	52	52	-48.0	1.96	7.00	-19.0	3.04	4.27	47.3	3.25	6.25
		R	4	4	58	58	47.4	1.70	3.84	-18.3	2.81	2.86	45.7	0.25	3.79
	1	L	3	3	37	37	-52.8	1.92	2.41	-20.5	1.33	4.17	50.9	2.66	3.57
		R	6	5	98	61	53.9	3.40	3.28	-19.4	3.66	3.76	50.4	3.86	3.58
	2	L	2	2	9	9	-47.2	1.84	27.9	-33.9	3.89	5.42	56.5	4.53	7.13
		R	2	2	15	15	54.7	0.25	5.97	-24.8	2.43	4.60	48.5	1.29	5.74
Index (D2)	3b	L	11	5	136	81	-45.2	4.39	4.47	-21.6	6.00	2.87	49.8	5.30	4.52
		R	5	4	71	58	44.5	0.63	3.36	-19.9	3.41	2.98	50.0	1.00	2.93
	1	L	4	3	46	34	-50.8	1.14	2.01	-21.4	2.37	3.05	50.7	5.72	2.98
		R	6	4	105	52	50.1	3.58	2.50	-20.5	3.80	2.76	52.3	4.69	2.57
	2	L	4	1	83	6	-43.6	4.60	1.23	-33.3	4.50	1.06	53.8	6.33	1.23
		R	2	1	35	12	54.2	0.46	2.39	-21.0	4.07	2.50	49.3	0.52	3.70
Middle (D3)	3b	L	9	6	96	66	-43.0	0.84	3.26	-21.6	2.08	3.40	53.4	3.10	3.53
		R	4	4	58	58	43.5	0.44	3.91	-21.3	2.06	3.85	53.5	1.31	4.41
	1	L	2	2	28	28	-48.4	0.78	7.77	-23.2	2.47	3.22	56.1	5.23	4.65
		R	4	4	52	52	48.0	4.79	4.69	-22.2	5.25	5.26	54.3	5.65	5.13
	2	L	2	1	22	6	-44.7	1.91	2.00	-33.6	1.56	1.66	58.0	2.55	2.34
		R	1	1	12	12	53.7	-	3.90	-25.8	-	2.60	51.5	-	5.00
Ring (D4)	3b	L	6	3	75	45	-39.9	0.81	3.37	-27.4	5.09	4.15	55.3	4.23	2.60
		R	3	2	22	22	40.9	0.79	3.73	-26.9	2.41	4.23	58.4	1.35	3.34
	1	L	1	1	10	10	-46.9	-	2.10	-28.7	-	3.10	63.8	-	3.10
		R	3	3	34	34	48.0	5.57	5.21	-25.0	8.34	4.90	56.7	7.68	4.01
	2	L	1	1	6	6	-45.8	-	2.20	-35.6	-	3.50	62.1	-	3.40
		R	1	1	12	12	54.8	-	5.10	-24.5	-	3.90	49.6	-	5.80
Little (D5)	3b	L	4	0	40	0	-38.7	0.91	-	-23.5	2.89	-	55.5	3.88	-
		R	2	1	14	12	40.0	1.63	3.40	-27.8	0.18	3.36	59.5	5.35	3.47
	1	L	3	3	23	23	-45.7	2.78	3.58	-29.5	0.62	3.41	60.5	7.37	4.72
		R	3	3	31	31	45.5	7.09	4.92	-24.3	6.68	4.07	59.9	8.22	4.18
	2	L	2	1	9	6	-44.9	0.99	1.42	-35.3	2.90	4.03	59.1	5.37	4.27
		R	2	2	15	15	53.9	2.72	2.95	-24.6	5.85	5.08	48.6	2.28	5.16
Palm	3b	L	3	1	24	8	-37.2	4.07	2.48	-34.3	6.61	1.37	60.4	2.19	1.56
		R	1	0	12	0	40.4	-	-	-35.0	-	-	62.4	-	-
Back	3b	L	2	1	26	16	-42.9	5.60	2.20	-24.9	1.03	1.29	52.2	2.06	1.12
		R	1	1	16	16	44.3	-	1.32	-25.7	-	1.80	54.5	-	1.13
	1	L	1	1	16	16	-52.9	-	1.49	-22.9	-	2.18	52.4	-	2.31
		R	2	1	33	16	41.8	11.4	1.59	-28.8	7.60	1.26	64.9	10.4	0.86
	2	L	1	1	16	16	-49.1	-	3.64	-31.0	-	3.64	51.8	-	3.64
		R	1	1	16	16	49.9	-	3.64	-28.7	-	3.64	54.5	-	3.64

Hem.: Hemisphere; N: total sample size across studies; X, Y, Z: MNI coordinates; BA3b, BA1, BA2:

Brodmann's areas; * Other areas in S1 or postcentral gyrus not given a BA label; MN: Median or radial nerve stimulation. M: Mean; SD_M: SD across study means; SD_P: SD across participants.

