

1           **Thermosensory micromapping of warm and cold sensitivity across**  
2                   **glabrous and hairy skin of male and female hands and feet**

3                           Davide Filingeri<sup>1,2</sup>, Hui Zhang<sup>2</sup>, Edward A. Arens<sup>2</sup>

4   <sup>1</sup>THERMOSENSELAB, Environmental Ergonomics Research Centre, Loughborough  
5   University, Loughborough, United Kingdom

6   <sup>2</sup> Center for the Built Environment, University of California at Berkeley, Berkeley, CA, USA

7

8   **Running head:** Warm and cold thermosensory mapping of human hands and feet

9   **Key words:** Thermoreceptors, Sensation, Sex, Skin, Body Temperature Regulation

10

11   **Corresponding author's address:**

12   Davide Filingeri, PhD

13   THERMOSENSELAB

14   Environmental Ergonomics Research Centre

15   Loughborough University

16   Loughborough, LE11 3TU

17   United Kingdom

18   Email: [d.filingeri3@lboro.ac.uk](mailto:d.filingeri3@lboro.ac.uk)

19   Phone: +44 (0) 1509 222661

20

21

## 22 **Abstract**

23 The ability of hands and feet to convey skin thermal sensations is an important contributor to  
24 our experience of the surrounding world. Surprisingly, the detailed topographical distribution  
25 of warm and cold thermosensitivity across hands and feet has not been mapped, although  
26 sensitivity maps exist for touch and pain. Using a recently developed quantitative sensory  
27 test, we mapped warm and cold thermosensitivity of 103 skin sites over glabrous and hairy  
28 skin of hands and feet in male ( $30.2 \pm 5.8$ y) and female ( $27.7 \pm 5.1$ y) adults matched for body-  
29 surface-area (M  $1.77 \pm 0.2$ m<sup>2</sup>; F  $1.64 \pm 0.1$ m<sup>2</sup>;  $p=0.155$ ).

30 Findings indicated that warm and cold thermosensitivity varies by 5-fold across glabrous and  
31 hairy skin of hands and feet, and that hands (warm/cold sensitivity:  $1.25/2.14$  vote $^{\circ}\text{C}^{-1}$ ) are  
32 twice as sensitive as the feet (warm/cold sensitivity:  $0.51/0.99$  vote $^{\circ}\text{C}^{-1}$ ). Opposite to what  
33 known for touch and pain sensitivity, we observed a characteristic distal-to-proximal increase  
34 in thermosensitivity over both hairy and glabrous skin (i.e. from fingers/toes to body of hands  
35 and feet), and found that hairy skin is more sensitive than glabrous. Finally, we show that  
36 body-surface-area-matched males and females presented small differences in  
37 thermosensitivity, and that these differences are constrained to glabrous skin only.

38 Our high-density thermosensory micromapping provides the most detailed thermosensitivity  
39 maps of hands and feet in young adults available to date. These maps offer a window into  
40 peripheral and central mechanisms of thermosensory integration in humans, and will help  
41 guiding future developments in smart skin and sensory neuroprostheses, in wearable energy-  
42 efficient personal comfort systems, and in sport and protective clothing.

43

44 **New & Noteworthy**

45 We provide the most detailed thermosensitivity maps across glabrous and hairy skin of hands  
46 and feet in males and females. Our maps show that: thermosensitivity varies by 5-fold across  
47 hands and feet; distal regions (e.g. fingers, toes) are less sensitive than proximal (e.g. palm,  
48 sole); hands are twice as sensitive as feet; males and females present small thermosensitivity  
49 differences. These findings will help guiding developments in sensory neuroprostheses,  
50 wearable comfort systems, and in sport/protective clothing.

51

## 52 **Introduction**

53 Temperature sensing is a fundamental input in most animal species, including humans (20,  
54 50). As homeothermic mammals, we rely on sensing the thermal state of our body and  
55 surroundings to regulate our body temperature (61). Yet temperature sensing in the form of  
56 skin thermal sensations is also a critical sensory attribute that enables our experience of the  
57 surrounding world (20). The warmth of a caress, or the coldness of dipping our toes in the  
58 sea, are common yet fundamental sensory experiences that accompany our life from its very  
59 first start, and that help shape our social and physical being (1, 11, 49). Such perceptual  
60 thermal experiences are often conveyed through humans' most important explorative and  
61 sensory structures, their hands and feet (52).

62 While there is vast knowledge about hands and feet as *thermoregulatory* structures for  
63 providing heat and cold defence responses (i.e. cutaneous vasodilation / vasoconstriction)  
64 (69), their function and characteristics as *thermosensory* structures have rarely been  
65 investigated (44). This is surprising, as detailed understanding of thermosensation in hands  
66 and feet has practical value in subjects such as helping restore naturalistic touch in amputees  
67 through sensory prosthesis and smart skin (9, 21, 41, 59, 63), and in designing effective  
68 personal comfort systems (73), thermal wearables (64), and sport and protective clothing  
69 (69).

70 In humans and primates, skin temperature sensing is mediated by free nerve endings of the  
71 A $\delta$ - and C-type classes (i.e. thermoreceptors) (6, 7, 13, 42), selectively conveying warm and  
72 cold afferent inputs via the anterolateral spino-thalamic tract, to neural centres located in the  
73 insular and somatosensory cortices (12, 16, 60). Human temperature sensing is not  
74 homogenous across the body (55), but in fact it varies significantly depending on the skin  
75 region (e.g. face and trunk are generally more sensitive than the limbs) (23, 26, 57). While  
76 commonly observed in humans (18, 23, 27, 53, 66), this sensory feature has not been fully

77 investigated in animal models of mammalian thermosensation (51, 71), leaving our  
78 understating of its underlying neurobiology somewhat speculative.

79 The presence of regional differences in temperature sensing in humans is in line with what  
80 has long been known about regional differences in touch sensitivity (2, 38), and more  
81 recently, in pain acuity (46). Interestingly, large topographical differences in touch and pain  
82 sensitivity are present across relatively small body areas, such as the palm of the hand. This  
83 glabrous skin region exhibits a proximal-to-distal (i.e. palm to fingertips) increase in touch  
84 sensitivity (37, 39), and in pain acuity (48).

85 Differences in touch and pain receptor densities across the hand (30, 38, 48), and in the size  
86 of the receptive fields of cortical neurons (47), contribute to the heterogeneous touch and pain  
87 sensitivity of our palms. This observation was first exemplified in the classic sensory  
88 homunculus developed by Penfield (58). In contrast to the knowledge above, it has not been  
89 fully elucidated yet whether thermosensitivity varies substantially across hands and feet, and  
90 whether the variation has a similar topography as touch and pain.

91 To date, only Li et al. (44) has attempted to characterize the topography of warm and cold  
92 sensitivity of the glabrous skin of the palm. By mapping thermosensitivity with threshold  
93 detection methods across 23 locations of the palm in males and females, this study indicated  
94 that warm and cold sensitivity varies largely across this relatively small area, with proximal  
95 sites (e.g. base of the palm) showing higher sensitivity than the distal sites (e.g. fingers) (44).

96 It was also found that females are on average more thermosensitive than males (44), although  
97 differences in body surface area between sexes could have contributed to this observation  
98 (i.e. the smaller females might have shown higher sensitivity due to the relatively larger  
99 proportion of their skin being stimulated).

100 While Li et al.' study (44) has provided initial evidence for the fact that the human palm  
101 could present a heterogeneous distribution of thermosensitivity, the study did not evaluate the

102 entire hand (i.e. no assessment of the hairy skin of the dorsum), nor the foot. It also used a  
103 methodology (i.e. threshold detection, where the smallest perceivable temperature change is  
104 identified) that is unlikely to be representative of a real-life, supra-threshold thermal stimulus  
105 (e.g. when dipping a finger in the bath to check its temperature). Finally, it assessed sexes  
106 differences without matching groups for body size, which might create a potential bias in the  
107 context of thermal spatial summation (17). As a result, our knowledge on the  
108 thermosensitivity of hands and feet in humans, and of its topographical distribution across the  
109 hairy (i.e. dorsum) and glabrous portions (i.e. palm and sole) of these sensory structures,  
110 remains limited.

111 To fill this gap, we mapped topographical differences in warm and cold thermosensitivity  
112 across 103 locations of both hairy and glabrous skin of the hand and foot in young males and  
113 females, using a magnitude estimation paradigm. We assessed sex differences by matching  
114 males and females for body surface area, in order to isolate the independent effect of sex on  
115 local thermosensitivity. We hypothesized that, in line what known for touch sensitivity and  
116 pain acuity, the distribution of skin thermosensitivity would vary across the hand and foot  
117 with a proximal-to-distal pattern (i.e. higher sensitivity from the body of hands and feet to  
118 fingertips and toes). Furthermore, we hypothesized that sex differences in thermosensitivity  
119 would be minimal between body surface area-matched male and female individuals.

120

121

## 122 **Methods**

123

### 124 *Participants*

125 Sixteen age-matched healthy adults, eight females and eight males, volunteered to participate  
126 in the present study. All participants were college students and junior researchers without any

127 neural or perceptual contraindications, non-smokers, moderately active (performing at least  
128 5h of exercise a week) and had lived in the Berkeley area (California, USA) for at least 3  
129 months prior to the test. Participants' characteristics are presented in Table 1.  
130 The male and female groups comprised an almost identical proportion of Caucasian (4F/3M)  
131 and Asian ethnicities (4F/5M). Female participants were well spread across a typical 28-day  
132 menstrual cycle (mean day= 15.4; SD= 8.9), with 4 of them taking oral contraceptives.  
133 In addition to being age-matched, male and female participants were purposely matched for  
134 body surface area (see Tab. 1). Spatial summation is a well-known phenomenon in thermal  
135 sensitivity (68), where given the same thermal stimulus, increasing the area of skin being  
136 thermally stimulated increases the magnitude of the resulting thermal sensation (14).  
137 Accordingly, matching males and females for body surface area ensured that a similar  
138 proportion of their body would be stimulated with our fixed-area thermal stimulus (i.e. a  
139 1.32cm<sup>2</sup> thermal probe; see Table 1 column "*proportion of BSA stimulated*"), and that any  
140 confounding effect driven by sex differences in body size would be limited (17). Body  
141 surface area correlates well with hand and foot surface areas, with the latter generally  
142 corresponding to ~1% of total body surface area (3, 56, 65)  
143 The project conformed to the Helsinki Declaration and was approved by the Institutional  
144 Committee for the Protection of Human Subjects of the University of California at Berkeley.  
145 Participants were naïve as to the purpose of the experiments and they each gave written  
146 informed consent. All testing occurred during the months of March and April.

147

#### 148 *Experimental design*

149 All participants took part in one experimental session, during which they underwent a  
150 standardized quantitative thermosensory test (duration ~1h) in a climatic chamber under  
151 thermo-neutral environmental conditions (air temperature= 23°C; relative humidity= 50%).

152 This quantitative test was adapted from the one we recently developed and tested in both  
153 healthy individuals (23, 24) and in neurological patients undergoing thermal stress (22).  
154 The thermosensory test was designed to quantify local thermosensitivity of 103 skin sites  
155 across the hairy and glabrous skin of hands and feet in response to locally applied skin  
156 warming and cooling stimuli (i.e.  $\pm 5^{\circ}\text{C}$  from a baseline temperature of  $31^{\circ}\text{C}$ ; duration of  
157 stimulation: 5s), whose temperature is within the range for maximal activation of both  
158 cutaneous cold (i.e.  $27 - 22^{\circ}\text{C}$ ) and warm (i.e.  $36 - 42^{\circ}\text{C}$ ) thermoreceptors (19). A schematic  
159 representation of the experimental design is presented in Fig. 1.  
160 Figure 2 presents the topographical distribution of the 103 skin sites mapped. We assessed  
161 both hairy and glabrous skin as there is evidence that thermosensitivity varies across these  
162 types of skin (67), owing to both physiological (e.g. density of sensory innervation; (55)) and  
163 biophysical factors (e.g. differences in thickness of the epidermal layer and related thermal  
164 conductance; (34)). Participants were trained to report on a 11-point Numerical Rating Scale  
165 (Fig. 1D) the magnitude of local thermal sensations elicited by the skin warming and cooling  
166 stimuli (Fig. 1C), which were delivered with a hand-held  $1.32\text{cm}^2$  thermal probe (Fig. 1A;  
167 NTE-2A, Physitemp Instruments Inc., USA; probe response rate:  $2.43^{\circ}\text{C}/\text{s}$ ) to each skin site  
168 (Fig. 1B) in a randomised order.  
169 The density and anatomical location of the 103 skin sites tested (Fig. 2) were chosen in order  
170 to map as much skin area as possible across hairy and glabrous skin of hands and feet, in  
171 relation to the size of the thermal probe. All tested skin sites were on the left side of the body,  
172 assuming bi-lateral symmetry (10).  
173 Local skin temperature ( $T_{\text{sk}}$ ) variations at the contact site between the skin and thermal probe  
174 were monitored and recorded before, during, and after the application of each stimulus, using  
175 a fast-response thermocouple microsensor (Fig. 1A; time constant: 0.005s; tip diameter:  
176 0.3mm; IT-1E, Physitemp Instruments Inc., USA), located on the probe's surface, and



177 interfaced with a Microprobe Thermometer (accuracy:  $\pm 0.1^{\circ}\text{C}$  between  $0\text{-}50^{\circ}\text{C}$ ; BAT-12,  
178 Physitemp Instruments Inc., USA). A single-blind psychophysical design was used for the  
179 present study, with the same investigator performing all testing.

180

### 181 *Experimental protocol*

182 Participants arrived to the laboratory on testing days, after having refrained from caffeine and  
183 alcohol in the 12h preceding the experiment. They changed into shorts and t-shirt (no shoes  
184 were worn), and moved into the climatic chamber.

185 Five wireless temperature sensors (iButtons, Maxim, USA) were taped to five skin sites on  
186 the right side of the body (i.e. cheek, bicep, abdomen, lateral lower back and back lower  
187 thigh) with medical tape (3M, USA) in order to record local  $T_{sk}$  (10-s intervals), to be used  
188 for the estimation of mean  $T_{sk}$  for the entire body according to the equation of Houdas and  
189 Ring (1982):

Whole body mean  $T_{sk}$

$$\begin{aligned} &= (\textit{Cheek}T_{sk} \times 0.07) + (\textit{Bicep}T_{sk} \times 0.19) + (\textit{Abdomen}T_{sk} \times 0.175) \\ &+ (\textit{LateralLowerBack}T_{sk} \times 0.175) + (\textit{Thigh}T_{sk} \times 0.39) \end{aligned}$$

190 Five-minute averages were determined for mean  $T_{sk}$  data.

191 Once instrumented, participants sat on a stool where they rested for the entire test. Thirty

192 minutes were allowed for adaptation to the environmental conditions, and for baseline

193 recordings. During this time, participants were familiarized with the quantitative

194 thermosensory test. The detailed procedures for familiarization and execution of the

195 quantitative thermosensory test are presented below, along with the methods for quantifying

196 and mapping local thermosensitivity.

197

### 198 *Quantitative thermosensory test: familiarization and calibration*

199 During the 30-min adaptation, participants were briefed about the general producers  
200 underlying the quantitative thermosensory test. They were informed that non-painful  
201 warming and cooling stimuli would be delivered separately to each of 103 different sites  
202 across their hands and feet using a thermal probe. To avoid any expectation bias, no  
203 information was given about the temperature of the stimuli, or whether the same stimuli  
204 would be applied to different skin areas.

205 The 103 skin sites targeted for stimulation were marked with a washable marker to assure  
206 consistency in the location of stimulation. Participants were then instructed that, when  
207 requested by the investigator, they would be expected to report the magnitude of the very first  
208 local thermal sensation resulting from each stimulus application. They would use a 0-10  
209 numerical rating scale whose anchor points 0 and 10 were respectively labelled as “Not  
210 hot/Not cold at all” and “Very Hot/Very Cold”. This scale is similar to the one used by  
211 Gerrett et al., (2014) and Ouzzahra et al. (2012) in similar studies, and its choice was based  
212 on extensive evidence supporting the applicability and reliability of numerical rating scales  
213 for somatic sensations in humans (19, 32).

214 To ensure consistency in the use of the scale, participants were calibrated to its anchor points.  
215 This was achieved by delivering 3 separate stimuli with the thermal probe to a representative  
216 skin site, and by asking participants to associate the resulting thermal sensations to the  
217 specific anchor point. The first stimulus corresponded to a temperature of 31°C, which was  
218 similar to that of the skin, and which induced neither a warm nor a cold thermal sensation.

219 After confirming the absence of any thermal sensation, participant were informed that they  
220 should associate the anchor point 0 “Not hot/Not cold at all”, to this absence of thermal  
221 sensation. The second and third stimuli corresponded to  $\pm 10^{\circ}\text{C}$  from a baseline temperature  
222 of 31°C. These cold and warm stimuli were twice as large as the warming and cooling stimuli  
223 that would be used for the quantitative thermosensory mapping (i.e.  $\pm 5^{\circ}\text{C}$  from a baseline

224 temperature of 31°C), and were delivered to induce thermal sensations that participants were  
225 instructed to associate to the “Very Hot/Very Cold” anchor points of the scale.  
226 Once the calibration was completed, participants underwent some practice trials where they  
227 were allowed to experience the actual testing stimuli (i.e.  $\pm 5^{\circ}\text{C}$  from a baseline temperature  
228 of 31°C) on a variety of skin sites, and were informed that these stimuli would be similar to  
229 the ones to be used during the thermosensory mapping. Participants were also encouraged to  
230 practice the use of the rating scale during these practice trials, and were informed that local  
231 sensations would have to correspond to their first sensation upon stimulation, and that this  
232 would be reported at the request of the investigator, within 5s of delivering the stimulus.  
233 Pilot studies indicated 5s as a sufficient time for the set stimuli to reach their target absolute  
234 temperatures (i.e. 26 and 36°C).  
235 The above described familiarization protocol ensured that all participants were calibrated to  
236 the scale and fully familiar with the testing procedures upon commencing the actual  
237 experiment.

238

### 239 *Quantitative thermosensory test: execution*

240 Upon termination of the familiarization, the quantitative thermosensory test initiated.  
241 Participants rested on a stool, facing away from the skin area stimulated. They were  
242 instructed to only focus on the numerical rating scale positioned in front of them, and to  
243 report their local sensation upon request. The hand or foot were then selected as the first  
244 extremity to be tested, according to a between-participants counterbalanced order.  
245 Testing for both the hand and the foot was split between the hairy (i.e. dorsum of hands and  
246 foot) and glabrous parts (i.e. palm of the hand and foot sole), and mapping of all skin sites on  
247 one part (e.g. palm of the hand) was completed, before moving to the next part (e.g. dorsum  
248 of the hand). A 5-min break was allowed in between testing of hands and feet.

249 Whenever the hand was tested, participants placed it on a fabric cushion on a table, with the  
250 palm resting in a comfortable position, facing either upwards or downwards. Whenever the  
251 foot was tested, participants placed their lower leg on a fabric cushion on a lowered stool,  
252 with the foot freely suspended beyond the stool.

253 Once a comfortable position was achieved, the investigator began testing of the first skin site.  
254 First, the investigator set the thermal probe at 31°C (i.e. neutral temperature) and placed this  
255 gently on the skin site to be tested, with a pressure sufficient to ensure full contact with the  
256 skin. Five seconds were allowed for the local  $T_{sk}$  to stabilize. This was monitored via the  
257 surface thermocouple, and was recorded before delivery of the first stimulus. Following on to  
258 the initial stabilization, the +5°C skin warming or the -5°C cooling stimulus was delivered,  
259 and after 5s from delivery, the participant was requested to report their local thermal  
260 sensation (Fig. 1C). Along with the local sensation, the local  $T_{sk}$  at the 5-s stimulation was  
261 also recorded, to determine the  $\Delta T_{sk}$  change from pre-stimulation. At this point, the probe  
262 was re-set to 31°C, and after a 5-s break, the second stimulus (i.e. a warming stimulus in case  
263 of a previous cooling one and vice versa) was delivered (Fig. 1C). Pilot studies indicated 5-s  
264 as a sufficient time to ensure that baseline  $T_{sk}$  and neutral sensations would be re-established.  
265 The order of delivery of warming and cooling stimuli was balanced within-participants.  
266 Once both warm and cold sensitivity was assessed on a skin site, the investigator moved the  
267 probe on the next skin site, and the same procedure as above, was performed until all skin  
268 sites were tested.

269

### 270 *Quantifying local thermosensitivity*

271 We collected data on local changes in  $T_{sk}$ , and local thermal sensations, for each of the 103  
272 skin site tested, as a result of both the skin warming and cooling stimuli.

273  $T_{sk}$  and local thermal sensations data were combined to calculate an index of local  
274 thermosensitivity as follow:

$$Thermosensitivity \left( \frac{vote}{^{\circ}C} \right) = \frac{thermal\ sensation\ (vote)}{\Delta\ local\ T_{sk}\ (^{\circ}C)}$$

275 This thermosensitivity index provided, for each skin site, a normalised indication of the  
276 sensation resulting from a unit change in local  $T_{sk}$ .

277

### 278 *Thermosensitivity maps*

279 To aid with visualization of regional thermosensory patterns, the data collected were used to  
280 generate high-density thermosensitivity maps. Maps were created separately for males and  
281 females, for hairy and glabrous skin, and for warming and cooling.

282 High-density thermosensory maps were generated using a custom written MatLab script (The  
283 MathWorks, Inc., USA). Average data per group (n=8) were entered into a matrix composed  
284 of the coordinates (X;Y) of the skin site of interest (which were based on representative  
285 images of the palm/dorsum of the hands and sole/dorsum of the foot, see Fig.2), and the  
286 associated thermosensitivity value (Z). MatLab interpolation and extrapolation functions  
287 were used to create HeatMap objects, which were then superimposed over images of the  
288 extremity of interest, and morphed accordingly with an imaging software (Photoshop; Adobe,  
289 USA).

290

### 291 *Statistical analysis*

292 In order to evaluate changes in whole-body thermal state during the test in male and females,  
293 mean  $T_{sk}$  data were analysed by means of a two-way mixed-model ANOVA, with sex as  
294 independent factor, and time as repeated factor.

295 In order to determine whether sensitivity to skin warming and cooling varied across skin sites  
296 and between male and females, thermosensitivity data were analysed separately for warming

297 and cooling stimuli, and for hairy and glabrous parts of hands and feet, by means of a two-  
298 way mixed-model ANOVA, with sex as independent factor and skin site as repeated factor.  
299 In the event of statistically significant main effects or interactions, post-hoc analyses were  
300 conducted with Fisher's LSD tests.

301 Analysis for the glabrous part of the hand included data for skin sites 1 to 23. Analysis for the  
302 hairy part of the hand included data for skin sites 24 to 49. Analysis for the glabrous part of  
303 the foot included data for skin sites 23 to 43. Analysis for the hairy part of the foot included  
304 data for skin sites 1 to 22 and 44 to 54.

305 In order to explore inter-individual variability in local thermosensitivity, coefficient of  
306 variations [i.e.  $(SD/mean)*100$ ] were calculated for each skin site tested for both warming  
307 and cooling stimuli, in both males and females. Mean differences in inter-individual  
308 variability between sexes were assessed by means of unpaired t-tests. Data were then  
309 summarised into heat maps to display skin sites of high and low inter-individual variability in  
310 local thermosensitivity.

311 In order to determine overall thermosensitivity differences between the hand and the foot,  
312 thermosensitivity data from hairy and glabrous skin sites were grouped for warm and cold  
313 sensitivity and for males and females, and compared between hands and feet by means of  
314 paired t-tests. Similarly, to determine overall thermosensitivity differences between glabrous  
315 (palms and soles) versus hairy skin (back of hands and feet), data from hands and feet were  
316 grouped for warm and cold sensitivity and for males and females, and compared between  
317 hairy and glabrous skin by means of paired t-tests.

318 Finally, correlation analyses between warm and cold thermosensitivity across all skin site  
319 tested were performed separately for males and females.

320 Data are reported as means, SD, and 95% Confidence Intervals. Observed power was  
321 computed using  $\alpha=0.05$ . Statistical analysis was performed using GraphPad Prism (version  
322 6.0; GraphPad Software, La Jolla, CA, USA).

323

324

## 325 **Results**

326

### 327 *Whole body mean $T_{sk}$*

328 Average mean  $T_{sk}$  did not change over the course of the experiment ( $F_{(10, 40)}=0.6063$ ;  
329  $p=0.799$ ) and was maintained within a neutral range (i.e. 31-34°C) (25), with no differences  
330 ( $F_{(1, 4)}=0.2124$ ;  $p=0.668$ ) between males (mean  $T_{sk}=32.14^{\circ}\text{C}$ ; SD 0.08) and females (mean  
331  $T_{sk}=31.64^{\circ}\text{C}$ ; SD 0.18).

332

### 333 *Hand: glabrous skin warm thermosensitivity*

334 In the male group, mean warm thermosensitivity across glabrous skin (i.e. sites 1 to 23) was  
335 0.89 vote/ $^{\circ}\text{C}$  [95% CI= 0.80, 0.98], and varied between a minimum of 0.55 to a maximum of  
336 1.22 vote/ $^{\circ}\text{C}$  (Fig. 3). In the female group, mean warm thermosensitivity across the same skin  
337 sites was 1.23 vote/ $^{\circ}\text{C}$  [95% CI= 1.09, 1.38], and varied between a minimum of 0.57 to a  
338 maximum of 1.68 vote/ $^{\circ}\text{C}$  (Fig. 3). Differences in warm thermosensitivity between males  
339 and females were not statistically significant ( $F_{(1, 14)}=1.97$ ;  $p=0.181$ ).

340 While no clear sex differences were observed, warm thermosensitivity varied significantly  
341 across the palm of the hand ( $F_{(22, 308)}=1.94$ ;  $p=0.007$ ), with regional patterns that were similar  
342 between male and females ( $F_{(22, 308)}=0.878$ ;  $p=0.624$ ).

343 The centre of the palm (skin site 17), along with the area at the base of the thumb (skin site  
344 19), presented some of the highest warm sensitivity in both males (site 17= 1.22 vote/ $^{\circ}\text{C}$ ; site

345 19= 1.16 vote/°C) and females (site 17= 1.54 vote/°C; site 19= 1.68 vote/°C). On the  
346 contrary, the thumb (skin site 22) and the intermediate portion of the fifth digit (skin site 11),  
347 presented some of the lowest warm sensitivity in both males (site 22= 0.55 vote/°C; site 11=  
348 0.92 vote/°C) and females (site 22= 0.87 vote/°C; site 11= 0.57vote/°C).

349 Statistical significance values for multiple sites comparison are listed in *Supplementary*  
350 *Material 1*.

351

### 352 *Hand: glabrous skin cold thermosensitivity*

353 In the male group, mean cold thermosensitivity across glabrous skin (i.e. sites 1 to 23) was  
354 1.49 vote/°C [95%CI= 1.40, 1.59], and varied between a minimum of 0.83 to a maximum of  
355 1.81 vote/°C (Fig.). In the female group, mean cold thermosensitivity across the same skin  
356 sites was 1.99 vote/°C [95%CI= 1.86, 2.12], and varied between a minimum of 1.17 to a  
357 maximum of 2.56 vote/°C (Fig. 3).

358 Cold thermosensitivity varied largely across the palm of the hand in both males and females  
359 ( $F_{(22, 308)} = 1.93$ ;  $p=0.008$ ). However, and contrary to what observed for warm  
360 thermosensitivity, we observed a tendency for the female group to present an overall higher  
361 cold thermosensitivity than their male counterparts ( $F_{(1, 14)} = 3.29$ ;  $p=0.090$ ).

362 Similar regional patterns of cold sensitivity were observed across the palm in both groups  
363 ( $F_{(22, 308)} = 1.00$ ;  $p=0.459$ ), with the base of the palm (skin site 20) presenting high sensitivity  
364 in both males (site 20= 1.82 vote/°C) and females (site 20= 2.39 vote/°C).

365 In addition, females presented significantly higher cold sensitivity than males on specific skin  
366 sites, such as the intermediate portion of the second digit (skin site 2; mean difference=+ 0.95  
367 vote/°C, [95%CI= 0.14, 1.75]), the distal portion of the fifth digit (skin site 10; mean  
368 difference=+ 0.90 vote/°C, [95%CI= 0.09, 1.70]), the middle part of the top of the palm (skin



369 site 14; mean difference 0.86 vote/°C, [95%CI= 0.05, 1.67]), and the medial area at the base  
370 of the palm (skin site 21; mean difference 0.81 vote/°C, [95%CI= 0.01, 1.61]).  
371 Statistical significance values for multiple sites comparison are listed in *Supplementary*  
372 *Material 1*.  
373  
374 *Hand: hairy skin warm thermosensitivity*  
375 In the male group, mean warm thermosensitivity across hairy skin (i.e. sites 24 to 49) was  
376 1.27 vote/°C [95%CI= 1.12, 1.42], and varied between a minimum of 0.28 to a maximum of  
377 1.79 vote/°C (Fig. 3). In the female group, mean warm thermosensitivity across the same skin  
378 sites was 1.42 vote/°C [95%CI= 1.27, 1.58], and varied between a minimum of 0.78 to a  
379 maximum of 2.12 vote/°C (Fig. 3). Differences in warm thermosensitivity between males  
380 and females were not statistically significant ( $F_{(1, 14)}= 0.3409$ ;  $p=0.568$ ).  
381 While no clear sex differences were observed, warm thermosensitivity varied largely across  
382 the dorsum of the hand ( $F_{(25, 350)}= 2.72$ ;  $p<0.0001$ ), with regional patterns that were similar  
383 between male and females ( $F_{(25, 350)}= 1.153$ ;  $p=0.280$ ).  
384 The proximal portion of the fourth digit (skin site 30), along with the area in between the  
385 metacarpophalangeal joint of the second digit and the base of the thumb (skin site 36),  
386 presented some of the highest warm sensitivity in both males (site 30= 1.74 vote/°C; site 36=  
387 1.79 vote/°C) and females (site 30= 1.97 vote/°C; site 36= 1.76 vote/°C). On the contrary, the  
388 area over the metacarpophalangeal joint of the second digit (skin site 33) and the middle area  
389 at the base of the hand (skin site 40), presented some of the lowest warm sensitivity in both  
390 males (site 33= 0.59 vote/°C; site 40= 0.99 vote/°C) and females (site 33= 1.12 vote/°C; site  
391 40= 0.79 vote/°C).  
392 Statistical significance values for multiple sites comparison are listed in *Supplementary*  
393 *Material 1*.

394

395 *Hand: hairy skin cold thermosensitivity*

396 In the male group, mean cold thermosensitivity across hairy skin (i.e. sites 24 to 49) was 2.19  
397 vote/°C [95%CI= 2.06, 2.32], and varied between a minimum of 1.63 to a maximum of 2.70  
398 vote/°C (Fig.). In the female group, mean cold thermosensitivity across the same skin sites  
399 was 2.52 vote/°C [95%CI= 2.41, 2.63], and varied between a minimum of 1.82 to a  
400 maximum of 3.04 vote/°C (Fig. 3).

401 While no sex differences were observed, ( $F_{(1, 14)}= 1.566$ ;  $p=0.231$ ), cold thermosensitivity  
402 varied significantly across the dorsum of the hand ( $F_{(25, 350)}= 1.98$ ;  $p=0.003$ ), with regional  
403 patterns that were similar between male and females ( $F_{(25, 350)}= 1.38$ ;  $p=0.103$ )

404 The area across the centre of the dorsum (skin sites 36 and 37) and the base of the thumb  
405 (skin site 39) presented some of the highest warm sensitivity in both males (site 36= 2.32  
406 vote/°C; site 37= 2.63 vote/°C; site 39= 2.71 vote/°C) and females (site 36= 2.82 vote/°C; site  
407 37= 2.46 vote/°C; site 39= 3.04 vote/°C). On the contrary, the area over the  
408 metacarpophalangeal joints of the second and fifth digits (skin sites 33 and 35), presented  
409 some of the lowest cold sensitivity in both males (site 33= 1.76 vote/°C; site 35= 1.66  
410 vote/°C) and females (site 33= 2.36 vote/°C; site 35= 1.82 vote/°C).

411 Statistical significance values for multiple sites comparison are listed in *Supplementary*

412 *Material 1.*

413

414 *Hand: inter-individual variability in thermosensitivity*

415 Inter-individual variability in warm thermosensitivity was greater in males than in females  
416 (mean difference= +10.5% [95% CI= 0.6, 20.4];  $p=0.038$ ), and ranged largely across the skin  
417 site tested, from a minimum of 39.2% (skin site 48) to a maximum of 186% (skin site 11) in

418 males (mean= 79.1%), and from a minimum of 34.4% (skin site 32) to a maximum of  
419 117.6% (skin site 42) in females (mean= 68.6%) (Fig. 5).  
420 Inter-individual variability in cold thermosensitivity was greater in males than in females  
421 (mean difference= +6.3% [95% CI= 1.2, 11.4];  $p=0.016$ ), and ranged largely across the skin  
422 site tested, from a minimum of 16.5% (skin site 26) to a maximum of 72.1% (skin site 11) in  
423 males (mean= 43.7%), and from a minimum of 31.1% (skin site 3) to a maximum of 81.1%  
424 (skin site 12) in females (mean= 37.37%) (Fig. 5).  
425 All in all, it appeared that inter-individual variability in thermosensitivity was: 1) more  
426 pronounced in males than in females for both warm and cold; 2) greater in some specific skin  
427 sites across the glabrous and hairy skin of the hand; and 3) greater overall for warm than cold  
428 sensitivity.

429

430 *Foot: glabrous skin warm thermosensitivity*

431 In the male group, mean warm thermosensitivity across glabrous skin (i.e. sites 23 to 43) was  
432 0.25 vote/ $^{\circ}\text{C}$  [95%CI= 0.19, 0.31], and varied between a minimum of 0 to a maximum of  
433 1.53 vote/ $^{\circ}\text{C}$  (Fig. 4). In the female group, mean warm thermosensitivity across the same skin  
434 sites was 0.46 vote/ $^{\circ}\text{C}$  [95%CI= 0.37, 0.55], and varied between a minimum of 0.21 to a  
435 maximum of 0.79 vote/ $^{\circ}\text{C}$  (Fig. 4).

436 Warm thermosensitivity varied largely across the sole of the foot in both males and females  
437 ( $F_{(20, 260)}= 2.17$ ;  $p=0.003$ ).

438 The centre portion of the sole (skin sites 35 and 38) presented some of the highest warm  
439 sensitivity in both males (site 35= 0.53 vote/ $^{\circ}\text{C}$ ; site 38= 0.38 vote/ $^{\circ}\text{C}$ ) and females (site 35=  
440 0.75 vote/ $^{\circ}\text{C}$ ; site 38= 0.79 vote/ $^{\circ}\text{C}$ ), while the distal part of the hallux (skin site 23) and the  
441 centre of the heel (skin site 43) presented some of the lowest warm sensitivity in males (site

442 23= 0.13 vote/°C; site 43= 0.08 vote/°C) and females (site 23= 0.26 vote/°C; site 43= 0.23  
443 vote/°C).

444 Despite neither sex presenting an overall higher sensitivity *per se* ( $F_{(1, 13)}= 3.03$ ;  $p=0.105$ ),  
445 there was a tendency for some specific skin sites to be more sensitive in females than in  
446 males ( $F_{(20, 260)}= 1.569$ ;  $p=0.060$ ).

447 Specifically, females presented significantly higher warm sensitivity than males on the  
448 superior portion of the arch (skin site 34; mean difference=+ 0.55 vote/°C, [95%CI= 0.14,  
449 0.96]), the centre (skin site 38; mean difference=+ 0.41 vote/°C, [95%CI= 0.01, 0.82]), and  
450 the lateral portion of the sole (skin site 39; mean difference +0.58 vote/°C, [95%CI= 0.17,  
451 0.99]).

452 Statistical significance values for multiple sites comparison are listed in *Supplementary*  
453 *Material 1*.

454

#### 455 *Foot: glabrous skin cold thermosensitivity*

456 In the male group, mean cold thermosensitivity across glabrous skin (i.e. sites 23 to 43) was  
457 0.75 vote/°C [95%CI= 0.55, 0.94], and varied between a minimum of 0.04 to a maximum of  
458 1.78 vote/°C (Fig. 4). In the female group, mean cold thermosensitivity across the same skin  
459 sites was 0.55 vote/°C [95%CI= 0.34, 0.75], and varied between a minimum of 0.04 to a  
460 maximum of 1.65 vote/°C (Fig. 4).

461 Cold thermosensitivity varied largely across the sole of the foot in both males and females  
462 ( $F_{(20, 260)}= 8.48$ ;  $p<0.0001$ ).

463 The area over the arch (skin sites 34 and 37) presented some of the highest cold sensitivity in  
464 both males (site 34= 1.45 vote/°C; site 37= 1.78 vote/°C) and females (site 35= 1.35 vote/°C;  
465 site 38= 1.09 vote/°C), while the distal part of the hallux (skin site 23) and the centre of the

466 heel (skin site 43) presented some of the lowest cold sensitivity in males (site 23= 0.47  
467 vote/°C; site 43= 0.04 vote/°C) and females (site 23= 0.29 vote/°C; site 43= 0.25 vote/°C).  
468 Despite neither sex presenting an overall higher sensitivity *per se* ( $F_{(1, 13)} = 0.73$ ;  $p=0.408$ ),  
469 there was a clear trend for some specific skin sites to be more sensitive in males than in  
470 females ( $F_{(20, 260)} = 2.04$ ;  $p=0.006$ ).

471 Specifically, males presented significantly higher cold sensitivity than females on the  
472 proximal part of the second toe (skin site 26; mean difference=+ 0.74 vote/°C, [95%CI= 0.05,  
473 1.43]), the distal part of the fourth toe (skin site 29; mean difference=+ 0.72 vote/°C,  
474 [95%CI= 0.03, 1.41]), and the centre portion of the arch (skin site 37; mean difference +0.69  
475 vote/°C, [95%CI= 0.01, 1.38]).

476 Statistical significance values for multiple sites comparison are listed in *Supplementary*  
477 *Material 1*.

478

479 *Foot: hairy skin warm thermosensitivity*

480 In the male group, mean warm thermosensitivity across hairy skin (i.e. sites 1 to 22 and 44 to  
481 55) was 0.52 vote/°C [95%CI= 0.45, 0.60], and varied between a minimum of 0.16 to a  
482 maximum of 0.89 vote/°C (Fig.). In the female group, mean warm thermosensitivity across  
483 the same skin sites was 0.65 vote/°C [95%CI= 0.55, 0.75], and varied between a minimum of  
484 0.16 to a maximum of 1.24 vote/°C (Fig. 4).

485 No sex differences in thermosensitivity were observed ( $F_{(1, 13)} = 1$ ;  $p=0.335$ ), and warm  
486 thermosensitivity varied largely across the dorsum of the foot ( $F_{(33, 429)} = 2.117$ ;  $p<0.001$ ),  
487 with regional patterns that were similar between male and females ( $F_{(33, 429)} = 0.93$ ;  $p=0.574$ ).

488 The central portion of the dorsum of the foot (skin sites 15, 16, 17), presented some of the  
489 highest warm sensitivity in both males (site 15= 0.89 vote/°C site; 16= 0.73 vote/°C; site 17=  
490 0.77 vote/°C) and females (site 15= 0.83 vote/°C site; 16= 0.78 vote/°C; site 17= 1.24

491 vote/°C). In contrast, the proximal portion of the hallux (skin site 1) and the distal portion of  
492 the fifth toe (skin site 8), presented some of the lowest warm sensitivity in both males (site 1=  
493 0.19 vote/°C; site 8= 0.45 vote/°C) and females (site 1= 0.32 vote/°C; site 8= 0.17 vote/°C).  
494 Statistical significance values for multiple sites comparison are listed in *Supplementary*  
495 *Material 1*.

496

497 *Foot: hairy skin cold thermosensitivity*

498 In the male group, mean cold thermosensitivity across hairy skin (i.e. sites 1 to 22 and 44 to  
499 55) was 1.23 vote/°C [95%CI= 1.09, 1.36], and varied between a minimum of 0.18 to a  
500 maximum of 2.01 vote/°C (Fig. 4). In the female group, mean cold thermosensitivity across  
501 the same skin sites was 1.18 vote/°C [95%CI= 1.07, 1.30], and varied between a minimum of  
502 0.48 to a maximum of 1.87 vote/°C (Fig. 4).

503 No sex differences in thermosensitivity were observed ( $F_{(1, 13)} = 0.02$ ;  $p=0.893$ ). Cold  
504 thermosensitivity varied largely across the dorsum of the foot ( $F_{(33, 429)} = 2.99$ ;  $p<0.0001$ ) with  
505 regional patterns that were similar for males and females ( $F_{(33, 429)} = 1.19$ ;  $p=0.213$ ).

506 The central portion of the dorsum of the foot (skin sites 15), exhibited some of the highest  
507 cold sensitivity in both males (site 15= 1.62 vote/°C site) and females (site 15= 1.88 vote/°C  
508 site).

509 In contrast, the proximal portion of the hallux (skin site 1) and the distal portion of the fourth  
510 toe (skin site 6), exhibited some of the lowest cold sensitivity in both males (site 1= 1.17  
511 vote/°C; site 6= 1.27 vote/°C) and females (site 1= 0.83 vote/°C; site 8= 0.67 vote/°C).

512 Statistical significance values for multiple sites comparison are listed in *Supplementary*  
513 *Material 1*.

514

515 *Foot: inter-individual variability in thermosensitivity*

516 Inter-individual variability in warm thermosensitivity was greater in males than in females  
517 (mean difference= +23.2% [95% CI= 7.4, 39.0]; p=0.004), and ranged largely across the skin  
518 site tested, from a minimum of 51.1% (skin site 7) to a maximum of 264.6% (skin site 43) in  
519 males (mean= 123.3%), and from a minimum of 44.7% (skin site 15) to a maximum of  
520 213.3% (skin site 1) in females (mean= 100.1%) (Fig. 5).

521 Inter-individual variability in cold thermosensitivity was similar between males and females  
522 (mean difference= +0.85% [95% CI= -16, 17.7]; p=0.920), yet ranged largely across the skin  
523 site tested, from a minimum of 37.8% (skin site 13) to a maximum of 264.6% (skin sites 42  
524 and 43) in males (mean= 94.9%), and from a minimum of 35.6% (skin site 18) to a maximum  
525 of 282.8% (skin site 30) in females (mean= 94%) (Fig. 5).

526 In sum, it appeared that inter-individual variability in thermosensitivity: 1) was more  
527 pronounced in males than in females with regards to warm sensitivity only; 2) was greater in  
528 some specific skin sites across the glabrous and hairy skin of the foot; 3) was overall greater  
529 for warm than cold sensitivity.

530

### 531 *Hand vs. Foot overall thermosensitivity*

532 Comparison between overall thermosensitivity of the hand versus the foot indicated that, for  
533 both males and females, the hand to be twice as warm sensitive (male hand vs. foot mean  
534 difference= 0.75 vote/°C [95% CI=0.46, 1.04], p=0.001; female hand vs. foot mean  
535 difference= 0.75 vote/°C [95% CI=0.45, 1.05], p=0.001), and twice as cold sensitive as the  
536 foot (male hand vs. foot mean difference= 0.93 vote/°C [95% CI=0.38, 1.47], p=0.006; female  
537 hand vs. foot mean difference= 1.32 vote/°C [95% CI=0.90, 1.75], p<0.001), (Fig. 6).

538

### 539 *Hairy vs Glabrous. skin overall thermosensitivity*

540 Comparison between overall thermosensitivity of hairy skin (back of hands and feet) versus  
541 glabrous (palms and soles) indicated the hairy skin to be more warm sensitive (male hairy vs.  
542 glabrous mean difference= 0.34 vote/°C [95%CI=0.20, 0.45],  $p<0.001$ ; female hairy vs.  
543 glabrous mean difference= 0.19 vote/°C [95%CI=0.02, 0.36],  $p=0.029$ ), and more cold  
544 sensitive (male hairy vs. glabrous mean difference= 0.59 vote/°C [95%CI=0.41, 0.77],  
545  $p<0.001$ ; female hairy vs. glabrous mean difference= 0.58 vote/°C [95%CI=0.31, 0.85],  
546  $p<0.001$ ) than glabrous skin, in both males and females (Fig. 7).

547

#### 548 *Association between overall warm and cold thermosensitivity*

549 Correlation analyses performed on data from all skin sites tested across hand and feet showed  
550 a significant association between warm and cold sensitivity in both males (Pearson  $r=0.80$   
551 [95%CI= 0.71, 0.86];  $R^2=0.64$ ;  $p<0.0001$ ) and females (Pearson  $r=0.83$  [95%CI= 0.76,  
552 0.88];  $R^2=0.69$ ;  $p<0.0001$ ) (Fig. 8), with a tendency for cold to be greater than warm  
553 sensitivity. The significant association between warm and cold sensitivity indicated that  
554 hands and feet contained areas that were highly sensitive to temperature changes *per se*,  
555 irrespective of their direction (i.e. warming or cooling).

556

#### 557 **Discussion**

558 Our high-density thermosensory micromapping resulted in the development of the most  
559 detailed thermosensitivity maps of hands and feet in healthy young adults available to date.

560 Overall, our findings indicate that:

- 561 1. Thermosensitivity to warm and cold varies largely by up to 5-fold across the glabrous  
562 and hairy portions of both hands and feet (Fig. 3, 4), with a distal-to-proximal  
563 organisation, and with hairy skin being more thermosensitive than glabrous (Fig. 7);
- 564 2. The hand is twice as thermosensitive as the foot (compare Fig. 3 and 4; see Fig. 6);



565 3. Body-surface-area-matched males and females present small differences in  
566 thermosensitivity of hands and feet, and that these differences are constrained to  
567 glabrous skin only;

568

569 *Thermosensitivity varies largely across hands and feet, and between skin types*

570 The heterogeneous topography of thermosensitivity we observed here presents a distal-to-  
571 proximal organisation on both the hand and the foot, with the palm and dorsum being more  
572 sensitive than the fingers (e.g. palm was twice as warm sensitive as the thumb; Fig. 3), and  
573 with the sole and dorsum being more sensitive than the toes (e.g. the area over the arch was  
574 three times as cold sensitive as the hallux; Fig. 4).

575 As this observation extends across both hairy and glabrous portions of both hands and feet, in  
576 both males and females, we suggest that the distal-to-proximal increase in thermosensitivity  
577 is likely to be a specific topographical feature of hands and feet thermosensitivity in humans.  
578 This finding is novel and surprising, particularly, as one would expect that due to their  
579 primary role in manipulation and gripping (8, 72), fingers and toes would be more sensitive  
580 than the rest of the hand and foot, as it is indeed the case for touch (37, 38) and pain  
581 sensitivity (48) of the palm.

582 A potential explanation to this finding is that, as opposed to tactile and pain sensations,  
583 thermosensation could play only a secondary role in exploratory touch; instead,  
584 thermosensory function could have developed to a greater sensitivity on skin regions other  
585 than fingers and toes (e.g. palms and soles), and particularly on hairy skin sites (e.g. dorsum  
586 of hands and feet), as its primary purpose is to support our thermoregulatory behaviour (20).  
587 The development of a higher thermosensitivity over hairy than glabrous skin would be  
588 biologically useful to help maintaining thermal homeostasis (Cabanac, 2011). As hairy skin  
589 covers the majority of our body, and as small changes over a large proportion of the body are

590 likely to result in higher rates of heat transfer to the environment (15), the higher  
591 thermosensitivity of hairy skin could help adjusting our thermoregulatory behaviour promptly  
592 in response to thermal stress, and prior to the engagement of energy-demanding autonomic  
593 heat- (i.e. sweating) and cold-defence (i.e. shivering) responses (62).

594 The hypothesis above is supported by our current findings, as we observed that hairy skin  
595 (i.e. dorsum of hand and foot) was more sensitive than glabrous skin (i.e. palm and sole) (see  
596 Fig. 7). Furthermore, previous psychophysical evidence has found a higher density of cold  
597 and warm sensitive spots on the hand/foot dorsum as opposed to the palm/sole, suggesting  
598 higher peripheral innervation of this type of skin (31). It could be therefore proposed that the  
599 hairy skin covering hands and feet could play a more specific thermosensory role than the  
600 glabrous skin of fingers and toes, as the latter is likely to be more of a specialized area for  
601 tactile than thermal sensitivity.

602 It is also likely that a distal-to-proximal increase in intra-epidermal nerve fibers innervation  
603 could be present across hands and feet, and that this could underlie some of the distribution of  
604 thermosensitivity observed within glabrous and hairy skin sites. Evidence is available for a  
605 distal-to-proximal increase in intra-epidermal nerve fibers density from the distal leg to the  
606 trunk (43), and this observation would support the hypothesis for which the density of  
607 thermosensitive fibres could decrease as one moves away from the core of the body and  
608 towards the upper and lower extremities (i.e. fingers and toes).

609 Finally, differences in skin thickness between fingers/toes and palm/soles, as well as between  
610 hairy and glabrous skin, and related changes in heat diffusion/extraction to/from the  
611 epidermal layers where thermoreceptors are positioned, could also contribute to partly  
612 explaining the observed distal to proximal organization in thermosensitivity (34). There is  
613 evidence indicating that hairy skin presents higher sensitivity than glabrous skin to heat pain,  
614 but only when thermal stimuli are delivered via conductive heating (34). When radiant heat

615 (e.g. laser pulses) stimulates the skin, regional differences between hairy and glabrous skin  
616 are eliminated (34), supporting the impact of thickness-depend mechanisms of heat transfer  
617 on stimulation of thermoreceptors. However, correlation between epidermal thickness and  
618 local thermosensitivity has been previously shown to be low across the palm (44).  
619 Furthermore, in the present study we observed the distal-to-proximal topographical trend to  
620 also extend across hairy skin, where differences in epidermal thickness between fingers/toes  
621 and the body of hands/feet are likely to be smaller than across glabrous skin. It is therefore  
622 likely that a combination of neurophysiological (e.g. peripheral innervation and central  
623 cortical representation) as well as biophysical factors (e.g. skin anatomy) could underlie the  
624 heterogeneous thermosensitivity we observed across hands and feet, as much as it is the case  
625 for touch and pain sensitivity of the palm (37, 48, 58).  
626 Irrespective of whether our observed differences within and between the hairy and glabrous  
627 skin of hands and feet are neurally- or anatomically-driven, it is remarkable to note that  
628 humans seem to be well aware of them, as reflected in some our most common and  
629 instinctive thermal behaviours. For example, it is common practice in many cultures to check  
630 whether one's baby has a fever by placing the dorsum of our hands (and not the palm nor  
631 fingers) on their forehead. Furthermore, it is part of public health advice in the United  
632 Kingdom to check a bath's temperature with one's elbow (and not finger) when bathing a  
633 baby (54). These examples illustrates well the thermosensory nature of hairy skin, and could  
634 support the intriguing hypothesis for which some of our most important adaptive thermal  
635 behaviours could be rooted in the topographical differences in our hands and feet  
636 thermosensitivity, as shown in our thermosensitivity maps.  
637  
638 *Hands are twice as thermosensitive as feet*

639 It is remarkable to note that the hand was on average twice as thermosensitive as the foot, in  
640 both males and females (Fig. 6). The higher thermosensitivity of hands than feet has been  
641 previously reported by our group (24) and by others (67), although such comparisons were  
642 based on a limited number of representative skin sites (e.g. the sole vs. the palm) (24). In  
643 expanding to thermosensory processing, these results are in line with evidence indicating that  
644 the presence of a greater cortical representation of hands as compared to feet in the human  
645 brain (58) is likely to underlie the greater sensitivity of the upper extremity to cutaneous  
646 stimulation. It could be therefore speculated that the higher thermosensitivity of the hands is  
647 likely to be more dependent on central (i.e. size of the central representation of target skin  
648 area), than on peripheral factors (i.e. skin receptors density), as it is the case for pain (48).  
649 Aside from its potential neural substrates, the pronounced difference in sensitivity between  
650 hands and feet is relevant in the context of its potential behavioural impact on  
651 thermoregulatory control and thermal comfort. Our observations indicate that a similar  
652 increase or decrease in local skin temperature would generate a perceptual signal twice as  
653 strong when arising from the hands as when arising from the feet. Along with the face, both  
654 hands and feet have been previously shown to have the strongest impact on thermal  
655 discomfort during exposure to warm and cold environments (4). In this context, it would  
656 therefore be worth establishing whether the greater sensitivity of the hand to a given skin  
657 temperature change would translate in a drive to behaviourally maintain/achieve/re-establish  
658 thermal comfort that is twice as strong as the one that would arise from a similar change in  
659 foot temperature.

660 It also interesting to note that, cold and warm sensitivities were highly associated across both  
661 hands and feet in both males and females (Fig. 8), although cold was overall higher than  
662 warm sensitivity. It has been repeatedly shown (44, 67) that there are particular “skin spots”  
663 with higher sensitivity to both warm and cold. Our findings for both hands and feet provide

664 further evidence for the presence of such spots that are highly sensitive to temperature change  
665 *per se*, irrespective of its direction (i.e. warming or cooling). Finally, our inter-individual  
666 variability analysis clearly showed modality- and region-dependent differences in individual  
667 variability in thermosensitivity, with variability being lower for cold than warm sensitivity,  
668 and for the hand as opposed to the foot (Fig. 5). The lower variability for cold is likely to be  
669 dependent on the higher cold than warm sensitivity of the skin, which was confirmed in this  
670 (Fig. 5) as well as in previous studies (20, 25, 28, 31). Interestingly, our finding of higher  
671 inter-individual variability for the foot than hand is novel, and could be dependent on the  
672 lower thermosensitivity of this region (see Fig. 6), which is likely to result in less  
673 homogenous thermal responses between individuals.

674

#### 675 *Males and females present small thermosensitivity differences*

676 A further major advance of this study is that we observed small sex differences in overall  
677 cold and warm thermosensitivity across hands and feet in our age- and body surface area-  
678 matched male and female groups. A slight trend was present, with females presenting a  
679 slightly higher sensitivity on glabrous (i.e. palms and soles), but not hairy (i.e. hand/foot  
680 dorsum), skin.

681 Numerous studies have analysed sex differences in thermosensitivity across the body, yet  
682 findings have been often contradictory, with females being alternatively reported as more  
683 sensitive (26, 27) or no different to males (67). Such contradictory evidence has often arisen  
684 from studies not matching sex groups for body surface area, and for the relative size of the  
685 stimulus (26, 44), with this resulting in the inability to ascribe potential thermosensitivity  
686 differences to sex differences *per se* (29), as opposed to size differences. To date, only the  
687 work by Inoue et al.(35) has provided evidence that differences in thermosensitivity across  
688 the body are still present (i.e. females are more sensitive than males) when both sexes present

689 similar body surface areas. However, as Inoue's work tested only a single area of hands and  
690 feet, the question remained as to the potential distribution of sex-related difference in  
691 thermosensitivity across the entire hand and foot.  
692 To overcome such gap in the literature, in this study we evaluated the distribution of  
693 thermosensitivity across the entire hand and foot in age- and body surface area-matched male  
694 and female and found that sex differences were overall small and only constrained to  
695 glabrous, and not hairy, skin.  
696 In showing that thermosensitivity across hands and feet is similar between males and females  
697 when these are matched for body surface area, our study complements previous evidence  
698 showing that sex differences in thermophysiological responses of hands and feet are reduced  
699 when male and female groups are matched by body surface area (36, 45).

700

#### 701 **Limitations**

702 The current study provides the most detailed topographical evaluation of the  
703 thermosensitivity of hands and feet in healthy young males and females. While the applied  
704 significance of our work lays in the detailed characterization of the thermal sensation that is  
705 likely to arise from thermal stimulation of a specific area of the skin under conditions that  
706 humans encounter on a daily base (e.g. touching a warm/cool surface), we also acknowledge  
707 that our findings provide limited evidence on the neurophysiological nature of the  
708 heterogeneous distribution of sensitivity across hands and feet as we observed it. Some  
709 methods are available to further explore whether such distribution of thermosensitivity could  
710 depend on the density of temperature-sensitive free nerve endings, or on their integration  
711 properties. These methods include: intraepidermal nerve fiber density via skin biopsy (40);  
712 and microneurography, to record *in vivo* neural activity from peripheral nerve fibers (70).  
713 While promising, the adoption of these techniques is also limited by some technical

714 challenges that could be at the root for the lack of their current use in combination with high  
715 density mapping studies such as ours. The use of skin biopsies to evaluate intraepidermal  
716 nerve fiber density is indeed limited by the number of skin sites that a typical participant is  
717 likely to agree to have punctured. The use of microneurography in the evaluation of  
718 thermoreceptors has been very limited (21) due to the difficulties in identify and recording  
719 from thermoreceptive fibers (note: only a handful of recordings from human thermoreceptors  
720 have been made to date; see e.g. (6, 7)). In face of such methodological challenges, studies  
721 endorsing animal models could be proposed as an alternative approach; yet, while commonly  
722 observed in humans (18, 23, 27, 53, 66), the presence of regional differences in  
723 thermosensitivity has not been fully investigated in models of mammalian thermosensation  
724 (51, 71), leaving our understating of its underlying neurobiology somewhat speculative. It is  
725 hoped that our current work will stimulate future attempts to better elucidate the neural  
726 mechanisms that underlie our characteristically heterogeneous skin thermosensitivity, by  
727 combining some of the methodologies listed above.

728

## 729 **Conclusions**

730 Our high-density thermosensory micromapping resulted in the development of the most  
731 detailed thermosensitivity maps of hands and feet in healthy young adults available to date.  
732 We found that thermosensitivity to warm and cold varied largely by up to 5-fold across the  
733 glabrous and hairy portions of human hands and feet, with hands being twice as sensitive as  
734 the feet. We observed a characteristic distal to proximal increase in thermosensitivity over  
735 both hairy and glabrous skin (i.e. from fingers/toes to body of hands and feet), and found that  
736 hairy is more sensitive than glabrous skin. We therefore argue that distal-to-proximal  
737 organization is a specific topographical feature of hand and feet thermosensitivity in humans,  
738 and that thermosensitivity differences between skin sites highlight the role of hairy skin in

739 behavioural thermoregulation, as opposed to the role of glabrous skin in exploratory touch.  
740 Finally, we determined that body-surface-area matched males and females present small  
741 differences in thermosensitivity and that these are constrained to glabrous skin only (i.e.  
742 females present slightly higher cold and warm sensitivity over the palm and sole respectively,  
743 while males present slightly higher cold sensitivity over the sole).  
744 Our novel findings fill a knowledge gap on the sensory function of human hands and feet.  
745 Also, by complementing the available evidence on the topography of touch and pain  
746 sensitivity, these findings provides a more comprehensive picture on the sensory function of  
747 two of our most important sensory and exploratory anatomical structures, i.e. our hands and  
748 feet. As well as providing a window into the peripheral and central mechanisms of  
749 thermosensory integration in humans, these maps will be valuable to guide future  
750 developments and design in smart skin and prosthesis, in wearable energy-efficient personal  
751 comfort systems, and in protective clothing.

752

### 753 **Competing interests**

754 The authors declare no competing interests.

755

### 756 **Author contributions**

757 DF, HZ, EA contributed to the conception and design of the work; DF performed the  
758 experiments and data analysis; DF, HZ, EA contributed to the interpretation of the results; DF  
759 drafted the work; DF, HZ, EA revised the work critically for important intellectual content.

760

### 761 **Funding**



762 This work was supported by the ARPA-E (Advanced Research Projects Agency- Energy,  
763 DOE) DELTA (Delivering Efficient Local Thermal Amenities) program under contract DE-  
764 AR0000529.

765

## 766 **Acknowledgements**

767 We would like to thank Mr Francisco Peralta (Mechanical Engineering graduate, University  
768 of California Berkeley) for developing the MatLab script used to produce the maps. We also  
769 thank the 16 volunteers for participating to the study.

770

771

## 772 **References**

- 773 1. **Ackerley R, Backlund Wasling H, Liljencrantz J, Olausson H, Johnson RD &**  
774 **Wessberg J.** Human C-Tactile Afferents Are Tuned to the Temperature of a Skin-  
775 Stroking Caress. *J Neurosci* 34: 2879–2883, 2014a.
- 776 2. **Ackerley R, Carlsson I, Wester H, Olausson H & Backlund Wasling H.** Touch  
777 perceptions across skin sites: differences between sensitivity, direction discrimination  
778 and pleasantness. *Front Behav Neurosci* 8: 54, 2014b.
- 779 3. **Amirshaybani HR, Crecelius GM, Timothy NH, Pfeiffer M, Siggers GC,**  
780 **Manders EK.** The natural history of the growth of the hand: I. Hand area as a  
781 percentage of body surface area. *Plast Reconstr Surg* 107: 726–733, 2001.
- 782 4. **Arens E, Zhang H, Huizenga C.** Partial- and whole-body thermal sensation and  
783 comfort—Part II: Non-uniform environmental conditions. *J Therm Biol* 31: 60–66,  
784 2006.
- 785 5. **Cabanac M.** Heat Stress and Behavior. *Compr Physiol* 2011, Supplement 14:  
786 *Handbook of Physiology, Environmental Physiology: 261-278. First published in*  
787 *print 1996. doi: 10.1002/cphy.cp040113, 1996.*
- 788 6. **Campero M, Baumann TK, Bostock H & Ochoa JL.** Human cutaneous C fibres  
789 activated by cooling, heating and menthol. *J Physiol* 587: 5633–5652, 2009.
- 790 7. **Campero M, Serra J, Bostock H & Ochoa JL.** Slowly conducting afferents  
791 activated by innocuous low temperature in human skin. *J Physiol* 535: 855–865,  
792 2001.

- 793 8. **Changizi M, Weber R, Kotecha R & Palazzo J.** Are wet-induced wrinkled fingers  
794 primate rain treads? *Brain Behav Evol* 77: 286–290, 2011.
- 795 9. **Chortos A, Liu J & Bao Z.** Pursuing prosthetic electronic skin. *Nat Mater* 15: 937-  
796 950, 2016.
- 797 10. **Claus D & Hilz M.** Methods of measurement of thermal thresholds. *Acta Neurol*  
798 *Scand* 76: 288-296, 1987.
- 799 11. **Craig A.** How do you feel? Interoception: the sense of the physiological condition of  
800 the body. *Nat Rev Neurosci* 3: 655–666, 2002.
- 801 12. **Craig A, Chen K, Bandy D & Reiman E.** Thermosensory activation of insular  
802 cortex. *Nat Neurosci* 3: 184–190, 2000.
- 803 13. **Darian-Smith I.** “Cold” fiber population innervating palmar and digital skin of the  
804 monkey: responses to cooling pulses. *J Neurophysiol* 36: 325-346, 1973.
- 805 14. **Darian-Smith I.** Thermal sensibility. *Compr Physiol* 2011, *Supplement 3: Handbook*  
806 *of Physiology, The Nervous System, Sensory Processes: 879-913. First published in*  
807 *print 1984. doi: 10.1002/cphy.cp010319*, 1984.
- 808 15. **Darian-Smith I & Johnson K.** Thermal sensibility and thermoreceptors. *J Invest*  
809 *Dermatol* 69: 146-153, 1977.
- 810 16. **Davis KD, Kwan CL, Crawley AP & Mikulis DJ.** Functional MRI study of  
811 thalamic and cortical activations evoked by cutaneous heat, cold, and tactile stimuli. *J*  
812 *Neurophysiol* 80: 1533–1546, 1998.
- 813 17. **Defrin R, Petrini L & Arendt-Nielsen L.** Spatial summation of thermal sensations  
814 depends on skin type and skin sensitivity. *Exp brain Res* 198: 29–36, 2009.
- 815 18. **Donaldson H.** On the temperature-sense. *Mind* os-X, 398–416, 1885.
- 816 19. **Farrar JT, Young JP, LaMoreaux L, Werth JL & Poole RM.** Clinical importance  
817 of changes in chronic pain intensity measured on an 11-point numerical pain rating  
818 scale. *Pain* 94: 149–158, 2001.
- 819 20. **Filingeri D.** Neurophysiology of skin thermal sensations. *Compr Physiol* 6: 1429–  
820 149, 2016.
- 821 21. **Filingeri D & Ackerley R.** The biology of skin wetness perception and its  
822 implications in manual function and for reproducing complex somatosensory signals  
823 in neuroprosthetics. *J Neurophysiol* 117: 1761–1775, 2017.
- 824 22. **Filingeri D, Chaseling G, Hoang P, Barnett M, Davis SL & Jay O.** Afferent  
825 thermosensory function in relapsing-remitting Multiple Sclerosis following exercise-  
826 induced increases in body temperature. *Exp Physiol* 102: 887-893, 2017a.

- 827 23. **Filingeri D, Fournet D, Hodder S & Havenith G.** Body mapping of cutaneous  
828 wetness perception across the human torso during thermo-neutral and warm  
829 environmental exposures. *J Appl Physiol* 117: 887–897, 2014.
- 830 24. **Filingeri D, Morris NB & Jay O.** Warm hands, cold heart: progressive whole-body  
831 cooling increases warm thermosensitivity of human hands and feet in a dose-  
832 dependent fashion. *Exp Physiol* 102: 100–112, 2017b.
- 833 25. **Filingeri D, Zhang H & Arens EA.** Characteristics of the local cutaneous sensory  
834 thermo-neutral zone. *J Neurophysiol* 117: 1797–1806, 2017c.
- 835 26. **Gerrett N, Ouzzahra Y, Coleby S, Hobbs S, Redortier B, Voelcker T & Havenith**  
836 **G.** Thermal sensitivity to warmth during rest and exercise: a sex comparison. *Eur J*  
837 *Appl Physiol* 114: 1451-1462, 2014.
- 838 27. **Gerrett N, Ouzzahra Y, Redortier B, Voelcker T & Havenith G.** Female thermal  
839 sensitivity to hot and cold during rest and exercise. *Physiol Behav* 152: 11–19, 2015.
- 840 28. **Green BG.** Temperature perception and nociception. *J Neurobiol* 61: 13–29, 2004.
- 841 29. **Greenspan JD & Kenshalo D.** The primate as a model for the human temperature-  
842 sensing system: 2 area of skin receiving thermal stimulation (spatial summation).  
843 *Somatosens Mot Res* 2: 315–324, 1985.
- 844 30. **Hauer P, Stocks A, McArthur JC, Cornblath DR & Griffin JW.** Epidermal Nerve  
845 Fiber Density. *Arch Neurol* 55: 1513–1520, 2008.
- 846 31. **Hensel H.** *Thermoreception and temperature regulation*, Issue 38 o. Academic Press,  
847 1981.
- 848 32. **Hjermstad MJ, Fayers PM, Haugen DF, Caraceni A, Hanks GW, Loge JH,**  
849 **Fainsinger R, Aass N & Kaasa S.** Studies comparing numerical rating scales, verbal  
850 rating scales, and visual analogue scales for assessment of pain intensity in adults: A  
851 systematic literature review. *J Pain Symptom Manage* 41: 1073–1093, 2011.
- 852 33. **Houdas Y & Ring E.** *Human body temperature-Its measurement and regulation.*  
853 Plenum Press, New York, NY, 1982.
- 854 34. **Iannetti GD, Zambreanu L & Tracey I.** Similar nociceptive afferents mediate  
855 psychophysical and electrophysiological responses to heat stimulation of glabrous and  
856 hairy skin in humans. *J Physiol* 577: 235–248, 2006.
- 857 35. **Inoue Y, Gerrett N, Ichinose-Kuwahara T, Umino Y, Kiuchi S, Amano T, Ueda**  
858 **H, Havenith G, Kondo N.** Sex differences in age-related changes on peripheral warm  
859 and cold innocuous thermal sensitivity. *Physiol Behav* 164: 86–92, 2016.
- 860 36. **Jay O & Havenith G.** Finger skin cooling on contact with cold materials: an

- 861 investigation of male and female responses during short-term exposures with a view  
862 on hand and finger size. *Eur J Appl Physiol* 93: 1–8, 2004.
- 863 37. **Johansson RS & Vallbo AB.** Detection of tactile stimuli. Thresholds of afferent units  
864 related to psychophysical thresholds in the human hand. *J Physiol* 297: 405–422,  
865 1979a.
- 866 38. **Johansson RS & Vallbo AB.** Tactile sensibility in the human hand: relative and  
867 absolute densities of four types of mechanoreceptive units in glabrous skin. *J Physiol*  
868 286: 283–300, 1979b.
- 869 39. **Johansson RS, Vallbo AB & Westling G.** Thresholds of mechanosensitive afferents  
870 in the human hand as measured with von Frey hairs. *Brain Res* 184: 343–351, 1980.
- 871 40. **Kawakami T, Ishihara M, Mihara M.** Distribution Density of Intraepidermal Nerve  
872 Fibers in Normal Human Skin. *J Dermatol* 28: 63–70, 2001.
- 873 41. **Kim J, Lee M, Shim HJ, Ghaffari R, Cho HR, Son D, Jung YH, Soh M, Choi C,**  
874 **Jung S, Chu K, Jeon D, Lee S-T, Kim JH, Choi SH, Hyeon T & Kim DH.**  
875 Stretchable silicon nanoribbon electronics for skin prosthesis. *Nat Commun* 5, 5747,  
876 2014.
- 877 42. **Konietzny F & Hensel H.** Warm fiber activity in human skin nerves. *Pflügers Arch*  
878 *Eur J Physiol* 267: 265–267, 1975.
- 879 43. **Lauria G, Holland N, Hauer P, Cornblath DR, Griffin JW, McArthur JC.**  
880 Epidermal innervation: changes with aging, topographic location, and in sensory  
881 neuropathy. *J Neurol Sci* 164: 172–178, 1999.
- 882 44. **Li X, Petrini L, Defrin R, Madeleine P & Arendt-Nielsen L.** High resolution  
883 topographical mapping of warm and cold sensitivities. *Clin Neurophysiol* 119: 2641–  
884 2646, 2008.
- 885 45. **Lunt H & Tipton M.** Differences in conductive foot cooling: a comparison between  
886 males and females. *Eur J Appl Physiol* 114: 2635–2644, 2014.
- 887 46. **Mancini F, Bauleo A, Cole J, Lui F, Porro CA, Haggard P & Iannetti GD.**  
888 Whole-body mapping of spatial acuity for pain and touch. *Ann Neurol* 75: 917–924,  
889 2014.
- 890 47. **Mancini F, Haggard P, Iannetti GD, Longo MR & Sereno MI.** Fine-grained  
891 nociceptive maps in primary somatosensory cortex. *J Neurosci* 32: 17155–17162,  
892 2012.
- 893 48. **Mancini F, Sambo CF, Ramirez JD, Bennett DLH, Haggard P & Iannetti GD.** A  
894 fovea for pain at the fingertips. *Curr Biol* 23: 496–500, 2013.

- 895 49. **McGlone F, Wessberg J & Olausson H.** Discriminative and Affective Touch:  
896 Sensing and Feeling. *Neuron* 82: 737–755, 2014.
- 897 50. **McKemy DD.** Temperature sensing across species. *Pflugers Arch* 454: 777–791,  
898 2007.
- 899 51. **Milenkovic N, Zhao W-J, Walcher J, Albert T, Siemens J, Lewin GR & Poulet**  
900 **JFA.** A somatosensory circuit for cooling perception in mice. *Nat Neurosci* 17: 1560–  
901 1566, 2014.
- 902 52. **Mountcastle VB.** *The Sensory Hand: Neural Mechanisms of Somatic Sensation.*  
903 Harvard University Press, 2005.
- 904 53. **Nakamura M, Yoda T, Crawshaw L, Yasuhara S, Saito Y, Kasuga M,**  
905 **Nagashima K & Kanosue K.** Regional differences in temperature sensation and  
906 thermal comfort in humans. *J Appl Physiol* 105: 1897–1906, 2008.
- 907 54. **National Health Service.** Washing and bathing your baby [Online]. 2015.  
908 <https://www.nhs.uk/conditions/pregnancy-and-baby/washing-your-baby/>.
- 909 55. **Norrsell U, Finger S & Lajonchere C.** Cutaneous sensory spots and the “law of  
910 specific nerve energies”: history and development of ideas. *Brain Res Bull* 48: 457–  
911 465, 1999.
- 912 56. **Oommen A, Mainker A, Oommen T.** A Study of the Correlation Between Hand  
913 Length And Foot Length In Humans. *J Anat Soc India* 54: 1–9, 2005.
- 914 57. **Ouzzahra Y, Havenith G & Redortier B.** Regional distribution of thermal  
915 sensitivity to cold at rest and during mild exercise in males. *J Therm Biol* 37: 517–  
916 523, 2012.
- 917 58. **Penfield W & Boldrey E.** Somatic Motor and Sensory Representation in Man. *Brain*  
918 4, 389–443, 1937.
- 919 59. **Raspopovic S, Capogrosso M, Petrini FM, Bonizzato M, Rigosa J, Di Pino G,**  
920 **Carpaneto J, Controzzi M, Boretius T, Fernandez E, Granata G, Oddo CM, Citi**  
921 **L, Ciancio AL, Cipriani C, Carrozza MC, Jensen W, Guglielmelli E, Stieglitz T,**  
922 **Rossini PM, Micera S.** Restoring Natural Sensory Feedback in Real-Time  
923 Bidirectional Hand Prostheses. *Sci Transl Med* 6, 222ra19-222ra19, 2014.
- 924 60. **Rolls ET, Grabenhorst F & Parris BA.** Warm pleasant feelings in the brain.  
925 *Neuroimage* 41: 1504–1513, 2008.
- 926 61. **Romanovsky A.** Thermoregulation: some concepts have changed. Functional  
927 architecture of the thermoregulatory system. *Am J Physiol Regul Integr Comp Physiol*  
928 292: R37-R46, 2007.

- 929 62. **Schlader ZJ, Coleman GL, Sackett JR, Sarker S, Chapman CL, Johnson BD.**  
930 Activation of autonomic thermoeffectors preceding the decision to behaviourally  
931 thermoregulate in resting humans. *Exp Physiol* 9: 1218–1229, 2016.
- 932 63. **Shao Y, Hayward V & Visell Y.** Spatial patterns of cutaneous vibration during  
933 whole-hand haptic interactions. *Proc Natl Acad Sci U S A* 113: 201520866, 2016.
- 934 64. **Smith M, Warren K, Cohen-Taguchi D, Shames S, Sprehn K, Schwartz J, Zhang**  
935 **H, Arens E.** Augmenting smart buildings and autonomous vehicles with wearable  
936 thermal technology. *Proceedings of HCI International*, July, Boston: 550-561.  
937 <https://escholarship.org/uc/item/9q24x8p3>, 2017
- 938 65. **Stettler DD, Das A, Bennett J, Gilbert CD.** Lateral connectivity and contextual  
939 interactions in macaque primary visual cortex. *Neuron* 36: 739–750, 2002.
- 940 66. **Stevens J.** Variation of cold sensitivity over the body surface. *Sens Processes* 3: 317,  
941 1979.
- 942 67. **Stevens J & Choo K.** Temperature sensitivity of the body surface over the life span.  
943 *Somatosens Mot Res* 15:13-28, 1998.
- 944 68. **Stevens J, Marks L & Simonson D.** Regional sensitivity and spatial summation in  
945 the warmth sense. *Physiol Behav* 13: 825–836, 1974.
- 946 69. **Taylor NAS, Machado-Moreira CA, van den Heuvel AMJ & Caldwell JN.** Hands  
947 and feet: physiological insulators, radiators and evaporators. *Eur J Appl Physiol* 114:  
948 2037–2060, 2014.
- 949 70. **Vallbo AB, Hagbarth K-E, Wallin BG.** Microneurography: how the technique  
950 developed and its role in the investigation of the sympathetic nervous system. *J Appl*  
951 *Physiol* 96: 1262–1269, 2004.
- 952 71. **Vriens J, Nilius B & Voets T.** Peripheral thermosensation in mammals. *Nat Rev*  
953 *Neurosci* 15: 573–589, 2014.
- 954 72. **Witney AG, Wing A, Thonnard J-L & Smith AM.** The cutaneous contribution to  
955 adaptive precision grip. *Trends Neurosci* 27: 637–643, 2004.
- 956 73. **Zhang H, Arens E & Zhai Y.** A review of the corrective power of personal comfort  
957 systems in non-neutral ambient environments. *Build Environ* 91: 15–41, 2015.
- 958

959 **Tables**

960

961 **Table 1.** Participants' characteristics, including age, mass, height, body surface area (BSA), and proportion of BSA stimulated by the fixed-size  
962 (i.e. 1.32cm<sup>2</sup>) thermal probe used, are reported for the male and female groups. Statistical differences between groups for each characteristic  
963 were assessed by means of independent group t-tests, with cut-off probability value for significance set at p=0.05.

964

	<b>Age (years)</b>	<b>Mass (Kg)</b>	<b>Height (m)</b>	<b>BSA (m<sup>2</sup>)</b>	<b>Proportion of BSA stimulated (%)</b>
<b>Males (n=8)</b>	30.2 ± 5.8	67.8 ± 13.4	1.69 ± 0.1	1.77 ± 0.2	0.0076 ± 0.0009
<b>Females (n=8)</b>	27.7 ± 5.1	58.0 ± 5.4	1.66 ± 0.1	1.64 ± 0.1	0.0081 ± 0.0005
<b>Probability</b>	0.381	0.076	0.546	0.155	0.184

965

966

967

968

969 **Figure legends**

970

971 **Figure 1.** Schematic representation of the experimental design and protocol. Panel A shows  
972 the combination of thermal probe and thermocouple microsensor used to deliver thermal  
973 stimuli and record changes in probe-skin interface temperature, respectively. Panel B shows  
974 application of the probe on a representative skin site of the palm. Panel C presents an  
975 overview of the stimulation protocol, where 5s-cooling and –warming pulses were delivered  
976 at the skin, in a counterbalanced order, and with 5s in between them. At the end of each 5s-  
977 stimulation, participants reported their local thermal sensation, using the numerical rating  
978 scale showed in panel D.

979

980 **Figure 2.** Topographical distribution of the 103 skin sites tested over the glabrous and hairy  
981 skin of hands and feet.

982

983 **Figure 3.** Warm and cold thermosensitivity maps for glabrous and hairy skin of the hand in  
984 males and females. Maps shows mean data for each sex group (n=8) and are based on the 49  
985 sites tested over the hand.

986

987 **Figure 4.** Warm and cold thermosensitivity maps for glabrous and hairy skin of the foot in  
988 males and females. Maps shows mean data for each sex group (n=8) and are based on the 54  
989 sites tested over the foot.

990

991 **Figure 5.** Inter-individual variability in thermosensitivity for the hand (upper half panel) and  
992 the foot (lower half panel). Heat maps are presented and show coefficients of variation for  
993 warm and cold thermosensitivity, in males (n=8) and females (n=8), and for all 103 skin sites



994 tested.

995

996 **Figure 6.** Hand and foot overall thermosensitivity in males and females. Each graph presents  
997 a comparison of the overall warm and cold thermosensitivity of the hand (49 sites) versus the  
998 foot (54 sites) for males (n=8) and females (n=8). It can be observed that the hand is  
999 significantly more sensitive than the foot for both warming and cooling, and in both males  
1000 and females. Probability values for statistical comparisons between hands and feet  
1001 thermosensitivity are shown.

1002

1003 **Figure 7.** Glabrous and hairy skin overall thermosensitivity in males and females. Each graph  
1004 presents a comparison of the overall warm and cold thermosensitivity of the glabrous skin of  
1005 both (includes all skin sites over palms and soles) versus the hairy skin (includes all skin sites  
1006 over back of hands and feet) for males (n=8) and females (n=8). It can be observed that the  
1007 hairy skin is significantly more sensitive than the glabrous skin for both warming and  
1008 cooling, and in both males and females. Probability values for statistical comparisons  
1009 between hairy and glabrous skin thermosensitivity are shown.

1010

1011 **Figure 8.** Association between overall warm and cold thermosensitivity in males and  
1012 females. Each graph presents the association between the warm and cold thermosensitivity of  
1013 all 103 skin sites tested across hands and feet in males (n=8) and females (n=8). Pearson  
1014 correlation coefficients and probability values for statistical significance are shown.

1015

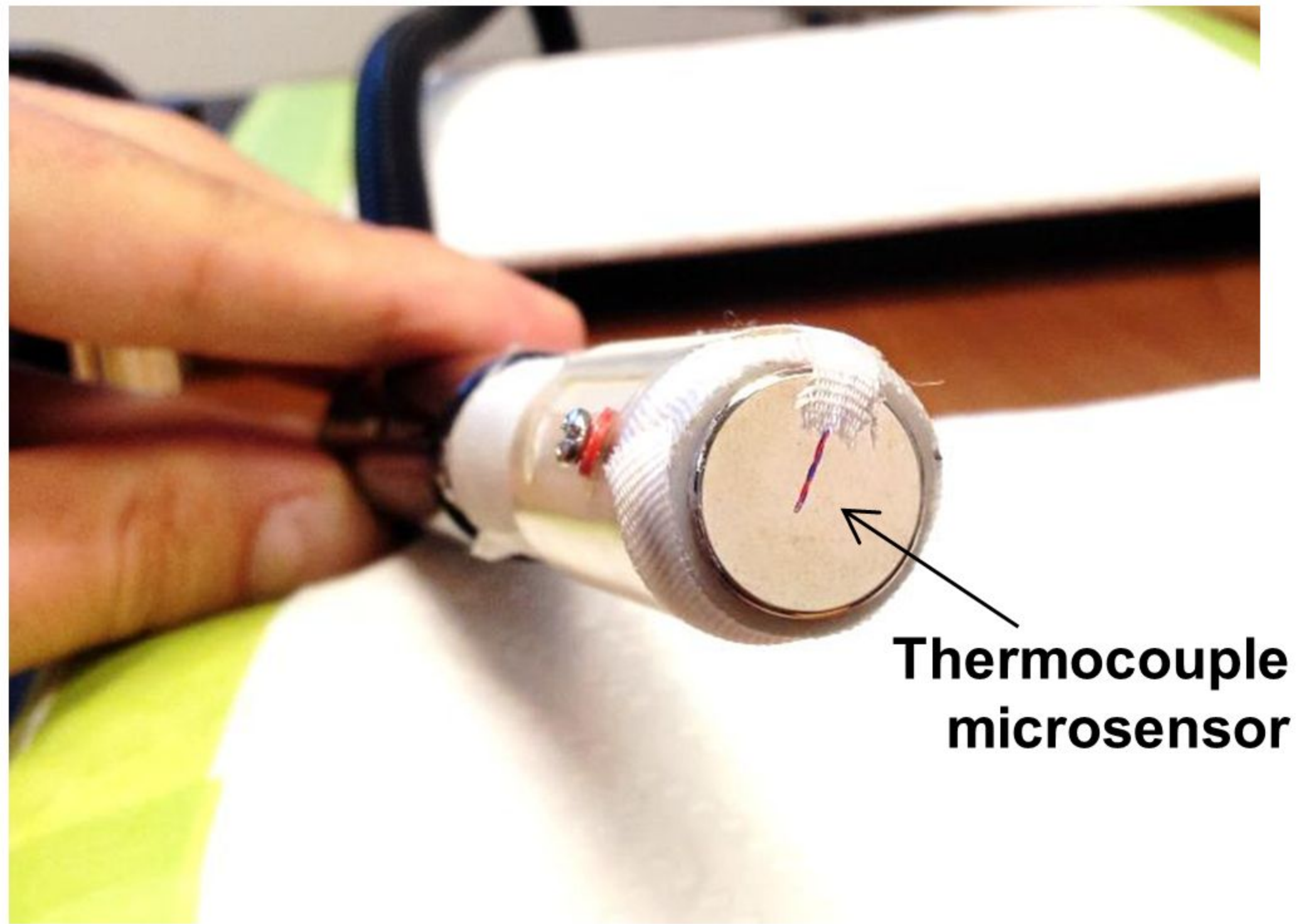
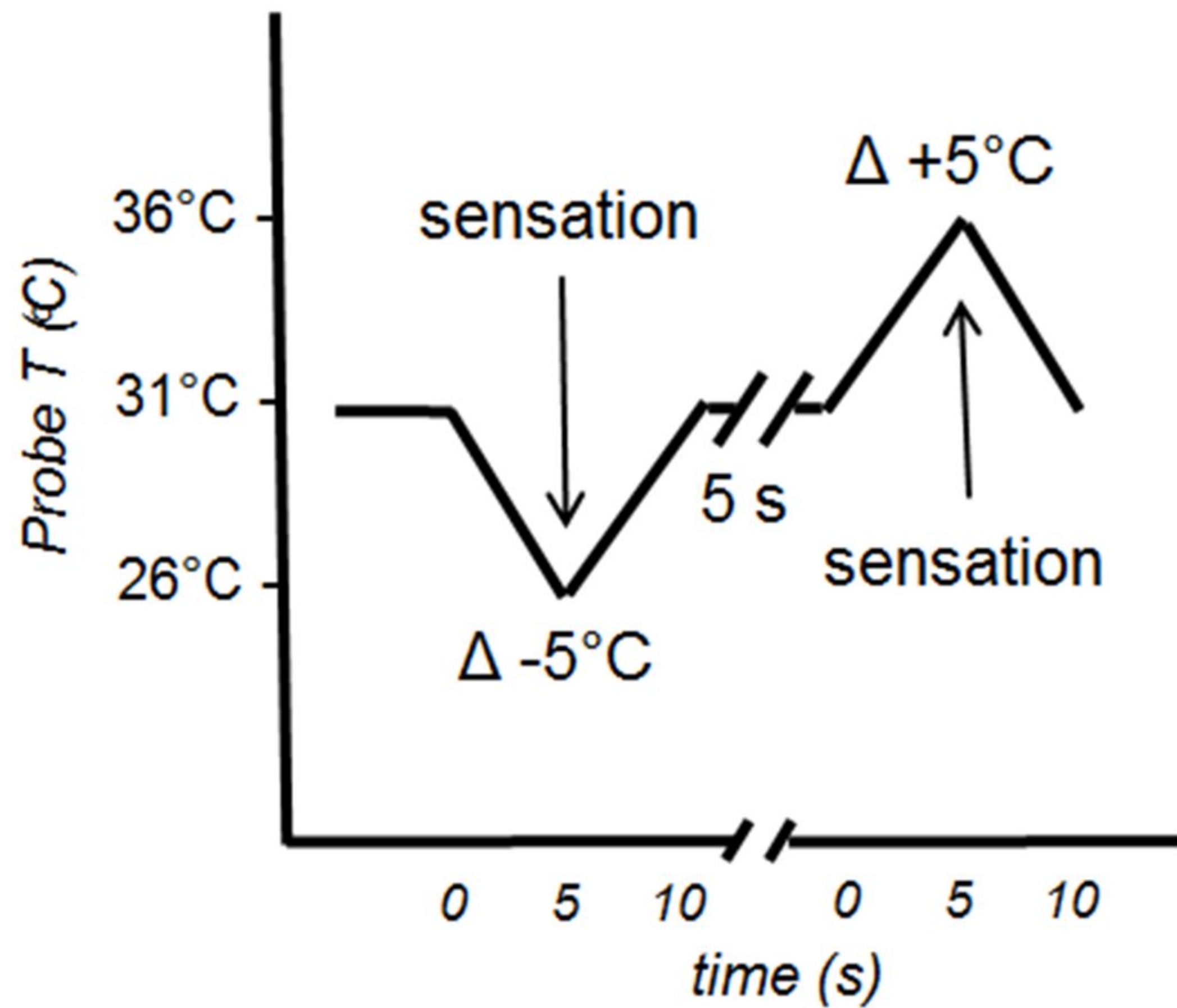
1016

1017

1018

1019

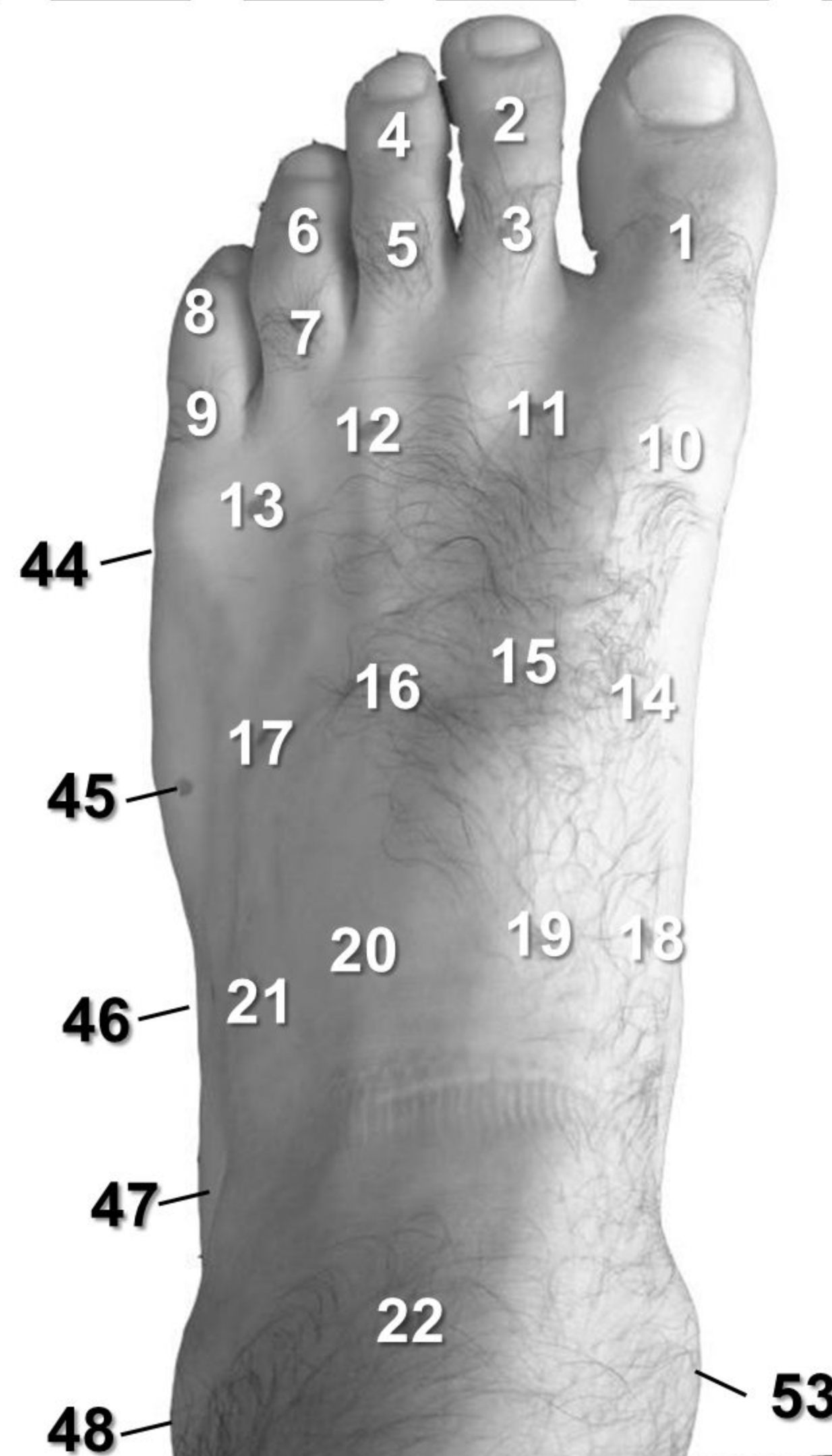
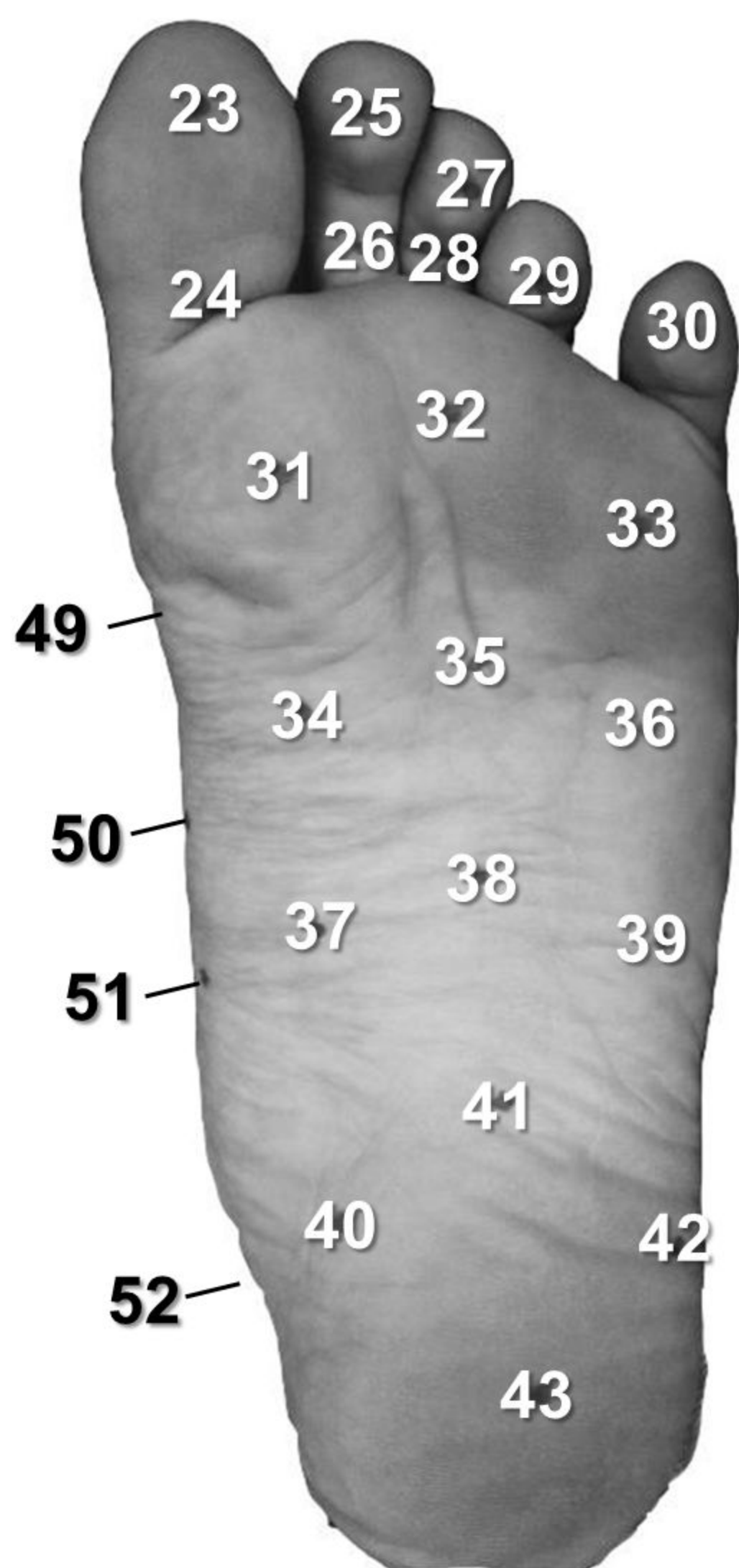
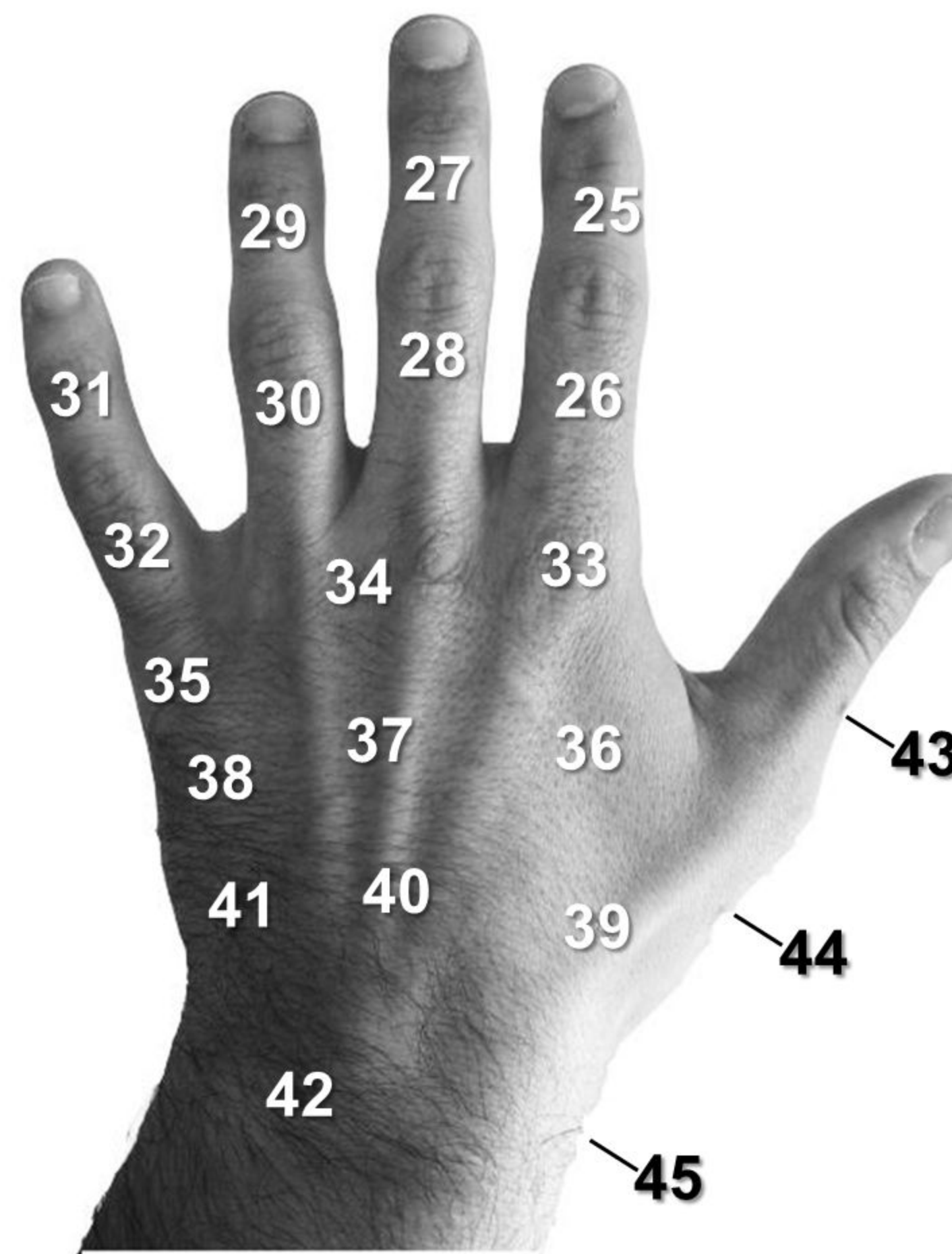
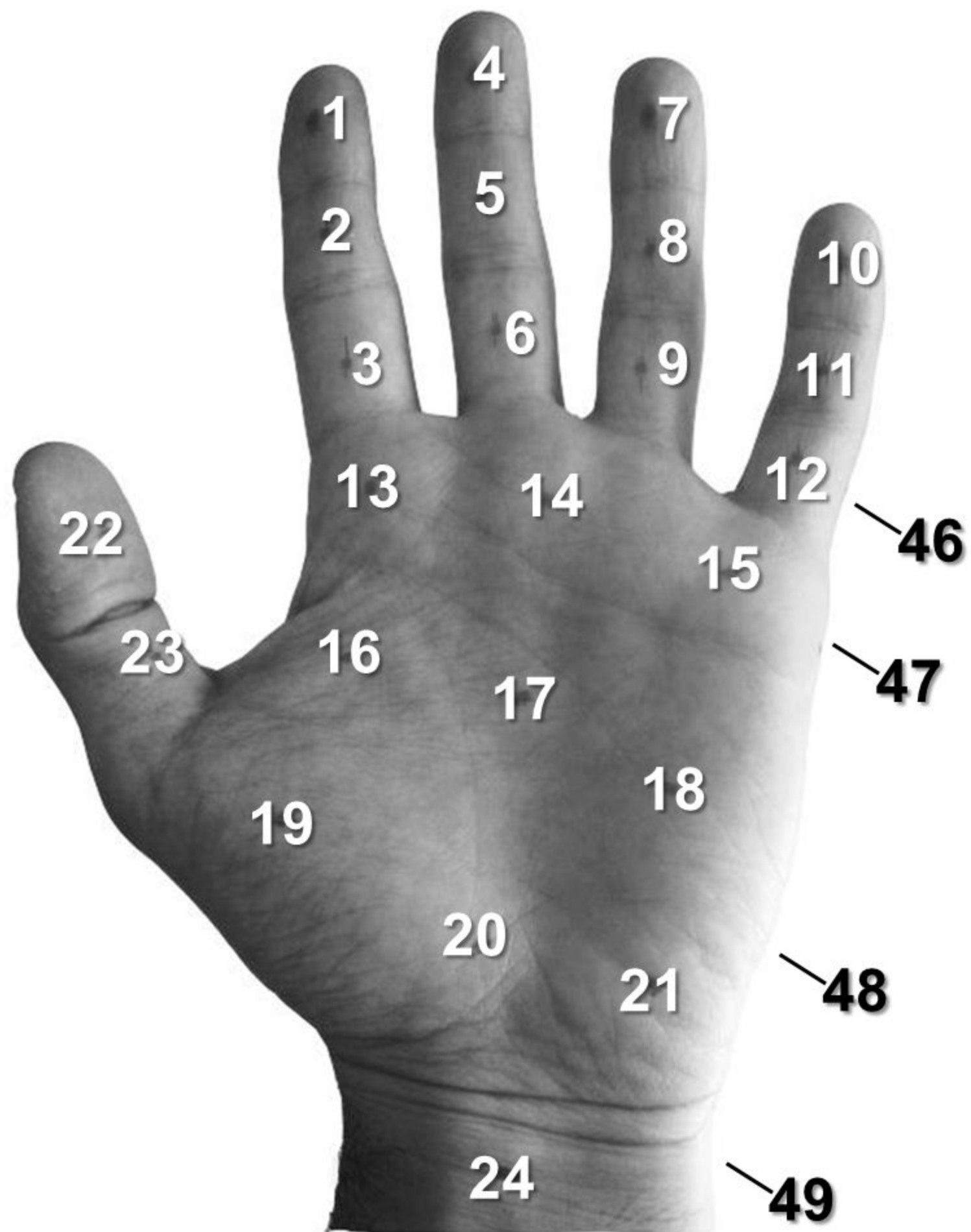
1020

**A****B****C****D**

Very Hot	10	Very Cold
	9	
	8	
	7	
	6	
	5	
	4	
	3	
	2	
	1	
Not hot at all	0	Not cold at all

# Glabrous

# Hairy



\*54 (posterior part of the ankle)

**Males**

**Females**

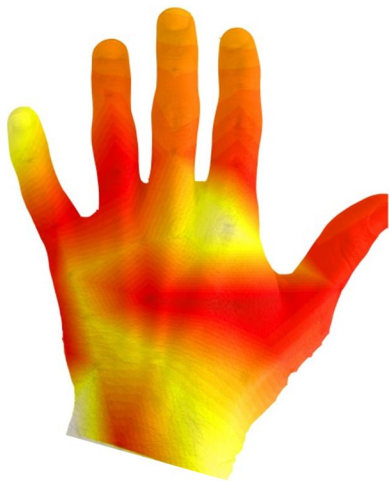
**Males**

**Females**

**Glabrous**

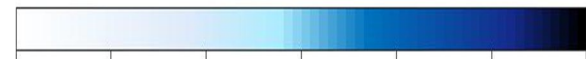


**Hairy**



**Warm thermosensitivity (vote/°C)**

**Cold thermosensitivity (vote/°C)**



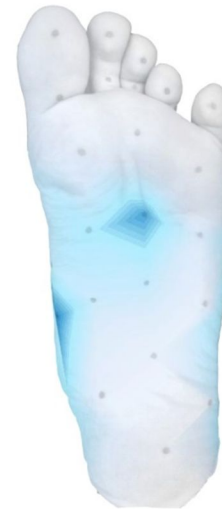
**Males**

**Females**

**Males**

**Females**

**Glabrous**

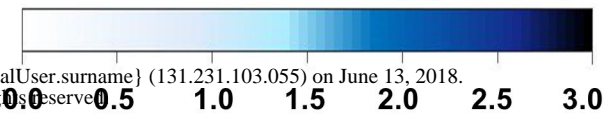
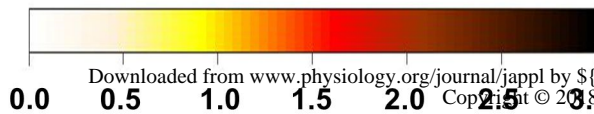


**Hairy**

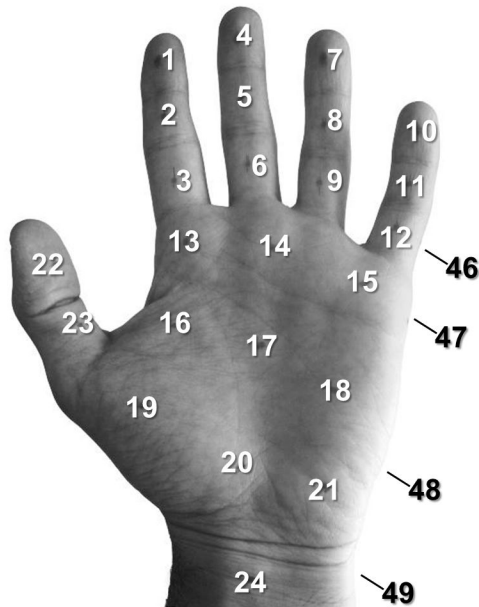


**Warm thermosensitivity (vote/°C)**

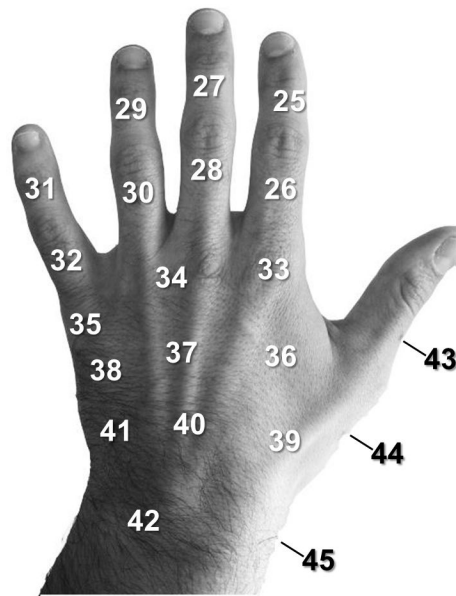
**Cold thermosensitivity (vote/°C)**



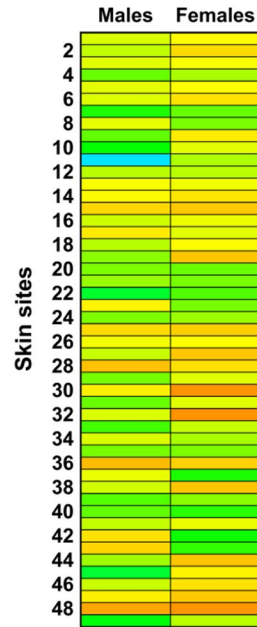
# Glabrous



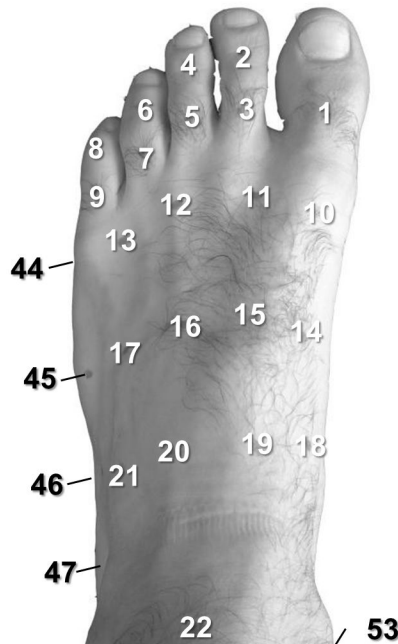
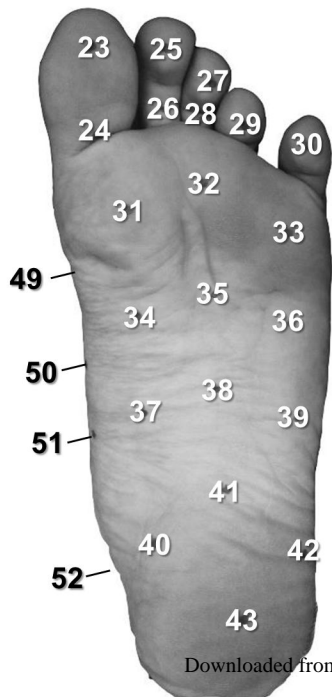
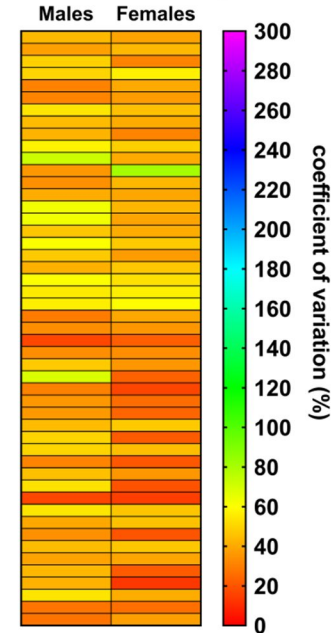
# Hairy



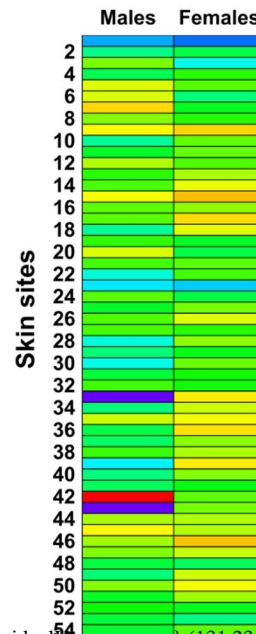
## Warm thermosensitivity



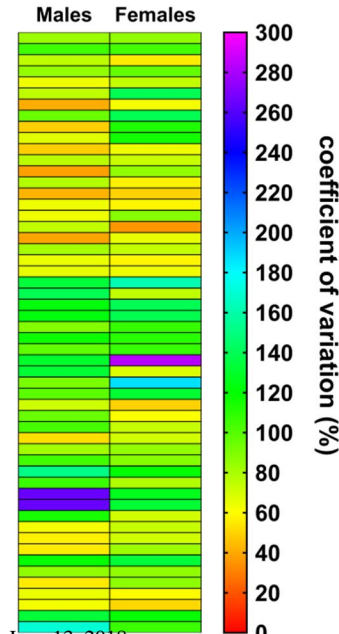
## Cold thermosensitivity



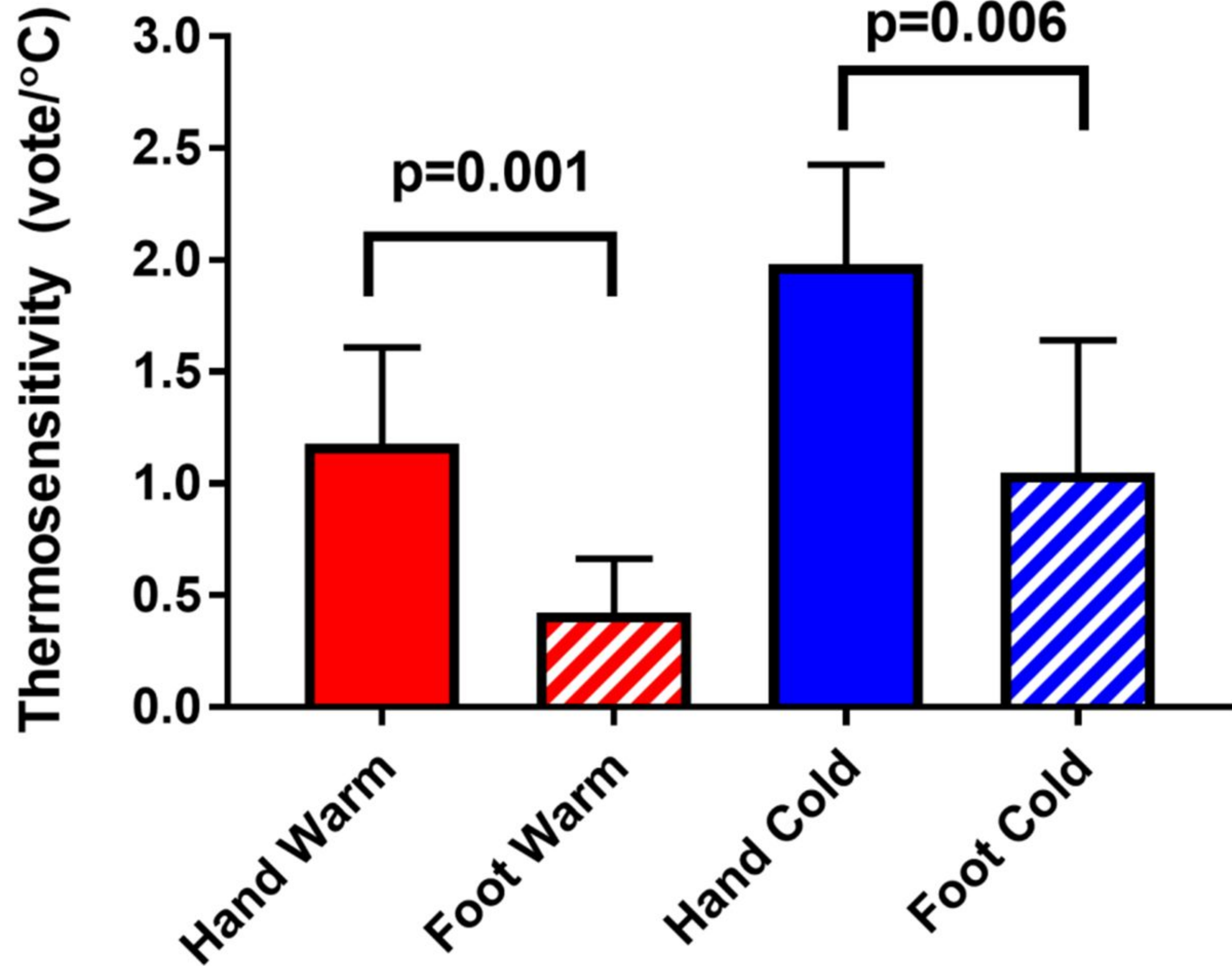
## Warm thermosensitivity



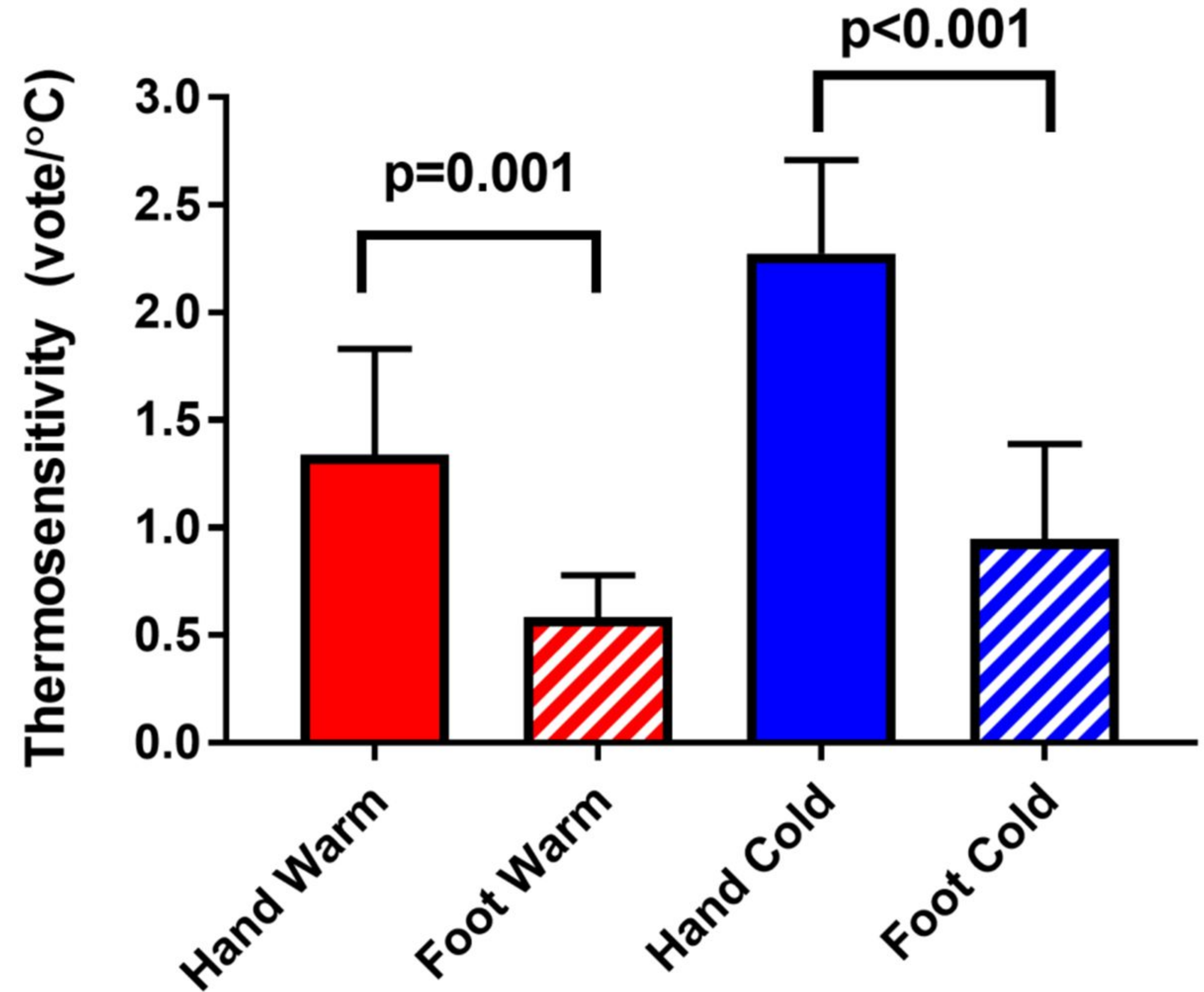
## Cold thermosensitivity



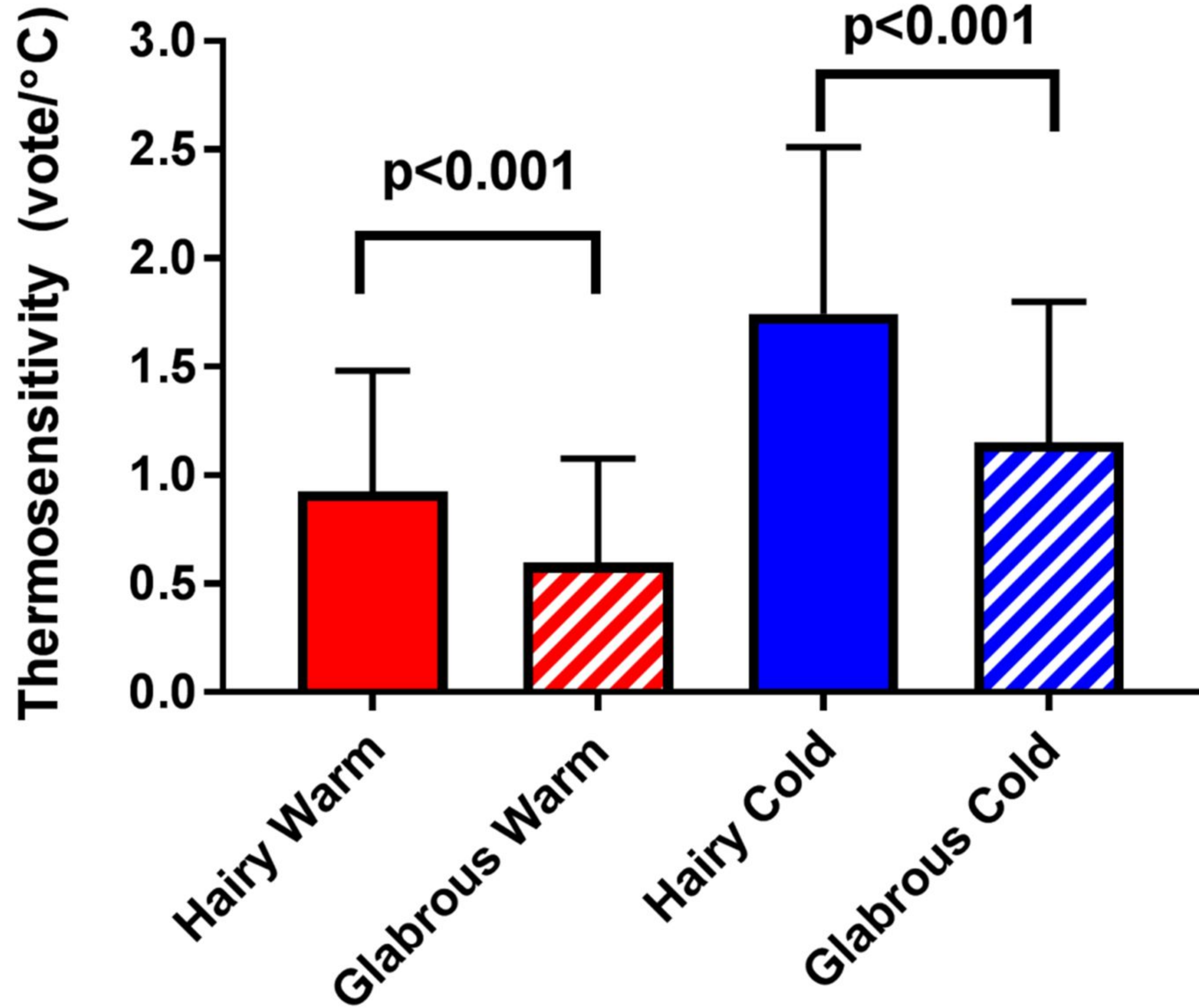
## Males



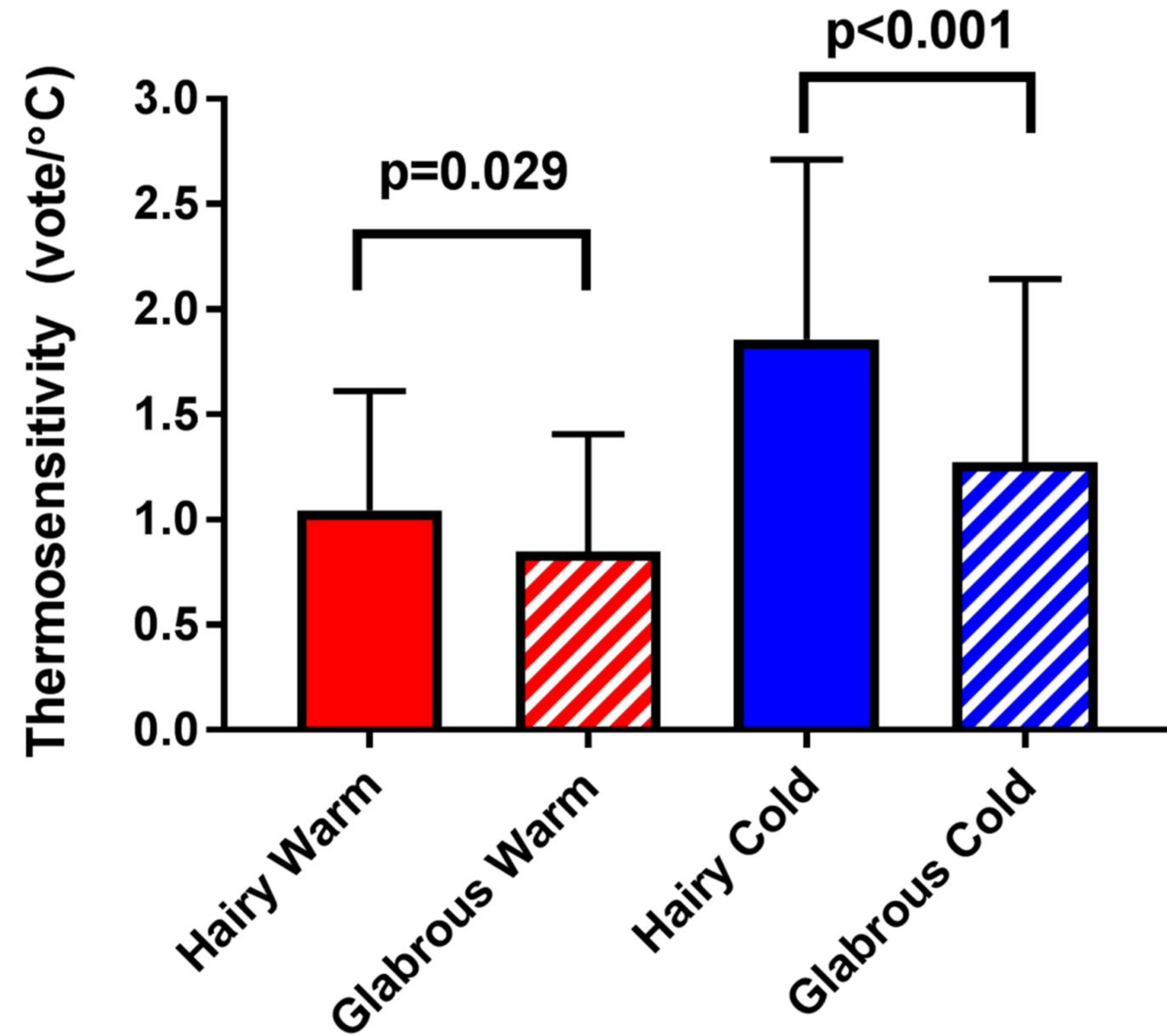
## Females



## Males

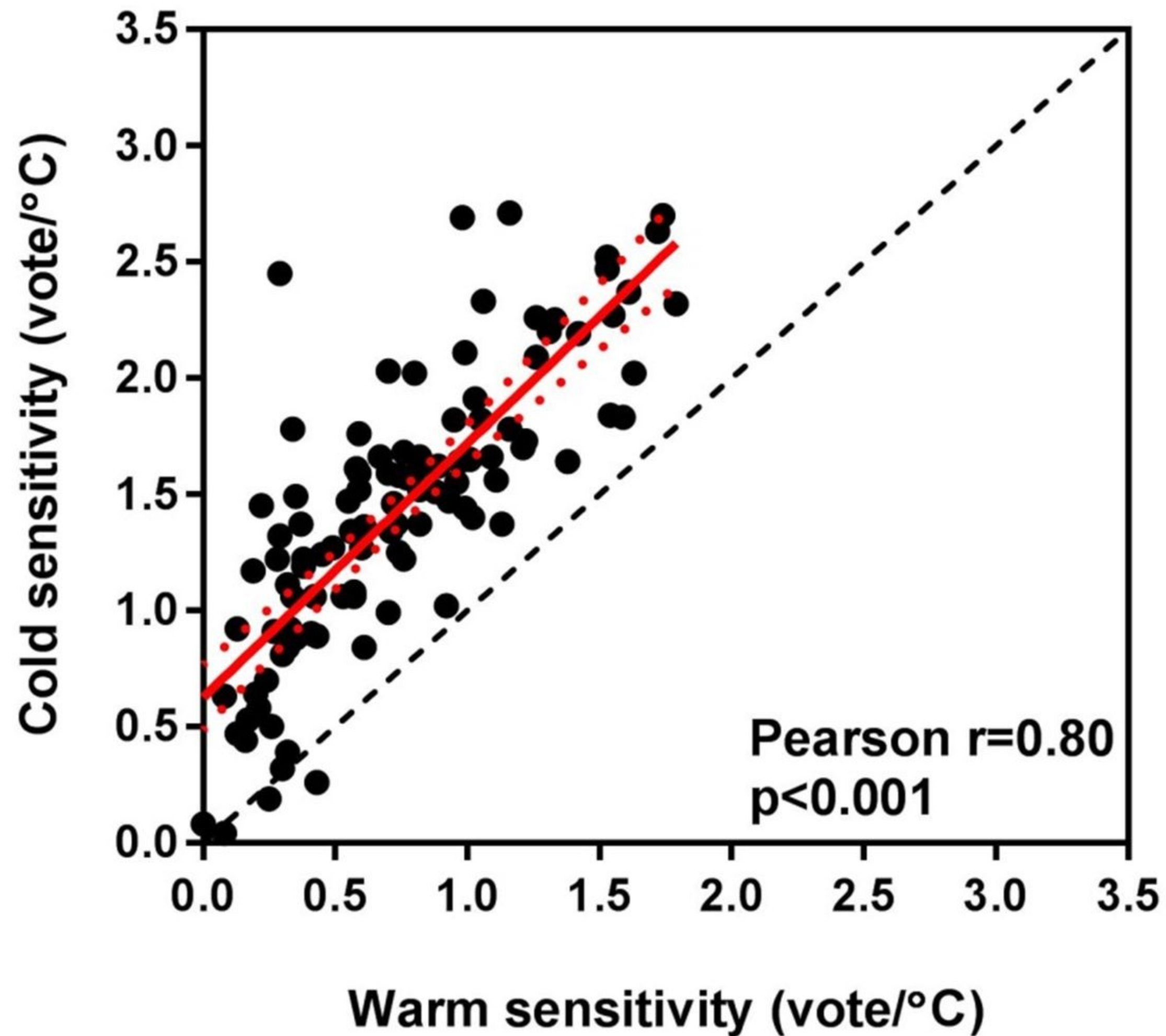


## Females





## Males



## Females

