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1 **An integrated thermal sensation scale for estimating thermal strain in water**

2 Maria Ntoumani ^{1,2}, Helen Soultanakis ^{2,3}, Eric Rivas ⁴, Benoit Dugué ⁵, Adam W.
3 Potter ⁶, Irena Yermakova ⁷, Angeliki Douka ², Konstantina Gongaki ²

4

5 ¹ Department of Physiology, Medical School, National and Kapodistrian University of
6 Athens, Athens, Greece

7 ² School of Physical Education and Sport Science, National Kapodistrian University,
8 Athens, Greece

9 ³ Human and Evolutionary Biology Section, Department of Biological Sciences,
10 University of Southern California, Los Angeles, California, USA.

11 ⁴ Microgravity Research, In-Space Solutions, Axiom Space Headquarters, Houston,
12 Texas, USA

13 ⁵ Université de Poitiers, Faculté des Sciences du Sport, UR 20296, laboratoire
14 "Mobilité, Vieillesse et Exercice (MOVE)", Poitiers, France

15 ⁶ Thermal and Mountain Medicine Division, U.S. Army Research Institute of
16 Environmental Medicine, Natick, Massachusetts, USA

17 ⁷ International Scientific - Training Centre for Information Technologies and Systems,
18 Kiev, Ukraine

19

20 Corresponding author: Maria Ntoumani, email: mantouma@med.uoa.gr

21

22 Acceptable definitions of thermal sensation for cold and hot water immersion do not
23 exist. The use of subjective thermal sensation scales remains unsolved with broad
24 psycho-physiological, and semantic implications. We hypothesize that perception of
25 thermal sensation could be a valid and reliable indicator for thermal strain during
26 exposure in water. We aimed to provide a theoretical background for behavioral
27 thermoregulation and neurocognition to support an integrated thermal sensation scale
28 for estimation of thermal load during head-out water immersion. This research used a
29 mixed methods approach. Domains were identified and items were measured for
30 thermal load to examine the content validity. Thereafter, we formed an integrated scale
31 based on standard 10551 of International Organization for Standardization (ISO).
32 Finally, we conducted a pilot study for the face validation of the scale based on a 30
33 min head-out water immersion at 26°C in healthy adults (females, n=4; males, n=4; age:
34 22.6 ± 8.0 years; body mass, 67.7 ± 9.5 kg; height, 169.0 ± 5.6 cm). We identified three
35 aspects (environment, physiological and behavioral thermoregulation) and a total of 18
36 items, of whom eight items (water temperature, immersion duration, core temperature,
37 skin temperature, body heat storage, shivering, thermal sensation, and thermal comfort)
38 were acceptable based on terms of scale-level content validity index (S-CVI = 92%).
39 Conditions incorporated into our scale included: icy <12°C, cold 12-24°C, cool 24-
40 29°C, neutral 29-38°C, warm 38-43°C, and hot >43°C. We found excellent face validity

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41 based on a reported homogenous cool feeling and physiological thermoregulatory
42 responses. Our study revealed our model could reasonably characterize body thermal
43 load though whole-body thermal sensation based on well-established thermoregulatory
44 mechanisms during water immersion. Further research is needed to validate the
45 accuracy of our behavioral model in a variety of water temperatures and in a larger
46 sample size.

47 **Keywords:** whole-body water immersion, thermoregulation, thermal sensation, scale
48 calibration

49 **Background**

50 Acceptable definitions of cold and hot water thermal sensation are not available. Prior
51 work has not conclusively determined if thermal sensation can be used as a reliable
52 indicator for estimating thermal strain during water exposure [1–4]. This problem is
53 multidimensional, because of the difficulty in understanding the perceptual meaning of
54 sensation, the variety of thermal scales and the difficulty in finding objective criteria
55 that could separate physiological responses from cognitive interpretation (Auliciems,
56 1981; Chatonnet & Cabanac, 1965; Lee et al., 2009; Schweiker et al., 2017). Metabolic
57 heat production and body heat gain or loss are important for modulating behavior that
58 motivates individuals to exit unbearable aquatic environments and could play a
59 significant role for understanding a novel thermal perception model specifically while
60 in water [2,9,10]. However, considering the challenges that affect the validity and
61 reliability of subjective scales, such as type of scales (visual analog, categorical,
62 numerical), number of categories, verbal descriptors, and leading question are
63 important to understand [7,8,11,12].

64 Thermal perception is expressed as the conscious state of how a person
65 perceives the external environment (i.e., sensation) influenced by skin and internal body
66 temperature and discriminates into cognitive-emotional experience (i.e., pleasantness,
67 comfort) and sensory experience (thermal sensation)(Fig. 1). Moreover, during water
68 immersion skin temperature contributes around 40% and core temperature around 60%
69 for whole-body temperature sensation. This ratio differs slightly in ambient conditions
70 for comfort, as both core and skin temperature contributes equally [13,14]. Also,
71 participants may be affected unconsciously by body heat storage that is reflected in
72 thermoeffector output (e.g., core and shell temperature) to vote their temperature
73 sensation [2,15]. Additionally, the pleasantness rating could provide useful information
74 about an individual's thermal alliesthesial status (e.g., normothermia, hyperthermia,
75 hypothermia) throughout the duration of water immersion [16].

76 Verbal anchoring phenomenon is often overlooked by many researchers, in
77 which thermal choice was affected by the type of scale, numerals, and experimental
78 conditions [1,3,8,17–24]. A typical verbal category universalizes the relationship
79 among a width of sensory stimulus with physical (water temperature) or physiological
80 parameters (e.g., body heat production, skin temperature), only when the
81 thermoregulatory theorems are fulfilled [25] However, scaling for thermal sensation

82 remains an unresolved case with mathematical and semantic aspects significantly
83 interplayed [8,11,19,24,26].

84 Alternatively, in psychometry, scaling of senses has been approached in a lot of
85 ways depending on research aims [25,27]. In particular, according to the fractionation
86 method, the fundamental infrastructure of a psychophysical scale, such as the inclusion
87 of the midpoint and the number of points, was shaped with practicality and a
88 satisfactory geometric or metric representation of the subjective feeling related to
89 concrete range of thermal stimulus [25,28]. The main thrust of this scientific thinking,
90 which was pursued by Lundgren et al. (2014), Glickman-Weiss et al. (1994), McIntyre
91 (1976), and Rohles (2007), lined up to statistical procedures (e.g., Pearson correlation,
92 ANOVA) with the aim of exhibiting a good fit to their thermal data. However, the above
93 authors characterized intuitively each thermal anchoring, thereby underestimating the
94 fallible nature of an abstract subjective measurement tool, such as visual analogue
95 scales [1,20], and value of linguistic assessment information [18,21,22,25,29].

96 The axiomatization method highlights general fundamentals like that of human
97 thermoregulation as followed in our research focused on the satisfaction of specific
98 discrete measured properties, such as body heat storage, body temperature, and thermal
99 perception [2,25,30]. With reference to the calibration of the ASHRAE and Bedford
100 scales, selection of seven points was not set intuitively as occurred with language
101 editing [9,22,25]. Indeed, the number seven stemmed from Miller's empirical
102 observations about the absolute judgement of equal-spaced auditory signals about 15dB
103 [25,27]. Nevertheless, the seven-categories conversion from pitch to thermal feeling
104 arose from a scientific concept dated back to the 1950s, in which nerve cells decode
105 and analyze all kind of senses (e.g., smell, sight, taste, temperature) exactly alike.
106 Therefore, it was speculated that thermal sensation distributes equally at the same rate
107 among operative temperatures [25,31]. Though, newer evidence contradicts the
108 equidistance of the ASHRAE scale [8,32–34], probably due to uneven activation of the
109 threshold thermoreceptors.

110 In general, thermosensing has a strong molecular basis, as it is recognized
111 through transient receptor potential ion channels (TRPs) located on the surface of nerve
112 cells. In general, the TRPs are listed according to temperature threshold activation in
113 response to cold and warm [35]. The cold TRPs are TRPM8 (12-28°C), TRPC5 (24-
114 37°C) and TRPA1 (<18°C) [36–40], and the warm TRPs are TRPV3 (30-37°C), TRPV4
115 (28-42°C), TRPM3 (30-35°C), TRPM2 (38-42°C), and TRPV1 (>43°C) [37,39,41–45].

116 Activation of these TRP ion channels can be derived from temperature, pH, and
117 chemicals (e.g., CO₂, H₂S, H₂O₂, common elements contained in thermal springs)
118 [46,47].

119 During water immersion, it is advantageous to be able to assess an individual's
120 thermal status during water immersion, in an efficient and non-invasive way to address
121 health risk situations (e.g., accelerated hypothermia or hyperthermia) [21,48]. In the
122 event of recovering a conscious victim from a rescue that can communicate, where time
123 is limited and no access to heat evaluation equipment is available, it would be a useful
124 tool to estimate thermal load via a thermal sensation scale [21]. However, if these
125 subjective scales have many points of selection accompanying with metonym
126 descriptors in situations of emergency, victims may not easily respond to them.

127 The purpose of this study is to provide a theoretical background for temperature
128 regulation to develop an integrated thermal sensation scale, which would combine
129 body, water, and environmental temperatures for the assessment of thermal status
130 during water exposure in humans.

131

132 **Hypothesis**

133 Given the suggestive evidence of the fundamental laws of thermodynamics between
134 body and environments, we hypothesize that thermal perception and thermal strain
135 assessment could be validated and serve as reliable indicators, not only in terrestrial but
136 also in aquatic environments [2,9]. This hypothesis is based on insights from a previous
137 scoping review that found an association between basic thermal descriptors for
138 temperature sensation and physiological thermoregulatory responses (e.g., body heat
139 storage) during water immersion, in which they are triggered as a causal reaction of the
140 activation of a range of TRPs' thermal thresholds, whose mechanism remains poorly
141 understood [2]. To date, few studies have examined thermosensation in aquatic
142 activities; while no attention has been given on the type of scale visual analog versus
143 categorical scale, semiotic status of the lexemes upon each scale and their hermeneutics
144 from the view of the participants and the external observers. We maintain our
145 reservations about whether thermal sensation scales measure only thermal sensation,
146 and not also thermal guessing [2]. Concerning number points and linguistic dimensions
147 in a categorical scale, we believe that more than seven thermal categories and adjectival
148 prepositions (e.g., slightly cool/warm) may confuse participants' choice affecting the
149 validity of the mental experience evidencing thermal guessing and not thermal

150 sensation. The former is a similar but longer neurocognitive process that shares a
151 common neural network with the evaluation of temperature feeling [2,12,49,50].
152 Developing an integrated thermal sensation scale for water exposures may have
153 practical application in real-world settings for spa workers, swimming coaches,
154 lifeguards, if and only if, basic verbal descriptors upon the subjective scale reflect
155 concrete thermal sensory experience while also accompanying discriminative
156 biological patterns. In this case, we will select the temperature vocabulary for our scale
157 according to the principle of discreteness and cross-linguistic after identifying the most
158 common everyday linguistic elements for human temperature sensation [2,7,50] with
159 the aim of being easily understood. So, this study provides a psychophysiological
160 integration theory for real-time monitoring of thermal load in water via a simplistic
161 approach that includes concrete perceptive words for thermal sensation and comfort
162 evaluation.

163

164 **Evaluation of Hypothesis**

165

166 To confirm our hypothesis, we needed to develop an integrated thermal sensation scale
167 following a mixed methods approach that is separated into three phases. In the first
168 phase we identified domains and items and examined their content validity for
169 approximation of thermal strain for water exposure. In the second phase, we formed the
170 integrated scale based on the ISO 10551 standard presenting the physiology of whole-
171 body water immersion. In the third phase we conducted a pilot study for assessment its
172 face validity and stability (test-retest design) utilizing 30 min head-out water
173 immersions at 26°C in healthy females (n=4) and males (n=4) (age: 22.6 ± 8.0 years,
174 body mass: 67.7 ± 9.5 kg, height: 169.0 ± 5.6 cm) with no thermal injury and medical
175 history. Written informed consent was given by all subjects who abstained from
176 strenuous exercise, smoking, alcohol, and caffeine consumption 24 hours prior trials,
177 while confirming a minimum of 6 hours sleep the previous night. The research protocol
178 had been approved by the Ethics and Bioethics Committee of the School of Physical
179 Education and Sport Science of the National and Kapodistrian University of Athens
180 (No 1162/12-02-2020) and was re-approved by the General Assembly of the Medical
181 School of the National and Kapodistrian University of Athens (No 42100-4/5/2022).

182

183 First Phase: Domain-Item Identification & Content Validation

184 Initially, we determined the purpose of our rational thermal scale following the
185 instructions of Boateng (2018), whose role was to predict not only the water
186 temperature but also psychophysiological values. Using data from our previous scoping
187 review we recognized three main dimensions: (i) environment, (ii) physiological
188 thermoregulation, (iii) and behavioral thermoregulation [2]. The environment was
189 defined as the physical quantities of weather (water and air temperature, humidity)
190 affecting human body. Physiological thermoregulation was defined as mechanistic
191 responses from an external or internal thermal stimulus. Behavioral thermoregulation
192 was defined as conscious perception of thermal sensation and thermal comfort. Further,
193 we analyzed all the factors for each dimension and compiled a form for being examined
194 the content validity by a group of specialized scientists in the field of thermophysiology.

195 Content validation was performed by the primary author (MN). The content
196 validation procedure, in which 18 items arranged into three domains (four items in
197 environment domain, nine items in physiology, and five items in behavioral
198 thermoregulation domain), and a panel of six scientists pursuing research on
199 thermoregulation accepted to evaluate on a 4-point scale the relevance of each item to
200 the measured domains after receiving a detailed content validation form (see Appendix
201 A). The ordinal point scale characterized by 1 = not relevant, 2 = somewhat relevant,
202 3 = quite relevant, and 4 = highly relevant. The content validity index computed for
203 each item (I-CVI) and domain following the common practices [52]; setting the
204 acceptable CVI value at 0.86. Also, overall scale validity index (S-CVI) was estimated
205 prior and after modifications. After suggestions from two reviewer's we agreed to
206 changes in the form and re-located an item from the physiological to behavioral domain.
207 Ten items were excluded due to a very low I-CVI score varied from 0.16 to 0.67, as a
208 result in improving at an excellent grade the S-CVI from 71% to 92%. Finally, only
209 eight items satisfied the criteria (water temperature, duration immersion, core
210 temperature, skin temperature, body heat storage, shivering, thermal sensation, and
211 thermal comfort) (see Table 1).

212

213 Second Phase: Development of the integrated sensation scale based on ISO 10551.

214 According to the ISO 10551 standard we formulated a new thermal sensation scale
215 based on the acceptable factors from content validation (see Fig. 2), with respect to
216 theory about neural sensory capacity - in which humans estimate correctly a sense lesser
217 to seven categorical levels - and with what is known about human thermoregulation and

218 thermal sensation in water for supporting the feasibility of an objective esthetic
219 experience (Hensel, 1976; Hensel & Schafer, 1984; Luce & Krumhansl, 1988; Miller,
220 1956; Ntoumani et al., 2023). Throughout the bibliography, we recognized six basic
221 labels for temperature sensation: icy, cold, cool, neutral (neither cold nor warm), warm,
222 hot, which constituted the thermal glossary for our scale. The “icy”, though it was not
223 included in ASHRAE vocabulary, we added as an extreme antonym of the hot endpoint
224 more suitable to represent extreme environmental stimuli [9,17,18,53–55]. Every
225 anchor was superimposed with molecular (TRPs) and physiological responses (body
226 heat, storage, core, and skin temperature) after 30 min of immersion. An acute 30 min
227 immersion was selected mostly due to normothermic status at 26°C that allowed us to
228 focus on the cornerstone role of skin thermoreceptors that theoretically contributed
229 mostly to thermal sensation [14,56]. Regarding visualization of body heat storage, the
230 thermal physiologist ER used the available raw data from Craig and Dvorak (1968) for
231 a range of water temperatures for spotlighting its causal association with conscious
232 responses [2].

233 Summarizing our data, we found a specific biological motif in the icy zone
234 <12°C where the core and body temperature declined. Though, the lack of evidence of
235 whole-body thermal sensation in extreme cold water temperatures suggests a
236 deteriorated feeling shift away from the “cold”. We represented icy as a lower
237 temperature range than the cold anchoring. Also, in the icy zone, we observed the cold
238 shock response accompanied by hyperventilation, increased heart rate and maximal
239 oxygen consumption owing to reflex activation of the sympathetic nervous system by
240 rapid changes of the skin thermal afferents. Besides, there was a high risk of cold
241 injuries, such as frostbite, which was assessed by finger skin temperature ($T_{Fsk} < 7\text{ °C}$)
242 and time-onset. Indeed, some unacclimatized naked subjects could not afford this
243 noxious water temperatures even for 10 minutes [57–62]. Another highlighted
244 observation, according to the thermal model of Mekjavic and Morrison (1985), was the
245 complete inactivation of cold thermoreceptors below 12°C; indeed, TRPA1 expressed
246 in C fibers stopped working at 12°C, while those expressed in A δ fibers were still
247 working at this concrete temperature range as appeared in Fig. 2 (Wang & Siemens,
248 2015; Zygmunt & Högestätt, 2014). Whole-body water immersion in the cold zone
249 reduced rectal body temperature, but not necessarily esophageal temperature; while it
250 evoked bradycardia, activation of the parasympathetic system and shivering
251 thermogenesis, mainly due to the action of TRPM8 [59,65–68]. In the cool zone, only

252 shivering sensation appeared within the first 30 minutes, while no changes were
253 observed to core temperature and other cardiovascular factors, such as oxygen
254 consumption [57,59,67]. The function of TRPM8 in synergy with TRPC5 may be
255 responsible for attenuated thermoregulatory response [38,39]. The neutral zone is a
256 dynamic intermediate state not presenting shivering thermogenesis, sweating activity,
257 and last but not least, changes in body temperature [57]. The human body has a very
258 sophisticated construction and function for its survival mirroring, on a molecular level,
259 in the complexity of neutral TRPs, as we spend the most of our time in indoor
260 thermoneutral places. In the warm zone, sweating rate, total dry heat loss, metabolic
261 alkalosis, core temperature, and heart rate were increased, possibly due to the action of
262 TRPV4 and TRPM2's action [14,41,69–74]. Simultaneously, we set the hot zone
263 mainly by the unbearable pain and discomfort caused by the warm TRPV1 ion channel
264 and the inability to complete an acute whole-body water immersion [75–78]. According
265 to epidemiological studies, hot baths (>43°C) was deemed deleterious due to the danger
266 of thermal injuries (burns, skin necrosis) and drowning – especially for prolonged
267 immersion [75,77,79].

268

269 Third phase: Face Validation

270 A test-retest design was followed to examine the face validity of the integrated
271 sensation scale, and its stability. Two repeated sessions, separated by at least one week,
272 were compared in this study. Participants immersed in a constant water of 26°C at the
273 shoulder level for 30 minutes. Each male participant wore a competitive swimsuit while
274 females wore a two-piece swimsuit. Prior and after water immersion, volunteers rested
275 in a sitting position for 5 minutes at an ambient indoor pool temperature of $25.4 \pm 1.5^\circ\text{C}$
276 (Thomas Traceable Memory Digital Thermometer, VWR Scientific, USA) and $61.8 \pm$
277 6.3% relative humidity (Mi Temperature and Humidity Monitor 2, Xiaomi, China) for
278 baselines measurements. On each trial, core temperature (T_{core} : Thermoscan 5, Braun ,
279 Germany), skin temperature on the right side of four body locations: forehead, chest,
280 hand, and thigh (T_{skin} : DS-273 1922L iButton, Maxim Integrated, USA) - that were
281 taped with a transpore medical material (Tegaderm, 3M Health Care, USA) and
282 calculated from the equation of Ramanathan (1964). Perception measurements were
283 recorded every 5 min intervals prior, during, and after immersion. First, we evaluated
284 firstly thermal sensation using our integrated scale (TS6), then assessed comfort
285 judgment using the ASHRAE 4-point comfort scale (TC) (Gagge et al. 1967). The

286 leading question for thermal sensation was *How do you perceive water?* followed by
287 the leading question for thermal comfort *How comfortable do you feel in water/ambient*
288 *environment now?*

289

290 **Data Analysis**

291 Perception scales are ordinal (6-point and 4-point), therefore non-parametric statistics
292 were selected. Shapiro–Wilk’s and Levene’s tests were used to check the normality and
293 the homogeneity of all data prior to analyses. Wilcoxon matched-pairs ranked test was
294 conducted for nonparametric data (thermal perception) every 5-min interval. For
295 normal data, we applied one-way repeated ANOVA, or Welch ANOVA when equal
296 variance assumption was not satisfied, at each time point for identifying any
297 physiological alteration followed by a post-hoc Bonferroni analysis for ANOVA or
298 Games-Howel analysis for Welch ANOVA, if needed. We set the significance level at
299 $p < 0.05$. Face validity of the 6-point integrated scale was examined only by asking the
300 participants how they felt in indoor pool. As no statistical analysis was supported for
301 this kind of validity, we associated observed body and environmental temperatures, that
302 were in line with the theoretical background of it.

303

304 **Empirical Data**

305 Environmental factors were equivalent between test-retest trials except from relative
306 humidity ($p < 0.01$) that reduced the second time trial clapping from $65.4 \pm 7.5\%$ to
307 $58.3 \pm 5.2\%$. Tympanic temperature (test $F(7, 56) = 0.639$ $p > 0.722$ vs retest $F(7, 56) =$
308 0.069 $p > 0.784$), heart rate (test $F(7, 46) = 1.127$ $p > 0.563$, vs retest $F(7, 46) = 1.652$
309 $p > 0.121$) and skin temperature (test $F(7, 56) = 86.272$ $p < 0.001$, vs retest $[F(7,56) =$
310 58.237 , $p < 0.001$) sustained stable between repetitions during water immersion. There
311 was a time-effect only on skin temperature and thermal perception, as these parameters
312 significantly changed in pre- and post-immersion compared to water immersion
313 duration ($p < 0.05$). For all physiological and perceptual values, there was no
314 statistically significant difference between first and second set of trials ($p > 0.05$). The
315 face validity of the integrated thermal sensation scale was excellent as proved by a
316 homogenous cool and slightly uncomfortable feeling in water for all measurements
317 without any alteration of core temperature as demonstrated in Fig. 3.

318

319 **Consequences of the hypothesis and discussion**

320 Our pilot study substantiates the hypothesis of the objective truth of thermal sensation,
321 in which water temperature could approximate thermal perception and body heat stress
322 and vice versa yielded to causal psychophysiological schema (Fig. 2). Our scale was
323 developed according to well-established neurophysiological and cognitive mechanisms
324 and divided into six temperature ranges: icy <12°C, cold 12-24°C, cool 24-29°C, neutral
325 29-38°C, warm 38-43°C and hot >43°C (Fig. 2). The fixed temperature ranges
326 represented the water temperature that coincided with the skin temperature of the
327 immersed body parts. The main findings of this experiment were the homogeneity of
328 thermoregulatory responses during the 30-minute immersion at 26°C, which were
329 aligned with the predictions of our behavioral thermoregulatory model. Of particular
330 interest was the common verbal expression of the thermal perception by all subjects,
331 selecting the basic descriptor "cool" for thermal sensation and "slightly uncomfortable"
332 for thermal comfort.

333 As previously reported, skin temperature is the principal input for thermal
334 sensation for a normothermic resting subject being consistent with our collective field
335 data [9,14,18]. When the mean body T_{sk} is within a range of TRP ion channels as tuning
336 with water temperature due to conduction heat exchange, a synergistic effect between
337 epidermal TRPs take place for the formation of thermosensation in the central level
338 according to combinatorial coding strategy [81,82]. The rate coding hypothesis, which
339 analyzes neural activity as the frequency of cold and warm thermoreceptors' firing rates
340 [83], was followed by Kingma et al. (2012) to advance a mathematical
341 neurophysiological model for thermal sensation. Even this model was alleged for its
342 accuracy for ± 0.5 -scale unit in the ASHRAE scale, a perusal of time-to-event data of
343 thermal sensation votes disclose a greater discrepancy. This may be due to structural
344 failure, as it did not account TRPs temperature sensors, equalized the coding strategy
345 between mammals (e.g. cat) and higher species like man, and limited predicted range
346 for ambient air temperatures above 12°C [9,56,82,83]. On the other side of specificity
347 rate coding, we proposed the concept of population coding that allow the combinatorial
348 co-activation of differential expression of skin TRPs that crosstalk with other somatic
349 cells in central or periphery level to explain the psychophysiological pattern of
350 temperature discrimination threshold [82,84]. That is, during water immersion at 26°C
351 in our study, some cool sensitive ion channels were triggered primarily from skin
352 thermal stimuli, enforcing even more this signal from the cool-mechanical afferents

353 provoking from muscle tremor during shivering thermogenesis, mostly observed in
354 unacclimatized participants [2,84].

355 Particular attention is needed to devote to linguistic editing of thermal
356 categories, chiefly to the escalation of the semantic nuance of the basic thermal
357 adjectives [19,24,55]. Indeed, adjectival descriptors (much too, too, comfortably,
358 slightly) that accompanied basic temperature terms (cool, neutral, warm) as for example
359 in the ASHRAE and Glickman-Weiss scale may further strengthened the amorphous
360 tendency of thermal sensation possibly resulting in a greater discrepancy and
361 measurement uncertainty among conscious responses [56,11,19,24,55,12,34,8,50]. It is
362 quite common voters to focus more on the central values than on the extremities upon
363 a scale e.g., selecting more easily “slightly cool” and then the “cool” anchor, when
364 rating near thermoneutral zone affecting by temperature, immersion duration and
365 personal characteristics. The cool temperature stimuli were expressed verbally identical
366 among all the subjects upon the 6-point thermal sensation scale, while in previous
367 studies, in which thermal sensitivity was rated using other sensorial scales has shown a
368 variety range from “cool” to “neutral” [2,12,34,56]. Furthermore, time response
369 increases as more increases the number of points and may steer to erroneous making-
370 decisions and may threaten the validity of thermal sensation [2,27,85].

371 Hitherto, conscious temperature judgment was supposed purely subjective in
372 water, ergo a poor indicator for body heat stress due to the absence or underestimation
373 of a mathematical connection of thermal perception with biometeorological factors
374 (e.g., ambient and body temperature) [4,83]. Indeed, methodological (e.g., water
375 temperature, thermal sensation scale), statistical designs and correlational analysis
376 either have violated some assumptions or have overridden holistic theoretical
377 knowledge with a consequence to fail to capture the whole “true” empirical evidence
378 for thermal sensation [1,3,4,56,63,83]. For example, Phik correlation coefficient, which
379 never has been used in behavioral thermoregulation studies, is working well both with
380 categorical (e.g., thermal sensation, comfort) and interval data (e.g., core and skin
381 temperature) appearing as an either linear or non-linear relationship. This tool allows
382 us to compare ‘apple and oranges’, but its calculation requires expensive software and
383 complex calculations [86]. Overall, we cohered theoretical with empirical
384 measurements about behavioral and physiological thermoregulation, as changes in
385 sensory cognitive performance during passive thermal stress are significantly

386 associated with changes in thermophysiological variables of individuals (Kingma et al.,
387 2020).

388

389 **Limitations**

390 The proposed integrated scale was superimposed exclusively with data during under
391 water exposure. In the present pilot study, we had checked only for face validity;
392 however, it is required a full validation of the scale using a greater variety of air and
393 water temperatures, while measuring temperatures in body and environment with
394 precise instruments than we had selected. Furthermore, a stronger design, to assess body
395 heat storage would include indirect calorimetry to measure metabolic heat production.
396 Additionally, Type I & II errors on Likert scales with no equivalent distances such as
397 in thermal sensation scales, e.g., ASHRAE scale, were usually derived from
398 misapplication of parametric statistics (t-test, ANOVA, Pearson correlation), anchoring
399 points, instrument sensitivity, and a reduced power [8,26,34,50]. Therefore, these
400 should have been taken altogether in serious consideration for a full validation of the
401 integrated sensation scale.

402

403 **Implications**

404 Using a thermal perception scale that is capable of estimating thermal strain could help
405 medical doctors and aquatic practitioners to prescribe aquatic exercise for concrete rate
406 of water temperature ranges. For example, if a swimmer with multiple sclerosis or
407 cardiac failure feels the water as “warm” from the beginning, this means that water
408 temperature is above the thermoneutral spot and can worsen his clinical symptoms.
409 Feeling the warmth sensation during exercise in cool water following our temperature
410 classification could be translated into an increasement of body heat storage. Thermal
411 sensation may act as an alarming precaution for coaches to modify the daily training
412 (e.g., by reducing intensity and increasing rest) for a safe and beneficial aquatic session.
413 Another application is in the lifeguarding domain, where a deterioration of coldness of
414 the sea bather may indicate the probability of hypothermia, when meteorological
415 conditions and immersion duration are already known. Montgomery’s work is one of
416 the most well-established thermophysiological model to predict somatic reactions (e.g.,
417 shivering, core and skin temperature) for head-in and head-out water activities applying
418 mostly for military purposes [87]. However, our data may be useful for the
419 advancement of such model’s equations to evaluate additionally thermal sensation and

420 comfort. From an ecological perspective, there is an urgent need to develop such a
421 simulated thermal perception tool to regulate thermal energy demands of pools for a
422 healthy comfortable working environment bearing in mind its main usage (e.g., leisure
423 activities, rehabilitation programs, sport), because its role determines the minimum
424 operational water temperature, and energy savings. Clearly, the type of sensation scales
425 (e.g., integrated 6-point, 7-point or 9-point extended ASHRAE) should be taken into
426 account by thermal modelers, as it influences the estimations for desired ambient
427 occasions [12,34]. Finding the optimal number of categories upon a scale for an easy
428 and valid thermal sensation measurement requires further studies to be conducted in a
429 variety of water temperatures, with greater sample size, also, measuring, if applicable,
430 body heat storage and time response via eye-tracking technology.

431

432 **Conclusion**

433 Our main finding supports our initial hypothesis that thermal expression capable of
434 predicting human thermoregulatory responses. In general terms, sensory phenomenon
435 for temperature in terms of neural events, physiological and psychological responses is
436 complex. What is new on our thermal sensation model is inclusion of the brand new
437 concept about temperature threshold of TRPs for providing a theoretical framework on
438 thermal perception, especially in the steady state. We critically analyze thermal votes
439 within the context of environmental physiology, neurophysiology, and psychometry.
440 These preliminary results suggest that the 6-point integrated sensation scale appeared a
441 homogenous sense among participants during water immersion duration with an
442 acceptable predictability for water and thermophysiological indices. A shift on the
443 central thermal votes (e.g., from cool to neutral) may be sensitive enough for the
444 detection of a thermoeffector alteration i.e., body heat storage during water immersion
445 duration. Our study revealed that our model could characterize body thermal load
446 though whole-body thermal sensation based on well-established thermoregulatory
447 mechanisms during water immersion. Further research will be needed to validate the
448 accuracy of our behavioral model in a variety of water temperatures and in larger
449 sample size.

450

451

452

453 **Funding Statement**

454 Funding not received for the study.

455

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459 **Ethical Approval**

460 The research protocol had been approved by the Ethics and Bioethics Committee of the

461 School of Physical Education and Sport Science at the National and Kapodistrian

462 University of Athens (No 1162/12-02-2020).

463

464

465 **References**

- 466 1. Hoffman RG, Pozos RS. Experimental hypothermia and cold perception. *Aviat Space*
467 *Environ Med.* 1989;60:964–9.
- 468 2. Ntoumani M, Dugué B, Rivas E, Gongaki K. Thermoregulation and thermal sensation
469 during whole-body water immersion at different water temperatures in healthy individuals:
470 A scoping review. *Journal of Thermal Biology.* 2023;112:103430.
- 471 3. Saycell J, Lomax M, Massey H, Tipton M. How cold is too cold? Establishing the minimum
472 water temperature limits for marathon swim racing. *British Journal of Sports Medicine.*
473 2019;53:1078–84.
- 474 4. Tipton M, Bradford C. Moving in extreme environments: open water swimming in cold
475 and warm water. *Extreme Physiology & Medicine.* 2014;3:12.
- 476 5. Auliciems A. Towards a psycho-physiological model of thermal perception. *Int J*
477 *Biometeorol.* 1981;25:109–22.
- 478 6. Chatonnet J, Cabanac M. The perception of thermal comfort. *Int J Biometeorol.*
479 1965;9:183–93.
- 480 7. Lee J-Y, Tochiara Y, Wakabayashi H, Stone EA. Warm or Slightly Hot? Differences in
481 Linguistic Dimensions Describing Perceived Thermal Sensation. *Journal of PHYSIOLOGICAL*
482 *ANTHROPOLOGY.* 2009;28:37–41.
- 483 8. Schweiker M, Fuchs X, Becker S, Shukuya M, Dovjak M, Hawighorst M, et al. Challenging
484 the assumptions for thermal sensation scales. *Building Research & Information.*
485 2017;45:572–89.
- 486 9. Gagge AP, Stolwijk JAJ, Hardy JD. Comfort and thermal sensations and associated
487 physiological responses at various ambient temperatures. *Environmental Research.*
488 1967;1:1–20.
- 489 10. Holmér I, Bergh U. Metabolic and thermal response to swimming in water at varying
490 temperatures. *Journal of Applied Physiology.* 1974;37:702–5.
- 491 11. Lee J-Y, Stone EA, Wakabayashi H, Tochiara Y. Issues in combining the categorical and
492 visual analog scale for the assessment of perceived thermal sensation: Methodological and
493 conceptual considerations. *Applied Ergonomics.* 2010;41:282–90.
- 494 12. Temel M, Johnson AA, Havenith G, Arnold JT, West AM, Lloyd AB. An examination of five
495 theoretical foundations associated with localized thermosensory testing. *Eur J Appl Physiol.*
496 2021;121:1943–54.
- 497 13. Frank SM, Raja SN, Bulcao CF, Goldstein DS. Relative contribution of core and cutaneous
498 temperatures to thermal comfort and autonomic responses in humans. *Journal of Applied*
499 *Physiology.* 1999;86:1588–93.
- 500 14. Rivas E, Newmire DE, Ben-Ezra V. Obese type 2 diabetics have a blunted hypotensive
501 response to acute hyperthermia therapy that does not affect the perception of thermal
502 stress or physiological strain compared to healthy adults. *Physiology & Behavior.*
503 2016;165:374–82.

- 504 15. Shimazaki Y, Yoshida A, Yamamoto T. Thermal responses and perceptions under distinct
505 ambient temperature and wind conditions. *Journal of Thermal Biology*. 2015;49–50:1–8.
- 506 16. Attia M, Engel P. Thermal pleasantness sensation: an indicator of thermal stress. *Europ J*
507 *Appl Physiol*. 1982;50:55–70.
- 508 17. Fine BJ. The effect of exposure to an extreme stimulus on judgments of some stimulus-
509 related words. *Journal of Applied Psychology*. 1961;45:41–4.
- 510 18. Glickman-Weiss EL, Hearon CM, Nelson AG, Robertson RJ. A Thermal Perception Scale for
511 Use during Resting Exposure to Cold Air. *Percept Mot Skills*. 1994;79:547–60.
- 512 19. Lehrer A. Static and dynamic elements in semantics hot warm cool cold. Paper in
513 *Linguistics*. 1970;3:349–73.
- 514 20. Leon GR, Koscheyev VS, Stone EA. Visual analog scales for assessment of thermal
515 perception in different environments. *Aviat Space Environ Med*. 2008;79:784–6.
- 516 21. Lundgren P, Henriksson O, Kuklane K, Holmér I, Naredi P, Björnstig U. Validity and
517 reliability of the Cold Discomfort Scale: a subjective judgement scale for the assessment of
518 patient thermal state in a cold environment. *J Clin Monit Comput*. 2014;28:287–91.
- 519 22. McIntyre DA. Thermal sensation. A comparison of rating scales and cross modality
520 matching. *Int J Biometeorol*. 1976;20:295–303.
- 521 23. Pantavou K, Koletsis I, Lykoudis S, Melas E, Nikolopoulou M, Tsiros IX. Native influences
522 on the construction of thermal sensation scales. *Int J Biometeorol*. 2020;64:1497–508.
- 523 24. Prator C. Adjectives of Temperature. *ELT Journal*. 1963;17:158–64.
- 524 25. Luce RD, Krumbhansl CL. Measurement, scaling, and psychophysics. *Stevens' handbook of*
525 *experimental psychology: Perception and motivation; Learning and cognition, Vols 1-2, 2nd*
526 *ed. Oxford, England: John Wiley & Sons; 1988. p. 3–74.*
- 527 26. Favero M, Luparelli A, Carlucci S. Analysis of subjective thermal comfort data: A statistical
528 point of view. *Energy and Buildings*. 2023;281:112755.
- 529 27. Miller GA. The magical number seven, plus or minus two: Some limits on our capacity for
530 processing information. *Psychological Review*. 1956;63:81–97.
- 531 28. Zhang H. *Human Thermal Sensation and Comfort in Transient and Non-Uniform Thermal*
532 *Environments*. UC Berkley; 2003.
- 533 29. Rohles F. Temperature & Temperament. *ASHRAE Journal*. 2007;
- 534 30. Stevens SS. On the Theory of Scales of Measurement. *Science*. 1946;103:677–80.
- 535 31. Sama A, Lawrence T. The Assumption of Equidistance in the Seven-point Thermal
536 Sensation Scale and a Comparison between Categorical and Continuous Metrics - ProQuest.
537 *ASHRAE Transactions [Internet]*. Atlanta: ASHRAE Transactions; 2019 [cited 2023 Jul 9]. p.
538 149–57. Available from:
539 [https://www.proquest.com/openview/d845a829adbd3f864b71fd96b233686a/1?pq-](https://www.proquest.com/openview/d845a829adbd3f864b71fd96b233686a/1?pq-origsite=gscholar&cbl=34619)
540 [origsite=gscholar&cbl=34619](https://www.proquest.com/openview/d845a829adbd3f864b71fd96b233686a/1?pq-origsite=gscholar&cbl=34619)

- 541 32. Kim J, Ryu J, Jeong B, de Dear R. Semantic discrepancies between Korean and English
542 versions of the ASHRAE sensation scale. *Building and Environment*. 2022;221:109343.
- 543 33. Schweiker M, Abdul-Zahra A, André M, Al-Atrash F, Al-Khatri H, Alprianti RR, et al. The
544 Scales Project, a cross-national dataset on the interpretation of thermal perception scales.
545 *Sci Data*. 2019;6:289.
- 546 34. Schweiker M, André M, Al-Atrash F, Al-Khatri H, Alprianti RR, Alsaad H, et al. Evaluating
547 assumptions of scales for subjective assessment of thermal environments – Do laypersons
548 perceive them the way, we researchers believe? *Energy and Buildings*. 2020;211:109761.
- 549 35. Li H. TRP Channel Classification. In: Wang Y, editor. *Transient Receptor Potential*
550 *Canonical Channels and Brain Diseases* [Internet]. Dordrecht: Springer Netherlands; 2017
551 [cited 2022 Oct 17]. p. 1–8. Available from: https://doi.org/10.1007/978-94-024-1088-4_1
- 552 36. Bautista DM, Siemens J, Glazer JM, Tsuruda PR, Basbaum AI, Stucky CL, et al. The
553 menthol receptor TRPM8 is the principal detector of environmental cold. *Nature*.
554 2007;448:204–8.
- 555 37. Lötsch J, Kringel D, Geisslinger G, Oertel BG, Resch E, Malkusch S. Machine-Learned
556 Association of Next-Generation Sequencing-Derived Variants in Thermosensitive Ion
557 Channels Genes with Human Thermal Pain Sensitivity Phenotypes. *International Journal of*
558 *Molecular Sciences*. 2020;21:4367.
- 559 38. Pan Y, Thapa D, Baldissera L, Argunhan F, Aubdool AA, Brain SD. Relevance of TRPA1 and
560 TRPM8 channels as vascular sensors of cold in the cutaneous microvasculature. *Pflugers*
561 *Arch - Eur J Physiol*. 2018;470:779–86.
- 562 39. Weyer-Menkhoff I, Pinter A, Schlierbach H, Schänzer A, Lötsch J. Epidermal expression of
563 human TRPM8, but not of TRPA1 ion channels, is associated with sensory responses to local
564 skin cooling. *Pain*. 2019;160:2699–709.
- 565 40. Zimmermann K, Lennerz JK, Hein A, Link AS, Kaczmarek JS, Delling M, et al. Transient
566 receptor potential cation channel, subfamily C, member 5 (TRPC5) is a cold-transducer in the
567 peripheral nervous system. *Proceedings of the National Academy of Sciences*.
568 2011;108:18114–9.
- 569 41. Denda M, Sokabe T, Fukumi-Tominaga T, Tominaga M. Effects of Skin Surface
570 Temperature on Epidermal Permeability Barrier Homeostasis. *Journal of Investigative*
571 *Dermatology*. 2007;127:654–9.
- 572 42. Masamoto Y, Kawabata F, Fushiki T. Intragastric Administration of TRPV1, TRPV3,
573 TRPM8, and TRPA1 Agonists Modulates Autonomic Thermoregulation in Different Manners
574 in Mice. *Bioscience, Biotechnology, and Biochemistry*. 2009;73:1021–7.
- 575 43. Nilius B, Bíró T, Owsianik G. TRPV3: time to decipher a poorly understood family
576 member! *The Journal of Physiology*. 2014;592:295–304.
- 577 44. Singh AK, McGoldrick LL, Sobolevsky AI. Structure and gating mechanism of the transient
578 receptor potential channel TRPV3. *Nat Struct Mol Biol*. 2018;25:805–13.
- 579 45. Vriens J, Voets T. Sensing the heat with TRPM3. *Pflugers Arch - Eur J Physiol*.
580 2018;470:799–807.

- 581 46. Mori Y, Takahashi N, Kurokawa T, Kiyonaka S. TRP channels in oxygen physiology:
582 distinctive functional properties and roles of TRPA1 in O₂ sensing. *Proceedings of the Japan*
583 *Academy, Series B.* 2017;93:464–82.
- 584 47. Wang H, Siemens J. TRP ion channels in thermosensation, thermoregulation and
585 metabolism. *Temperature.* 2015;2:178–87.
- 586 48. Douma MJ, Aves T, Allan KS, Bendall JC, Berry DC, Chang W-T, et al. First aid cooling
587 techniques for heat stroke and exertional hyperthermia: A systematic review and meta-
588 analysis. *Resuscitation.* 2020;148:173–90.
- 589 49. Nagashima K, Nakata H, Harada T, Kato I, Sadato N. Differences in the neural networks of
590 thermal sensation with and without evaluation process. *IBRO Neuroscience Reports.*
591 2022;13:274–83.
- 592 50. Wang J, Wang Z, de Dear R, Luo M, Ghahramani A, Lin B. The uncertainty of subjective
593 thermal comfort measurement. *Energy and Buildings.* 2018;181:38–49.
- 594 51. Boateng GO, Neilands TB, Frongillo EA, Melgar-Quiñonez HR, Young SL. Best Practices for
595 Developing and Validating Scales for Health, Social, and Behavioral Research: A Primer.
596 *Frontiers in Public Health* [Internet]. 2018 [cited 2022 Apr 2];6. Available from:
597 <https://www.frontiersin.org/article/10.3389/fpubh.2018.00149>
- 598 52. Polit DF, Beck CT. The content validity index: Are you sure you know what's being
599 reported? critique and recommendations. *Research in Nursing & Health.* 2006;29:489–97.
- 600 53. Hensel H. Correlations of neural activity and thermal sensation in man. *Sensory*
601 *Functions of the Skin in Primates* [Internet]. Elsevier; 1976 [cited 2023 Aug 13]. p. 331–53.
602 Available from: <https://linkinghub.elsevier.com/retrieve/pii/B9780080212081500291>
- 603 54. Hensel H, Schafer K. Thermoreception and Temperature Regulation in Man. In: Ring EFJ,
604 Phillips B, editors. *Recent Advances in Medical Thermology* [Internet]. Boston, MA: Springer
605 New York; 1984 [cited 2023 Jun 24]. p. 51–64. Available from: [https://doi.org/10.1007/978-](https://doi.org/10.1007/978-1-4684-7697-2_8)
606 [1-4684-7697-2_8](https://doi.org/10.1007/978-1-4684-7697-2_8)
- 607 55. Sutrop U. Basic temperature terms and subjective temperature scale. 1998;4:60–104.
- 608 56. Kingma BRM, Schellen L, Frijns AJH, Van Marken Lichtenbelt WD. Thermal sensation: a
609 mathematical model based on neurophysiology: *Neurophysiology of thermal sensation.*
610 *Indoor Air.* 2012;22:253–62.
- 611 57. Craig AB, Dvorak M. Thermal regulation of man exercising during water immersion.
612 *Journal of Applied Physiology.* 1968;25:28–35.
- 613 58. Daanen HA, Struijs N van der. The Risk Index for Frostbite [Internet]. TNO Defence
614 Security and Safety Soester-Berg (Netherlands); 2005 May. Available from:
615 <https://apps.dtic.mil/sti/citations/ADA454799>
- 616 59. Hayward MG, Keatinge WR. Roles of subcutaneous fat and thermoregulatory reflexes in
617 determining ability to stabilize body temperature in water. *The Journal of Physiology.*
618 1981;320:229–51.

- 619 60. Solianik R, Skurvydas A, Vitkauskienė A, Brazaitis M. Gender-specific cold responses
620 induce a similar body-cooling rate but different neuroendocrine and immune responses.
621 *Cryobiology*. 2014;69:26–33.
- 622 61. Tipton M, Collier N, Massey H, Corbett J, Harper M. Cold water immersion: kill or cure?
623 *Experimental Physiology*. 2017;102:1335–55.
- 624 62. Wakabayashi H, Kaneda K, Sato D, Tochiara Y, Nomura T. Effect of non-uniform skin
625 temperature on thermoregulatory response during water immersion. *Eur J Appl Physiol*.
626 2008;104:175–81.
- 627 63. Mekjavic IB, Morrison JB. A Model of Shivering Thermogenesis Based on the
628 Neurophysiology of Thermoreception. *IEEE Transactions on Biomedical Engineering*.
629 1985;BME-32:407–17.
- 630 64. Zygmunt PM, Högestätt ED. TRPA1. In: Nilius B, Flockerzi V, editors. *Mammalian*
631 *Transient Receptor Potential (TRP) Cation Channels: Volume I* [Internet]. Berlin, Heidelberg:
632 Springer; 2014 [cited 2023 Jul 13]. p. 583–630. Available from: [https://doi.org/10.1007/978-](https://doi.org/10.1007/978-3-642-54215-2_23)
633 [3-642-54215-2_23](https://doi.org/10.1007/978-3-642-54215-2_23)
- 634 65. Lee DT, Toner MM, McArdle WD, Vrabas IS, Pandolf KB. Thermal and metabolic
635 responses to cold-water immersion at knee, hip, and shoulder levels. *J Appl Physiol* (1985).
636 1997;82:1523–30.
- 637 66. O'Brien C, Young AJ, Lee DT, Shitzer A, Sawka MN, Pandolf KB. Role of core temperature
638 as a stimulus for cold acclimation during repeated immersion in 20°C water. *Journal of*
639 *Applied Physiology*. 2000;89:242–50.
- 640 67. Tikuisis P, Gonzalez RR, Pandolf KB. Thermoregulatory model for immersion of humans in
641 cold water. *J Appl Physiol* (1985). 1988;64:719–27.
- 642 68. Tikuisis P, Jacobs I, Moroz D, Vallerand A, Martineau L. Comparison of thermoregulatory
643 responses between men and women immersed in cold water. *Journal of applied physiology*
644 (Bethesda, Md : 1985). 2000;89:1403–11.
- 645 69. Allison TG, Reger WE. Thermoregulatory, cardiovascular, and psychophysical response to
646 alcohol in men in 40 degrees C water. *Journal of Applied Physiology*. 1992;72:2099–107.
- 647 70. Fujishima K. Thermoregulatory responses during exercise and a hot water immersion and
648 the affective responses to peripheral thermal stimuli. *Int J Biometeorol*. 1986;30:1–19.
- 649 71. Kojima D, Nakamura T, Banno M, Umemoto Y, Kinoshita T, Ishida Y, et al. Head-out
650 immersion in hot water increases serum BDNF in healthy males. *International Journal of*
651 *Hyperthermia*. 2018;34:834–9.
- 652 72. Rodrigues P, Trajano GS, Wharton L, Minett GM. Muscle temperature kinetics and
653 thermoregulatory responses to 42 °C hot-water immersion in healthy males and females.
654 *Eur J Appl Physiol*. 2020;120:2611–24.
- 655 73. Stephens J, Argus C, Driller M. The Relationship between Body Composition and Thermal
656 Responses to Hot and Cold Water Immersion. *Journal of Human Performance in Extreme*
657 *Environments* [Internet]. 2014;11. Available from:
658 <https://docs.lib.purdue.edu/jhpee/vol11/iss2/1>

- 659 74. Weston CF, O'Hare JP, Evans JM, Corrall RJ. Haemodynamic changes in man during
660 immersion in water at different temperatures. *Clin Sci (Lond)*. 1987;73:613–6.
- 661 75. An J, Lee I, Yi Y. The Thermal Effects of Water Immersion on Health Outcomes: An
662 Integrative Review. *International Journal of Environmental Research and Public Health*.
663 2019;16:1280.
- 664 76. Clark WC, Carroll JD, Yang JC, Janal MN. Multidimensional scaling reveals two dimensions
665 of thermal pain. *J Exp Psychol Hum Percept Perform*. 1986;12:103–7.
- 666 77. Hardy JD, Stolwijk J a. J, Hammel HT, Murgatroyd D. Skin temperature and cutaneous
667 pain during warm water immersion. *Journal of Applied Physiology*. 1965;20:1014–21.
- 668 78. Wang YY, Chang RB, Liman ER. TRPA1 is a component of the nociceptive response to
669 CO₂. *J Neurosci*. 2010;30:12958–63.
- 670 79. Cerovac S, Roberts AHN. Burns sustained by hot bath and shower water. *Burns*.
671 2000;26:251–9.
- 672 80. Ramanathan NL. A new weighting system for mean surface temperature of the human
673 body. *Journal of Applied Physiology*. 1964;19:531–3.
- 674 81. Paricio-Montesinos R, Schwaller F, Udhayachandran A, Rau F, Walcher J, Evangelista R, et
675 al. The Sensory Coding of Warm Perception. *Neuron*. 2020;106:830-841.e3.
- 676 82. Xiao R, Xu XZS. Temperature Sensation: From Molecular Thermosensors to Neural
677 Circuits and Coding Principles. *Annual Review of Physiology*. 2021;83:205–30.
- 678 83. Hensel H, Konietzny F. Problems of Correlating Cutaneous Sensation with Neural Events
679 in Man. In: Kenshalo DR, editor. *Sensory Functions of the Skin of Humans* [Internet]. Boston,
680 MA: Springer US; 1979 [cited 2023 Aug 13]. p. 261–77. Available from:
681 https://doi.org/10.1007/978-1-4613-3039-4_14
- 682 84. Ma Q. Labeled lines meet and talk: population coding of somatic sensations. *J Clin Invest*.
683 2010;120:3773–8.
- 684 85. Matell MS, Jacoby J. Is there an optimal number of alternatives for Likert-scale items?
685 Effects of testing time and scale properties. *Journal of Applied Psychology*. 1972;56:506–9.
- 686 86. Baak M, Koopman R, Snoek H, Klous S. A new correlation coefficient between
687 categorical, ordinal and interval variables with Pearson characteristics. *Computational
688 Statistics & Data Analysis*. 2020;152:107043.
- 689 87. Montgomery LD. A model of heat transfer in immersed man. *Ann Biomed Eng*.
690 1974;2:19–46.
- 691
692

693 **Table 1.** I-CVI and S-CVI of the 6-point integrated scale.

Identification of the thermoregulatory factors to assess heat stress

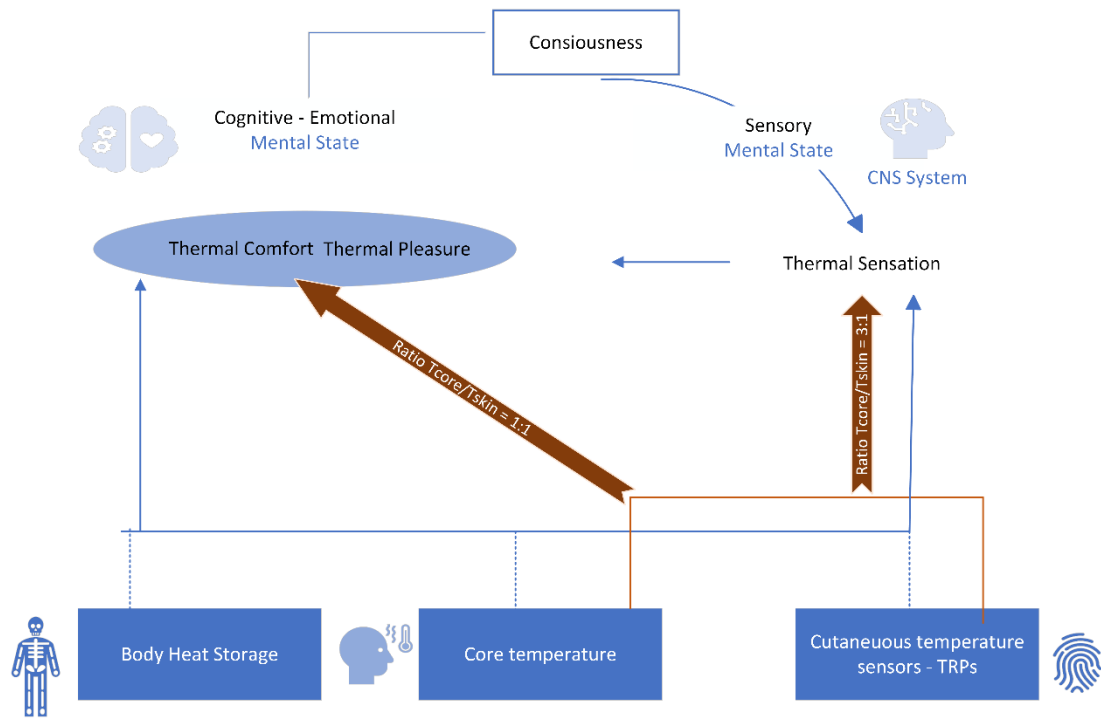
Listed below are some factors for assessing thermal stress during whole-body water immersion

- Please indicate the appropriateness of factors to measure thermal sensation (Domain 1 & 2) or thermal stress (Domain 3):

	1	2	3	4	CVI
	the item is not relevant	the item is somewhat relevant	the item is quite relevant	the item is highly relevant	
1. Domain: <i>Environment</i>					
1	Water temperature				1.00
2	Air temperature				0.71
3	Humidity				0.57
4	Duration immersion				0.86
2. Domain: <i>Physiological Thermoregulation</i>					
5	Core temperature				0.86
6	Skin temperature				0.86
7	Body Heat Storage				0.86
8	Heart rate				0.29
9	Ventilation				0.29
10	Shivering				1.00
11	Sweating				0.57
12	Pain				0.57
13	TRP's (transient receptor potential ion channels)				0.71
14	Thermal Injuries				0.57
3. Domain: <i>Subjective - Behavioral Thermoregulation</i>					
15	Thermal Neutral Zone				0.57
16	Thermal Comfort Zone				0.57
17	Thermal sensation				0.86
18	Thermal comfort				0.86
	S-CVI				0.70
	S-CVI (after removal factors with I-CVI < 0.57)				0.92

694

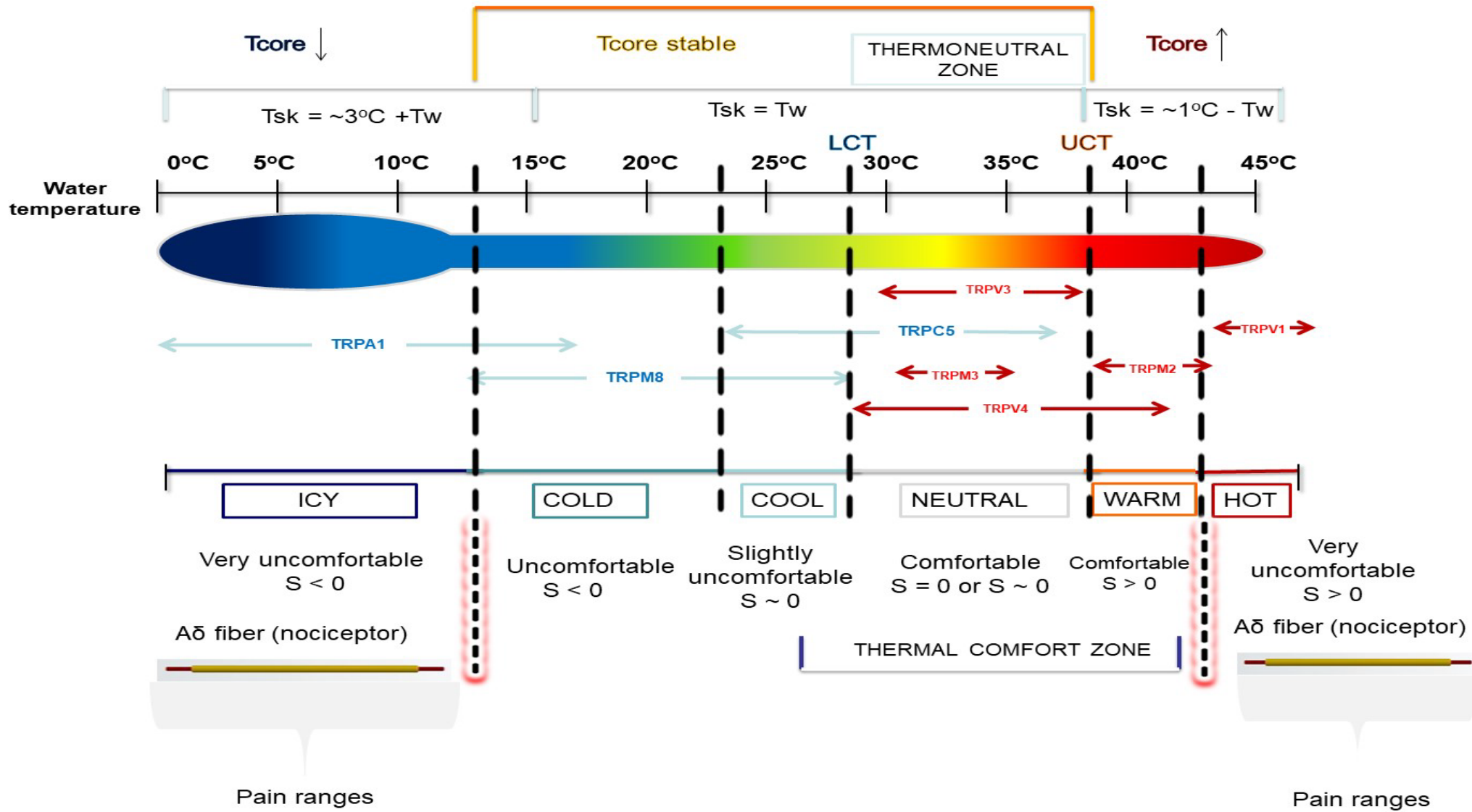
695



696

697 Figure 1. Thermoeffector relationship between physiological indices and conscious mental
698 state

699



701 **Fig. 2** depicts TRP ion channels activation matched with our 6-point thermal scale. Each selected temperature ranges has been chosen depending
702 on how a subject expressed his own thermal sensation after a 30 min water immersion and with what is known about the activation of TRP ion
703 channels. TRP, transient receptor potential channel; Tsk, skin temperature; Tcore, Core body temperature; S, heat storage; LCT, lower critical
704 temperature; HCT, higher critical temperature (Ntoumani et al., 2022).

705

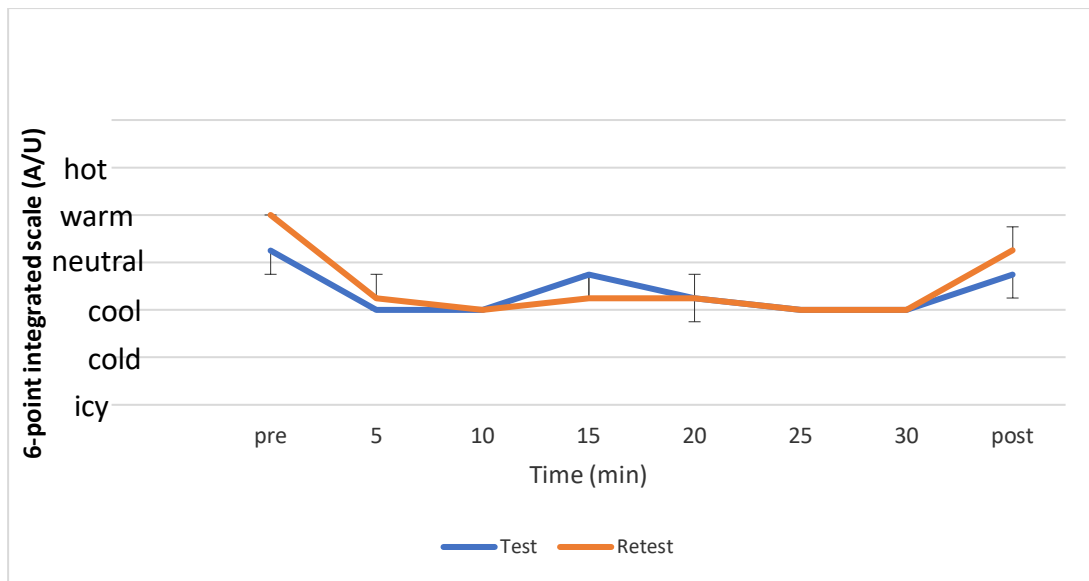


Figure 3. Time-course of thermal sensation votes based on the 6-point integrated sensation scale during the experiment; Mean \pm SE.